Low-Cost Sensors for Healthier Indoor Air Quality in Impacted Communities

FINAL REPORT

Contract 22RD020

CALIFORNIA AIR RESOURCES BOARD

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Glossary of Acronyms

AQ	Air quality
AQI	Air quality index
AQMD	Air quality management district
AQ-SPEC	Air Quality Sensor Performance Evaluation Center
BLE	Bluetooth low energy
CARB	California Air Resources Board
CO	Carbon monoxide
CO_2	Carbon dioxide
DIY	Do-it-yourself
EC	Electrochemical
EPA	Environmental Protection Agency
FEM	Federal Equivalent Method
FRM	Federal Reference Method
GPS	Global positioning system
h × w × d	height × width × depth
H_2S	Hydrogen sulfide
HCHO	Formaldehyde
IAQ	Indoor air quality
in.	Inches
LCS	Low-cost sensors
MAE	Mean absolute error
MOS/MOX	Metal oxide semiconductor
NAAQS	National Ambient Air Quality Standards
NDIR	Nondispersive infrared
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
O_3	Ozone
OPC	Optical particle counter
PID	Photoionization detector
PM	Particulate matter
PM_1	Particles < 1 µm
$PM_{2.5}$	Fine particulate matter (< 2.5 µm)
PM_{10}	Coarse particles (< 10 µm)
ppb	Parts per billion

ppm	Parts per million
R^2	Coefficient of Determination
RH	Relative humidity
SO_2	Sulfur dioxide
SO_x	Sulfur oxides
T	Temperature
TVOC/tVOC	Total volatile organic compounds
$\mu g\ m^{-3}$	Micrograms per cubic meter
μm	Micrometers
US/U.S.	United States
VOCs	Volatile organic compounds

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Executive Summary

Indoor air quality (IAQ) significantly influences human health and well-being, especially in impacted communities where socioeconomic factors and residential proximity to pollution sources increase exposure risks. In these communities, low-cost sensors (LCS) can offer an accessible, user-friendly, and cost-effective solution for monitoring indoor air pollution to facilitate informed decision-making and improve IAQ. Thus, the overarching goal of this project is to produce a white paper that critically summarizes LCS technologies for indoor applications, comprehensively reviews past efforts that evaluate the utility of these devices for assessing IAQ, and establishes actionable guidance for impacted communities with adoption recommendations on LCS technologies and strategies to mitigate indoor air pollution.

This white paper summarizes the extensive range of commercially-available LCS technologies for IAQ monitoring, and highlights their key performance considerations and limitations. These efforts benefited from guidance provided by government agencies such as the US Environmental Protection Agency and the South Coast Air Quality Management District (i.e., the Air Quality Sensor Performance Evaluation Center). LCS, as defined in this white paper, are packaged devices that can be readily deployed "out of the box" and meet specific price criteria for both single- (less than \$500) and multi-pollutant (less than or equal to \$2,500) devices. The market survey identified 30 single-pollutant and 42 multi-pollutant LCS devices from 31 different manufacturers. For these devices, associated performance evaluations, data quality considerations, technical investments, and operational factors for LCS deployments were further explored.

This investigation highlights several important findings about the current state of LCS and their performance for IAQ measurements. For instance, the performance of particulate matter (PM) LCS is often limited in detecting very small particles (<0.3 µm), which are prevalent in indoor environments from sources like cooking and candle burning. PM LCS are also limited in detecting sources with larger supermicron particles (>1 µm) such as dust, which can be a relevant source in some indoor environments. Additionally, the response of PM sensors to different sources can vary significantly, making them less reliable for the diverse range of indoor air pollution sources. For gas-pollutant LCS, performance evaluations were more challenging to find in the scientific literature and other agency resources, as most studies focused on individual sensing components rather than integrated devices, which are the primary focus of this white paper.

From the available references, gas-pollutant LCS were found to be prone to cross-interference from non-target pollutants and sensitive to environmental parameters. The lack of sensitivity for

some gas LCS, e.g., NO_2 and VOCs, due to high detection limits, also constrains their utility for IAQ management and targeting indoor sources for mitigation. This section of the white paper underscores the need for technological advancements of LCS toward improving their accuracy, reliability, and robustness for air quality measurements, particularly in indoor environments. In addition, establishing standards for LCS performance (e.g., ASTM D8405-21 for $PM_{2.5}$) across different pollutants and environments is crucial for systematically validating these devices and assessing their capabilities and limitations in a standardized manner.

This second section of this white paper includes a comprehensive review of IAQ monitoring studies using LCS within a participatory framework, requiring the engagement, involvement, or collaboration of occupants. The review particularly focuses on studies engaging communities disproportionately impacted by indoor air pollution. Despite the increasing applications of LCS for air pollutant measurements and the growing field of IAQ research, only 29% of the narrowly scoped and reviewed studies specifically addressed impacted populations within the literature retrieval period. This gap shows a lag in community-facing efforts of IAQ data collection; nonetheless, the reviewed studies provide valuable insights and lessons learned, particularly in leveraging LCS to address disparities in IAQ across impacted communities.

Findings from the small number of studies show that impacted communities frequently experience high levels of indoor air pollution, sometimes exceeding prior findings in other homes and established air quality guidelines. The studies also suggest that improving IAQ in impacted communities can be facilitated by leveraging LCS for community engagement and education, developing and disseminating affordable tools and solutions, advocating for policy changes, and advancing LCS technical improvements. Longitudinal studies are recommended for capturing chronic exposure and seasonal variations, to provide a deeper understanding of health impacts and intervention efficacy. Furthermore, continued integration of mobile applications, wearables, and digital tools with LCS, as well as scaling successful models of community-facing engagement, can address widespread IAQ issues and promote environmental equity in impacted communities.

The white paper also collates insights from stakeholder interviews with an LCS manufacturer, IAQ researchers, members of impacted communities, and LCS users to understand the challenges, needs, and experiences related to these devices. These interviews highlight the need for targeted public education on IAQ, LCS monitoring indoors, data interpretation, indoor air pollution sources, and mitigation strategies. IAQ researchers emphasize the need for standardized testing protocols and the role of regulators in shaping guidelines for LCS validation across manufacturers.

LCS users and community members note the importance of improving LCS accessibility, including the availability of technical support and affordable solutions or programs to improve IAQ.

Additionally, community members report concerns about landlord retaliation when attempting to address IAQ issues in residential housing, highlighting the challenges vulnerable populations face in advocating for healthier living environments. They also stressed the need for increased public education on the hazards of poor IAQ in both homes and workplaces. Interview insights point to the broader need for systemic changes, including stronger tenant protections, increased regulatory oversight, and community-driven initiatives to improve IAQ, while aligning technological advancements of LCS with the most pressing needs across stakeholders, including manufacturers, researchers, air quality agencies, and communities.

Finally, recommendations for various stakeholders are presented based on the content reviewed and summarized throughout this white paper. These recommendations are aimed at driving the adoption of LCS in impacted communities to sustain healthier IAQ. They include accessible allocation of funding and resources to communities, supporting community-led air monitoring projects, and fostering partnerships with a wide range of stakeholders, including air quality agencies, environmental organizations, and research institutions. Expanding these efforts locally and statewide can ensure that adequate resources and expertise are directed to overburdened communities to advance environmental equity and public health. While a detailed assessment of these recommendations is beyond the scope of this white paper, it serves as a general foundation to continue guiding community-focused IAQ initiatives and regulatory decision-making toward fostering healthier indoor environments and encouraging collaboration among key stakeholders.

Overall, findings from this white paper suggest that while calibration and high data confidence are crucial for research-oriented LCS applications, they may be less critical for community-level IAQ efforts, where LCS can still serve as valuable tools for identifying pollution trends and informing interventions. This white paper further demonstrates that by leveraging the capabilities and cost-effectiveness of LCS, while understanding their limitations and integrating them into broader IAQ strategies, individuals and communities can create safer indoor environments, ultimately protecting their health, comfort, and well-being.

1 Introduction

Ambient air pollution remains the leading environmental risk factor for human morbidity and premature mortality worldwide[1] with long-term exposure as a major driver in the development of non-communicable diseases.[2] Characterizing ambient air pollutants such as fine particulate matter ($PM_{2.5}$), ozone (O_3), and other criteria air pollutants with designated national standards set by the United States Environmental Protection Agency (the EPA) are therefore necessary for sustaining healthy communities.

Indoor air pollution is also a major health concern responsible for millions of premature deaths,[3,4] and is the third leading cause of disability-adjusted life years globally.[5] Since people spend over two-thirds of their time indoors and often at home,[6] indoor air quality (IAQ) can greatly influence one's well-being and exposure to air pollutants.[7,8] Studies have shown that indoor air is frequently more contaminated with elevated concentrations of pollutants that can exceed outdoor levels.[9] Whereas activities such as cooking, cleaning, and combustion events (e.g., smoking and candle burning) contribute to indoor emissions, a fraction of indoor pollution also derives from the infiltration of outdoor air pollutants.

Infiltration of outdoor pollution into indoor spaces is mediated by several factors including building characteristics, such as build quality (age, design, tightness) and ventilation (natural or mechanical), as well as seasonal home dynamics and outdoor conditions.[10] For instance, newer buildings designed under more stringent energy efficiency standards have tighter envelopes,[11] which reduce the infiltration of outdoor pollution. However, this can raise concerns about indoor pollution and its implications. Further complicating IAQ is that indoor environments lack promulgated air quality standards and regulations assessing IAQ,[12,13] which may lead to epidemiological studies underestimating risk in determining one's personal exposure to air pollution (which is a combination of indoor and ambient pollution).[14,15]

This reality can manifest in significant disparities across indoor environments as IAQ can vary due to factors impacted by socioeconomic status[16] (e.g., building characteristics, indoor activities, occupant density, indoor sources, etc.), and the unequal distribution of outdoor sources of pollution, which adversely impacts low-income and racial-ethnic minority groups.[17,18] Furthermore, with trends of increasing outdoor pollution from anthropogenic emissions[19] and more frequent wildfires across the United States,[20] indoor environments become crucial as safeguards against air pollutants.[16,21] Yet, communities with low-income and racial-ethnic minority groups are less likely to benefit from the protection of their homes due to higher probabilities of inhabiting substandard housing in communities with adverse health attributes.[22–24] Additionally, the use of air filtration systems in vulnerable communities is often overlooked or unavailable due to financial constraints and a lack of information.[24,25] As a result, populations in vulnerable communities are often limited in ways to reduce exposure to pollutants indoors.

If provided with the capacity to accurately measure air pollution indoors, low-income and racial-ethnic minority communities can take actions to reduce exposure.[21,26–30] However, there is sparsely available data exploring IAQ in impacted communities that incorporate community-facing methods of data collection. Community efforts to collect such data often face barriers such as a lack of technical knowledge on suitable instrumentation options, size and costs of conventional instrumentation, inconvenient and complex methods for sample collection and analysis, and data interpretation hurdles.[31,32] Low-cost air quality sensor technologies can reduce these barriers by building capacity for communities to play a central role in air pollution monitoring.[33,34] These devices are more accessible, practical, easy to use, and cost-effective for acquiring air quality data and providing quantitative information on sampled air pollutants. Low-cost sensors (LCS) also offer high-resolution monitoring of IAQ that facilitates source identification of indoor emissions in real time, which is invaluable to managing and mitigating exposure.

LCS have proliferated in recent years and have been used widely for various applications, including ambient[35–37] and IAQ monitoring.[27,38,39] However, individual and community-scale indoor monitoring using LCS remains understudied. Much of the available data on IAQ remains largely research-driven on already established sensor networks[40] that tend to be deficient in impacted communities.[41,42] As a result, there is a need to provide technical and scientific guidance on the uses, benefits, and challenges associated with using LCS for monitoring IAQ in impacted communities. This white paper aims to synthesize information on current LCS for IAQ applications, identify key considerations from evidence-based studies, and provide useful insights for their deployment and utility in impacted communities to facilitate decision-making and improve IAQ.

2 Task summary and work described in this project

2.1 Overview

The objective of this project is to develop a white paper synthesizing information on the uses and benefits of LCS technologies for IAQ monitoring, and develop a LCS guidance document for facilitating healthier IAQ in impacted communities.

The project included four (4) tasks: (1) conduct a market survey of LCS used for IAQ monitoring and analyze how sensors compare; (2) provide an overview of previous research efforts characterizing IAQ using LCS, including those performed in impacted communities; (3) administer interviews to relevant stakeholders with experience working with LCS, as well as individuals in impacted communities with experience or interest in adopting these technologies for IAQ monitoring; and (4) develop a white paper and guidance document for impacted communities to facilitate the use of LCS for monitoring IAQ and reducing exposures.

The objective of the guidance document is to provide (1) data-driven recommendations on appropriate sensor selection, specifications, objectives, and performances; (2) culturally specific adoption limitations; and (3) ethical and practical interventions to improve IAQ.

2.2 Task 1: Review of LCS Technologies

Task 1 involved the completion of an extensive market survey of commercially-available low-cost air quality sensing technologies, which derived knowledge and information from existing peer-reviewed articles and gray literature from industry manufacturers and federal, state, and local agencies (e.g., the EPA). Investigating LCS on the market required the implementation of inclusion criteria to meet the objectives of this project. These criteria are described as follows:

- **LCS Definition.** LCS considered in this white paper are low-cost air monitoring devices that are "housed" within a casing or enclosure, and are sold as a unit to be used straight out of the package. Therefore, these are commercially-available LCS devices (e.g., PurpleAir monitors), which are user-friendly for community members in terms of set-up, operation, and data access. Mass-produced single pollutant sensors (e.g., Plantower PMS5003) costing ~$10-$35 were not included in the market survey as a result of the specified LCS definition. However, some of these single pollutant sensors have widespread use as the internal components in packaged LCS devices sold by different manufacturers. Different from packaged LCS devices which often have integrated displays to show air pollutant data, require a common internet connection, a mobile application, or a combination of all three, [43] single pollutant sensors often need additional equipment like a PC connection to transmit and log data using proprietary software for data retrieval. This might be a hindrance to the target audience of this project, so these sensors were excluded from the survey.

- **IAQ Application.** Only LCS described as being suitable for IAQ or intended for use in indoor environments by the sensor manufacturer were included in the market survey. Indoor environments typically have a smaller range of changing environmental conditions (e.g., temperature, relative humidity, and airflow), but exhibit greater short-term changes in air pollutant concentrations. While many commercially-available LCS can be used both indoors and outdoors, those specifically intended for indoor applications are likely optimized and designed to accommodate indoor conditions.
- **LCS Measurements.** Only LCS providing real- or near-real-time measurements were considered.
- **LCS Pollutants.** Only LCS measuring the EPA's national ambient air quality standards (NAAQS) criteria pollutants (www.epa.gov/naaqs) and hazardous air pollutants (www.epa.gov/haps) were considered. We focus on these pollutants as they are considered harmful to public health and the environment and are consistently monitored nationwide by air quality (AQ) agencies.
- **LCS Market Availability.** LCS that were initially available on the market for any time period, but are currently no longer available for purchase or have been discontinued, were not included in the market survey.
- **Price Point and Purchase Options.** LCS considered in this white paper are those priced at less or equal to (≤) $500 for measuring a single pollutant or ≤ $2500 for measuring at least two pollutants. Some LCS are available to buy directly from the manufacturer platform or through other retailers while others require requesting a quote from the manufacturer; both were included in the review.
- **LCS Market Leaders and Alternatives.** The LCS market features several well-known devices, such as the PurpleAir PA-II monitors, which often serve as users' initial exposure to LCS and IAQ monitoring. However, internet marketplaces like "Amazon.com" offer a wide array of LCS options spanning various, often lower, price points. Given the extensive

selection of more affordable alternatives on these platforms, the market survey focused only on the best-selling and popular LCS.

- **LCS Performance Evaluations.** Only performance evaluations of LCS with at least one measured pollutant alongside reference-grade, EPA's federal equivalence method (FEM) and federal reference method (FRM), or research/professional grade instruments are reported in this white paper if available. There is a lack of standardization for LCS performance evaluations across studies,[44] leading to non-uniformity of statistical measures used. Performance of LCS against reference instruments is most often quantified in literature with a linear model calculating for the coefficient of determination (R^2) and related measures[45]. Given that a linear regression is most used in evaluating LCS, this white paper reports validation results of manufacturer-calibrated LCS using R^2, when available.

2.3 Task 2: Evidence of IAQ Assessment Efforts using LCS

Task 2 involved summarizing peer-reviewed literature using LCS for IAQ monitoring efforts, including those performed in impacted communities. The scope of these LCS IAQ studies is centered around their participatory nature, requiring some type of presence, involvement, engagement, or collaboration with occupants or residents in an indoor environment. This scope is important to illuminate any challenges or limitations with LCS deployment, monitoring, and maintenance indoors, and to glean lessons learned for application in impacted communities. Additional information relevant from participatory studies includes exploring occupant behavior influence on IAQ, interventions for managing and improving IAQ, engaging targeted communities with culturally specific adoptions, and addressing challenges and limitations with LCS. Studies focusing on the deployment and evaluation of LCS devices in indoor environments were not considered.

Accordingly, Web of Science, Scopus, and PubMed scientific databases were used to search and retrieve related peer-reviewed journal articles aligning with the defined scope. The main keywords and phrases used for retrieving articles were as follows: "indoor air quality" OR "indoor air pollution" OR "indoor environment quality" AND "low-cost sensor" AND "occupant" OR "resident" OR "community" OR "citizen". Selection criteria as described below were applied to further filter the articles found:

- **Geography/Location.** Studies involving LCS for IAQ applications were limited to the United States due to nuanced metrics used in defining communities of low-income and racial-ethnic minority groups that may not apply in other countries. Also building construction differs in the United States compared to other countries.

- **Indoor Environment.** Studies simulating indoor conditions in laboratory or chamber settings were not considered. Only those LCS studies performed within a normally occupied indoor environment (e.g., home, school, office) were considered.
- **Primary and Secondary Studies.** Here, primary studies refer to the studies that centered on a participatory research campaign or the direct collection of data. Secondary studies are defined as those that centered on crowdsourcing data, and did not involve the deployment of new monitors. Recent publications of crowdsourced IAQ data from LCS networks[21,40,46] have offered useful insights into the need for community-scale IAQ monitoring due to socioeconomic and racial-ethnic disparities where these sensors are deployed.[41] All articles with both primary and secondary sourced IAQ data were considered.

Based on the scope and selection criteria, 368 research articles were initially retrieved from the literature search (last retrieved August 2024). After a scan of their titles and abstracts, 30 studies remained, with additional 14 studies found from retrieved articles' references and other sources for close review of the full text. Then, 13 studies were found to be out of scope for Task 2. In total, 31 studies using LCS to characterize IAQ with participatory elements remained to address Task 2 objectives. Figure 2.3.1 shows the graphical representation of the literature review process.

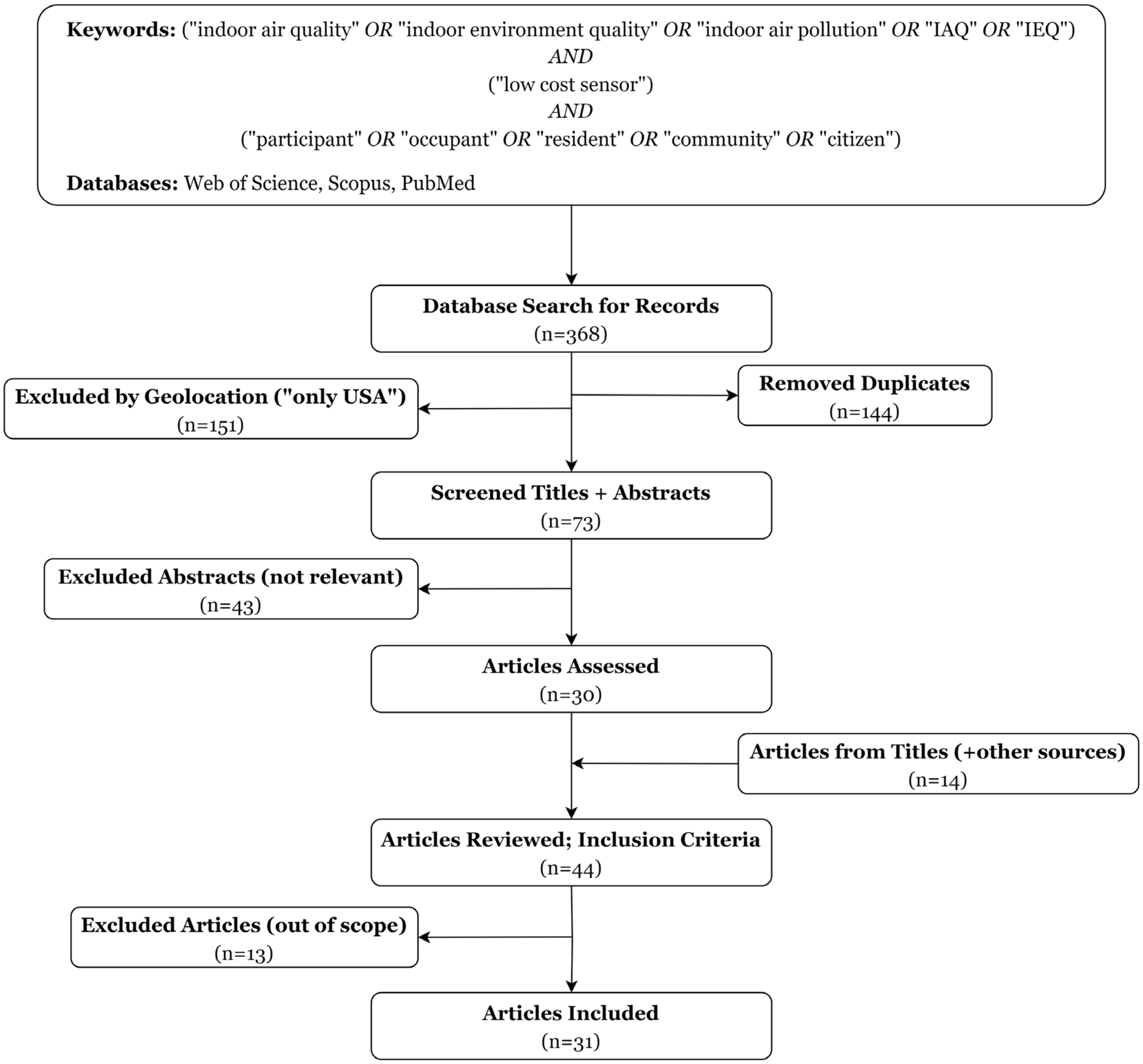

Figure 2.3.1. Systematic literature review process.

2.4 Task 3: Insights from Stakeholder Interviews on LCS for IAQ Monitoring

Task 3 included the formation of recommendations for best practices, facilitated by interviews with relevant experts and stakeholders to aggregate information on the needs, challenges, and experiences related to LCS devices. Semi-structured interviews were conducted with four targeted stakeholders: LCS manufacturers, IAQ researchers, representatives from impacted communities, and regular users of LCS. Interview questions covered the following topics: best practices in using LCS, deployment, collection, performance considerations, quality assurance, life cycles, study locations, outdoor pollution conditions, participant demographics, participant engagement and compliance, participant incentives, and challenges faced.

A total of 10 interviews from targeted stakeholders were conducted, recorded and transcribed. A detailed summary of the information from the four stakeholder groups was synthesized from drawing parallels and identifying key themes across responses. These themes included best practices, caveats, unique experiences, and recommendations. Interview content was then sorted into these groups to provide a comprehensive understanding of the stakeholders' perspectives. Stakeholders' interviews contributed to the development of actionable insights and strategies presented in the guidance document accompanying this white paper.

2.5 Task 4: Draft White Paper and Guidance Document

Task 4 includes the development of a white paper based on summarized findings from Tasks 1-3, including:

(1) Summary tables of market available LCS for IAQ monitoring with relevant categories (e.g., costs, technical specifications, and performance evaluations)

(2) Summary of research studies using LCS for IAQ measurements, especially those done in impacted communities

(3) Summary of challenges faced by impacted communities in using LCS for IAQ monitoring, resources needed to narrow the gaps and improve IAQ, and recommendations for future research studies and development of LCS

Task 4 also includes the development of a guidance document for IAQ monitoring with LCS in impacted communities based on summarized information from the market survey, literature review of LCS studies, and stakeholder interviews. The guidance was created in plain language to be accessible to impacted communities and the general public, and included components such as:

(1) A streamlined table of LCS available for IAQ monitoring with associated information: manufacturer, model, unit price, measured pollutants and parameters

(2) Guidance on sensor selection and considerations, setup, deployment, and maintenance

(3) An overview of data handling and data interpretation from LCS to guide decision making based on monitoring data

(4) Descriptions of typical indoor air pollution scenarios, such as wildfire events and emissions from indoor activities (e.g., cooking) with accompanied considerations and methods to reduce exposures

(5) A compilation of resources such as links to the federal and state guidance (e.g., the EPA, the South Coast Air Quality Management District) on LCS, fact sheets about indoor air, and guidelines for indoor air pollutants

3 Review of LCS Technologies

3.1 Overview

LCS technologies offer a lower-cost, portable, ease-of-use alternative to regulatory monitors and research instruments.[34,47] The recent technological advancements and fast-paced growth of LCS for air quality monitoring have allowed an extensive range of these devices to enter the market with varying applications[44,48–50]. The ever-increasing availability of LCS options in the market and number of projects utilizing these devices has resulted in several studies comparatively examining LCS technologies, often through performance evaluations.[45,51,52]

Regulatory air quality agencies at federal, state, and local levels have also taken interest in consolidating information on LCS to enhance scientific understanding and promote best practices for using these devices for diverse end users (e.g., individuals, communities, schools, researchers, environmental agencies, industries, etc.). Specific efforts in this area are evident within EPA's Indoor Environments Division with LCS information found in the "Air Sensor Technology and IAQ" section on EPA's website (www.epa.gov/indoor-air-quality-iaq/air-sensor-technology-and-indoor-air-quality). Additionally, EPA provides LCS-related resources and performance evaluations through its "Air Sensor Toolbox" website (www.epa.gov/air-sensor-toolbox). A useful resource found within EPA's Air Sensor Toolbox is "*The Enhanced Air Sensor Guidebook*",[47] which expands on best practices to support LCS use. Though the focus is heavily placed on LCS utility for outdoor and ambient applications, *The Enhanced Air Sensor Guidebook* presents stepwise foundational information on air quality and LCS monitoring.

The South Coast Air Quality Management District (AQMD) has also made significant contributions to LCS knowledge through the Air Quality Sensor Performance Evaluation Center (AQ-SPEC). AQ-SPEC (www.aqmd.gov/aq-spec) was established to characterize the performance of commercially-available LCS and provide guidance on data quality and interpretation. AQ-SPEC has become a respected resource within the growing sensor user community, and frequently consulted for information and recommendations regarding the accuracy and reliability of LCS available on the market. Following the awarding of EPA's Science to Achieve Results (STAR) grant in 2015, South Coast AQMD deployed nearly 400 LCS across California while working collaboratively with 14 different communities.[53] This large effort resulted in the curation of an Education Toolkit centered around equipping California communities with knowledge to select, use, and maintain LCS while correctly interpreting their data. A key component of this Toolkit is the published guide "*Community in Action: A Comprehensive Educational Toolkit on Air Quality Sensors*".[54] This guidebook, part of AQ-SPEC resources, directly supports AQ-SPEC's mission by providing additional guidance on air quality project planning, LCS operation, and data handling and interpretation.

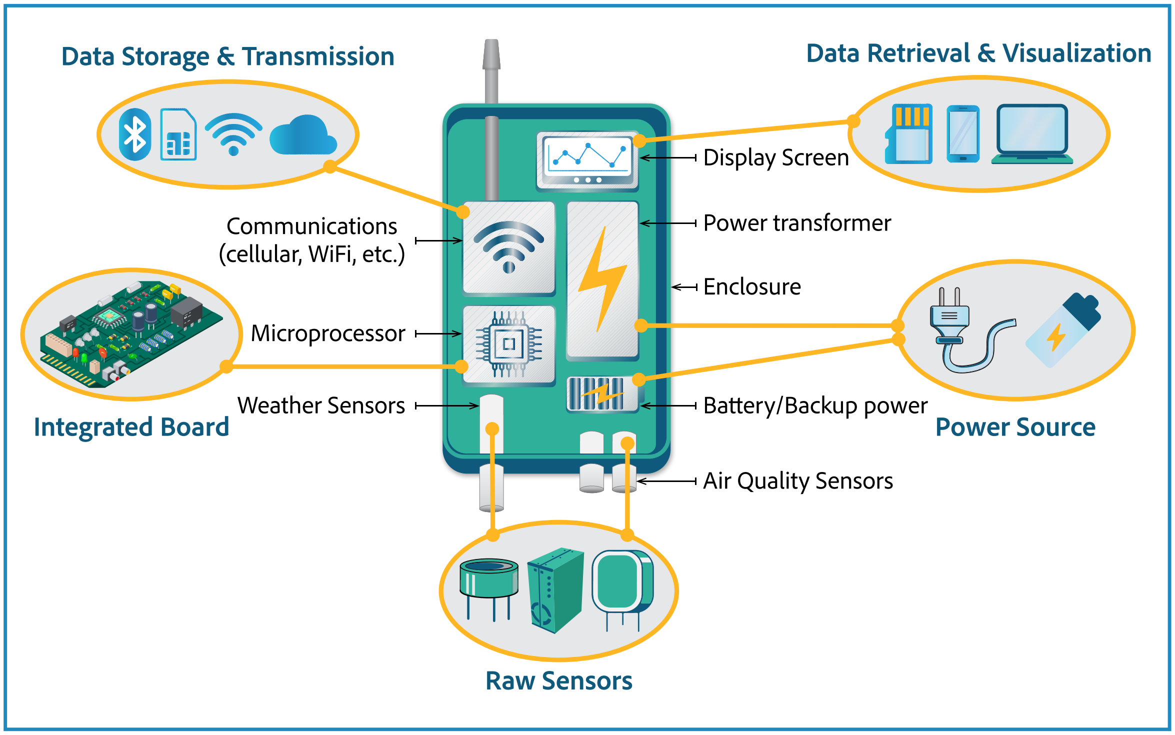

Figure 3.1.1. Typical LCS components.
Adapted from Figure 1-1 in EPA's *The Enhanced Air Sensor Guidebook (2022)*[47]

AQ-SPEC's evaluations and resources along with EPA's Air Sensor Toolbox provided an excellent foundation for initiating a market survey of commercially available LCS suitable for IAQ monitoring. This initial groundwork was expanded upon by identifying additional LCS devices mentioned in research studies, exploring air quality-related forums and websites (e.g., see the air, https://seetheair.org/), and examining popular LCS listings on internet marketplaces. In total, the finalized market survey for commercially available LCS packaged devices suitable for IAQ monitoring comprised 72 LCS devices from 31 different manufacturers. These devices met the predetermined inclusion criteria covering both single- and multi-pollutant LCS devices (see Section 2.2). Each LCS surveyed was summarized across various categories, including manufacturer and model, costs and purchase options, pollutants measured and parameters, technical specifications, performance assessments, data access and storage, and other relevant information. Figure 3.1.1 illustrates the typical LCS device components measuring one or more pollutants, which varies by manufacturer. A LCS device includes an enclosure with sensors to detect air pollutants and weather parameters, a power source, a microprocessor for controlling the LCS, and data transmitting electronics (e.g., radio waves/infrared signal for Wi-Fi)Air Pollutant Sensor Technologies

Air pollutant sensors are often integrated within commercially-available packaged LCS devices and measure NAAQS criteria pollutants and some hazardous air pollutants. These sensors use select technologies for measuring different air pollutant types, which generally fall within five categories[47,49] as follows: light scattering, electrochemical (EC), metal oxide semiconductor (MOS/MOX), non-dispersive infrared (NDIR), and photoionization detector (PID) (Table 3.2.1).

Given the integration of pollutant sensors within packaged LCS devices, specific manufacturers and their associated sensors have become widely used due to their accessibility, reliability, and reputation. These widely used pollutant sensors, which were identified through the LCS market survey and literature analysis, are provided in Table 3.2.2. Following the specified definition of LCS in this white paper (see Section 2.2), detailed descriptions of these pollutant sensors are not summarized here; however, information and performance evaluations of some of these pollutant sensors can be found elsewhere.[36,43,55–62]

Table 3.2.1. Sensor technologies and target air pollutants.

Sensor Technology	Pollutant(s)
Light (or nephelometric) Scattering - Often referred to as a laser or optical particle counter (OPC) by manufacturer	Particulate matter at different size fractions (e.g., $PM_{1.0}$, $PM_{2.5}$, PM_{10})
Electrochemical Sensors (EC)	Gas pollutants including ozone (O_3), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide (SO_2), volatile organic compounds (VOCs)
Metal Oxide Semiconductors (MOS/MOX)	
Non-Dispersive InfraRed (NDIR)	For IR active pollutant gases Most commonly used for carbon dioxide (CO_2)
Photoionization detectors (PID)	Total VOCs

Table 3.2.2. Pollutant sensors commonly found within packaged LCS devices.

Manufacturer	Sensor/Model	Pollutant(s)	Technology
Plantower[63]	PMS sensors (e.g., PMS5003)	$PM_{1.0}$, $PM_{2.5}$, PM_{10}	Laser
Shinyei[64]	PPD sensors (e.g., PPD42NJ)	> $PM_{1.0}$ and > $PM_{2.5}$	Laser
Sensirion[65]	SPS30, SEN54	$PM_{1.0}$, $PM_{2.5}$, PM_4, PM_{10}	OPC
Piera Systems[66]	IPS-7100	$PM_{0.1}$, $PM_{0.3}$, $PM_{0.5}$, $PM_{1.0}$, $PM_{2.5}$, PM_5, PM_{10}	OPC
Alphasense[67,68]	OPC-N3, OPC-R2	PM_1, $PM_{2.5}$, $PM_{4.25}$, PM_{10}	OPC
Alphasense[67,68]	Gas sensors (e.g., CO-B4)	O_3, CO, NO, NO_2, SO_2, HCHO	EC
SPEC Sensors[69]	Gas sensors	O_3, CO, NO, NO_2, SO_2, HCHO	EC

3.2 Single- and Multi-Pollutant LCS Devices on the Market

A total of 30 single-pollutant and 42 multi-pollutant LCS devices from 31 different manufacturers (see Tables 3.3.1 and 3.3.2) met the inclusion criteria from the market survey (Section 2.2). Single-pollutant LCS are ≤ \$500 per unit while multi-pollutant LCS are ≤ \$2500 per unit. Each single- and multi-pollutant LCS device is summarized for relevant information in Tables 3.3.3 and 3.3.4, and Tables 3.3.5 and 3.3.6 respectively. Tables 3.3.3 and 3.3.5 provides LCS manufacturer and model, cost/pricing and purchasing channels, sizing and weight, power needs, and related information while Tables 3.3.4 and 3.3.6 provide technical specifications, including pollutants measured, the associated sensor technology if available, range and accuracy details, other parameters, and data access and storage information. All included information about commercially-available LCS is accurate as of June 2024, and is subject to change at any time.

Table 3.3.1. Single-pollutant LCS devices for IAQ monitoring passing inclusion criteria.

Manufacturer	LCS/Model
AirValent	Wireless CO_2 Monitor
Applied Particle Technology	Minima
Davis Instruments	AirLink
Dylos Corporation	DC1100
Dylos Corporation	DC1100 with PC interface
Dylos Corporation	DC1100 Pro
Dylos Corporation	DC1100 Pro with PC interface
Dylos Corporation	DC1700 Battery
Dylos Corporation	DC1700-PM
Ecowitt	WH41
Ecowitt	WH43
Elitech	Temtop P600
Elitech	Temtop P100
Eve	Eve Room
HabitatMap	Airbeam 3
InkBird	CO_2 Detector (IAM-T1)
Netatmo	Smart IAQ Monitor
Piera Systems	Canaree A1
Piera Systems	Canaree I1
PurpleAir	PA-II-SD
PurpleAir	PA-II
PurpleAir	PA-II-Flex
PurpleAir	Zen
PurpleAir	Touch (PA-I)
SAF Tehnika	Aranet4
SmartAir	CO_2 Monitor
TSI	BlueSky 8143
uRADMonitor	SMOGGIE-PM
uRADMonitor	SMOGGIE-CO_2
uRADMonitor	SMOGGIE-GAS

Table 3.3.2. Multi-pollutant LCS devices for IAQ monitoring passing inclusion criteria.

Manufacturer	LCS/Model
Aethair (formerly AirThinx)	Aethair IAQ
Air Gradient	AirGradient ONE (9th generation)
air-Q	Light
air-Q	Basic
air-Q	Pro
AirThings	View Plus
AirThings	Wave Plus
Amazon	Smart Air Quality Monitor
Atmotech Inc.	Atmotube PRO
Atmotech Inc.	Atmocube
Awair	Element/2nd edition
Awair	Omni
Ecowitt	WH45
Edimax	Al-2002W
Edimax	Al-2003W
Edimax	Al-2004W
Elitech	Temtop M10
Elitech	Temtop M10i
Elitech	Temtop M100
Elitech	Temtop P1000
Elitech	Temtop M2000 2nd gen
Elitech	Temtop M2000C 2nd gen
Elitech	Temtop LKC-1000E
Elitech	Temtop LKC-1000S+ 2nd gen
IKEA	Vindstyrka
IQAir	AirVisual Pro (formerly AirVisual Node)
IQAir	AirVisual Outdoor
Kaiterra	Sensedge
Kaiterra	Sensedge Mini
Kaiterra	Sensedge Mini Outdoor
NuWave Sensors	AirSentric
Piera Systems	Canāree I5
Qingping	Air Monitor 2
Qingping	Air Monitor Lite
Qingping	CO_2 Monitor
TSI	BlueSky 8145
TSI	AirAssure
uHOO	Smart Air Monitor
uRADMonitor	MODEL A3
uRADMonitor	MODEL A4
Wicked Device	Air Quality Egg Indoor V2
Wicked Device	Air Quality Egg Outdoor V2

Table 3.3.3. Specifications (a) of single-pollutant LCS devices for IAQ monitoring.

Manufacturer	LCS/Model	Unit Price	Purchase	Weight	Dimensions (h × w × d in)	Battery/Power	Resources	Notes
AirValent[70]	Wireless CO_2 Monitor	$190	Buy direct Link	50 grams (g)	2 × 2 × 0.5	Battery (rechargeable, USB-C, 5-30 days, 5 Volts (V) 1 Ampere (A))	User Manual	Automatic self-calibration
Applied Particle Technology[71]	Minima	—	Quote Link	357 g	1 3.35 × 2.67 × 1.17	Battery (rechargeable, <1000 milliampere (mA), 8-10 hour (hr))	Setup	—
Davis Instruments[72]	AirLink	$215	Buy direct Link	106 g	2 × 3.5 × 1	Power (USB, 5V direct current (DC))	Setup User Manual Datasheet	4.3 oz (121 g) with mounting bracket; Near-silent fan; mount or standalone
Dylos Corporation[73]	DC1100	$199.99	Buy direct Link	544 g	7 × 4.5 × 3	Power (adapter)	Manufacturer Webpage	Early player in the LCS market
Dylos Corporation[73]	DC1100 with PC interface	$239.99	Buy direct Link	544 g	7 × 4.5 × 3	Power (adapter)	Manufacturer Webpage	Early player in the LCS market
Dylos Corporation[73]	DC1100 Pro	$260.99	Buy direct Link	544 g	7 × 4.5 × 3	Power (adapter)	Manufacturer Webpage	Early player in the LCS market
Dylos Corporation[73]	DC1100 Pro with PC interface	$289.99	Buy direct Link	544 g	7 × 4.5 × 3	Power (adapter)	Manufacturer Webpage	Early player in the LCS market
Dylos Corporation[73]	DC1700 Battery	$425	Buy direct Link	544 g	7 × 4.5 × 3	Power (adapter); Battery (rechargeable, 6 hr)	Manufacturer Webpage	Early player in the LCS market
Dylos Corporation[73]	DC1700-PM	$475	Buy direct Link	544 g	7 × 4.5 × 3	Power (adapter); Battery (rechargeable, 6 hr)	Manufacturer Webpage	Early player in the LCS market
Ecowitt[74]	WH41	$71.99	Buy direct Link	—	2.7 × 4 × 2.8	NI-MH Battery (rechargeable, 1.2V, 2 weeks)	User Manual	$29.99 (required Wi-Fi getaway) $22.99 (optional digital LCD display)
Ecowitt[74]	WH43	$65.99	Buy direct Link	—	2.7 × 4 × 2.8	Power (USB adapter, 5V 1A); Batteries (2× AA, 1.5V)	User Manual	$29.99 (required Wi-Fi getaway) $22.99 (optional digital LCD display)
Elitech[75]	Temtop P600	$65.99	Buy direct Link	300 g	7 × 2.6 × 1.3	Li Battery (rechargeable, 5V 1A DC)	User Manual	Comparison chart of Elitech LCS
Elitech[75]	Temtop P100	$159.99	Buy direct Link	—	6.9 × 2.6 × 1.2	Li Battery (4200 milliampere-hour (mAh) rechargeable, 5V 2A DC)	User Manual	Comparison chart of Elitech LCS
Eve[76]	Eve Room	$99.95	Buy direct Link	44 g	2.1 × 2.1 × 0.5	Li Battery (500 mAh rechargeable, 6+ weeks, 5V)	Setup	Compatible with HomePodt/Apple Home

Manufacturer	LCS/Model	Unit Price	Purchase	Weight	Dimensions (h × w × d in)	Battery/Power	Resources	Notes
HabitatMap[77]	Airbeam 3	$249	Buy direct Link	170 g	4.26 × 3.74 × 1.04	Power (USB-C); Li battery (rechargeable, 3350 mAh, 17-31 hrs)	User Manual Datasheet	Palm-sized
InkBird[78]	IAM-T1 CO_2 Monitor	$129.99	Buy direct Link	138 g	3.1 × 2.95 × 1.18	Battery (2× AA, 2500 mAh, 4 years at 10 minutes (min))	Setup User Manual	Standalone or mount
Netatmo[79]	Smart IAQ Monitor	$119.99	Buy direct Link	172 g	6.1 × 1.8 × 1.8	Power (5V 550 mA)	Setup	Compatible with HomeKit/Apple Home
Piera Systems[80]	Canāree A1	$219	Buy direct Link	42 g	3.5 × 2.4 × 0.8	Power (USB)	Datasheet User guide	—
Piera Systems[80]	Canāree I1	$269	Buy direct Link	42 g	3.5 × 2.4 × 0.8	Power (USB, 5.5V 100 mA)	Datasheet User guide	—
PurpleAir[81]	PA-II-SD	$259	Buy direct Link	357 g	3.5 × 3.5 × 5	Power (USB, 5V 0.18A)	Setup Community Forum	$9.99 (optional USB power adapter)
PurpleAir[81]	PA-II	$229	Buy direct Link	357 g	3.5 × 3.5 × 5	Power (USB, 5V 0.18A)	Setup Community Forum	$9.99 (optional USB power adapter)
PurpleAir[81]	PA-II-Flex	$289	Buy direct Link	357 g	3.5 × 3.5 × 5	Power (USB, 5V 0.18A)	Setup Community Forum	Replaceable PMS6003 sensors
PurpleAir[81]	Zen	$299	Buy direct Link	—	3.5 × 3.5 × 4	Power (USB, 5V 0.18A)	Setup Community Forum	Replaceable PMS6003 sensors
PurpleAir[81]	Touch (PA-I)	$209	Buy direct Link	—	4.25 × 3 × 2.25	Power (USB, 5V 0.18A)	Setup Community Forum	$9.99 (optional USB power adapter)
SAF Tehnika[82]	Aranet4	$249	Buy direct Link	104 g	2.80 × 2.80 × 0.94	Alkaline battery (2× AA, 2 years at 5 min)	Setup User Manual Datasheet	Portable; long (> 1 year) battery life; avoid exposure to VOCs, acids or bases, and etching substances (e.g., ammonia, hydrogen peroxide)
SmartAir[83]	CO_2 Monitor	$69.99	Buy direct Link	129 g	3 × 3 × 1.1	Li Battery (rechargeable, 2600 mAh, USB-C, 30 days);	Info	Mountable
TSI[84]	Blue Sky 8143	—	Quote Link	159 g	6 × 5.5 × 4.5	Power (5V 1 Watt (W))	Datasheet User Manual	Mountable; Designed for outdoor use for applicable indoors
uRADMonitor[85]	SMOGGIE-PM	$199	Buy direct Link	95 g	2.8 × 1.85 × 1.65	Power (micro-USB, 5V 500 mA)	Datasheet	Possible integration with home assistants (e.g., Alexa)
uRADMonitor[85]	SMOGGIE-CO_2	$199	Buy direct Link	50 g	1.4 × 1.4 × 0.79	Power (micro-USB, 5V)	Datasheet	—
uRADMonitor[85]	SMOGGIE-Gas	$389	Buy direct Link	—	1.6 × 1.7 × 1.1	Power (micro-USB, 5V)	Datasheet	Mountable; One gas at a time

All information is accurate as of June 2024 and is subject to change at any time.

Table 3.3.4. Specifications (b) of single-pollutant LCS devices for IAQ monitoring.

Manufacturer	LCS/Model	Pollutant	Sensor/ Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
AirValent[70]	Wireless CO_2 Monitor	CO_2	NDIR; SCD41 (Sensirion)	400-30,000 ppm; Resolution (Res): 1 ppm	400-5000 ppm → ± 40 + 5% ppm	Temperature (T), Relative humidity (RH); AQ indicator	BLE → AirValent app (historical data); Internal storage (54 days at 1 min); Res: 1, 2, 5, 10 or 15 min	E-ink display; Mobile application
Applied Particle Technology[71]	Minima	PM_1; $PM_{2.5}$; PM_{10}	OPC	0-1000 µg m^{-3}	—	T, RH; GPS	Wi-Fi/BLE/LTE → cloud (APT dashboard); Res: 15 seconds (s)	Website
Davis Instruments[72]	AirLink	PM_1; $PM_{2.5}$; PM_{10}	Laser; PMSA003 (Plantower)	Res: 1 µg m^{-3}	± 10 µg m^{-3}	T, RH; AQI	Wi-Fi → WeatherLink Cloud; Res: 1-min	Website; Mobile application
Dylos Corporation[73]	DC1100	Particles (>1 µm) (>5 µm)	Laser; (Dylos)	—	—	—	Device (≤ 30 days storage); Res: min, hr, or day	LCD display
Dylos Corporation[73]	DC1100 with PC interface	Particles (>1 µm) (>5 µm)	Laser; (Dylos)	—	—	—	Device (≤ 30 days storage); Res: min, hr, or day	LCD display; Serial output
Dylos Corporation[73]	DC1100 Pro	Particles (>0.5 µm) (>2.5 µm)	Laser; (Dylos)	—	—	—	Device (≤ 30 days storage); Res: min, hr, or day	LCD display
Dylos Corporation[73]	DC1100 Pro with PC interface	Particles (>0.5 µm) (>2.5 µm)	Laser; (Dylos)	—	—	—	Device (≤ 30 days storage); Res: min, hr, or day	LCD display; Serial output
Dylos Corporation[73]	DC1700 Battery	Particles (>0.5 µm) (>2.5 µm)	Laser; (Dylos)	—	—	Internal clock	Device (≤ 10,000 samples); Res: min, hr, or day	LCD display; Serial output
Dylos Corporation[73]	DC1700-PM	$PM_{2.5}$; PM_{10}; Particles (>0.5 µm) (>2.5 µm)	Laser; (Dylos)	—	—	Internal clock	Device (≤ 10,000 samples); Res: min, hr, or day	LCD display; Serial output
Ecowitt[74]	WH41	$PM_{2.5}$	—	0-999 µg m^{-3}; Res: 1 µg m^{-3}	0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10% at 20 ± 5°C	AQI	Wi-Fi → WS ViewPlus App; Res: 10 min	Mobile application; Website
Ecowitt[74]	WH43	$PM_{2.5}$	Laser; HPM Series (Honeywell)	0-999 µg m^{-3}; Res: 1 µg m^{-3}	<100 µg m^{-3} → ±15 µg m^{-3}; >500 µg m^{-3} → ±15% at 25 ± 5°C	AQI	Wi-Fi → WS ViewPlus App; Res: 10 min	Mobile application; Website
Elitech[75]	Temtop P600	$PM_{2.5}$; PM_{10}	Laser; PMJG-200 (Temtop)	0-999 µg m^{-3} Res: 0.1 µg m^{-3}	—	AQI	Device (20,000 hr)	LCD display
Elitech[75]	Temtop P100	$PM_{2.5}$; PM_{10}	Laser; $PM_{2.5}$ sensor (Temtop)	0-999 µg m^{-3} Res: 0.1 µg m^{-3}	$PM_{2.5}$: 0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%; PM_{10}: 0-100 µg m^{-3} → ±15 µg m^{-3}; 100-500 µg m^{-3} → ±15%;	T, RH; AQI	Wi-Fi/BLE → Temtop App	Touch LCD display; Mobile application

Manufacturer	LCS/Model	Pollutant	Sensor/ Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Eve[76]	Eve Room	VOCs	—	—	—	T, RH	Wi-Fi/BLE → cloud	E-ink display; Mobile application
HabitatMap[77]	Airbeam 3	$PM_{2.5}$; PM_{10}	Laser; PMS7003 (Plantower)	0-500 μg m^{-3} Res: 1 μg m^{-3}	0-100 μg m^{-3} → ±10 μg m^{-3}; 100-500 μg m^{-3} → ±10%;	T, RH; GPS; Internal clock	Wi-Fi/Cellular/BLE → cloud (AirCasting app); SD card; Res: 1 min	Website; Mobile application; Serial output
InkBird[78]	IAM-T1 CO_2 Detector	CO_2	NDIR; (SenseAir)	0-9999 ppm; Res: 1 ppm	0-5000 ppm → ±30ppm + 3% of reading	T, RH, Pressure (P); AQ indicator	BLE → InkBird app (historical data); Internal storage (30 days); Res: 1, 2, 5, 10 min	E-Ink display
Netatmo[79]	Smart IAQ Monitor	CO_2	—	0-5000 ppm	—	T, RH; Noise	Wi-Fi → cloud	Mobile application
Piera Systems[80]	Canāree A1	$PM_{0.1}$ - PM_{10}	OPC; IPS-7100 (Piera)	0-6000 μg m^{-3}; Res: 0.1 μg m^{-3}	$PM_{0.1\text{-}2.5}$: 0-50 μg m^{-3} → ± 5 μg m^{-3} >50 μg m^{-3} → ± 10% $PM_{5\text{-}10}$: 0-50 μg m^{-3} → ± 10 μg m^{-3} >50 μg m^{-3} → ± 20%	—	Plug in USB (laptop/Aruba access point) → cloud (SenseiAQ software)	LED AQ indicator; Website
Piera Systems[80]	Canāree I1	$PM_{0.1}$ - PM_{10}	OPC; IPS-7100 (Piera)	0-6000 μg m^{-3}; Res: 0.1 μg m^{-3}	$PM_{0.1\text{-}2.5}$: 0-50 μg m^{-3} → ± 5 μg m^{-3} >50 μg m^{-3} → ± 10% $PM_{5\text{-}10}$: 0-50 μg m^{-3} → ± 10 μg m^{-3} >50 μg m^{-3} → ± 20%	—	Wi-Fi/Ethernet/BLE/USB → cloud (SenseiAQ software)	LED AQ indicator; Website
PurpleAir[81]	PA-II	PM_1; $PM_{2.5}$; PM_{10}	Laser; 2× PMS5003 (Plantower)	0-500 μg m^{-3}	0-100 μg m^{-3} → ±10 μg m^{-3}; 100-500 μg m^{-3} → ±10%;	T, RH; AQI; GPS; Internal clock	Wi-Fi → cloud (PurpleAir Map/dashboard)	Website & API
PurpleAir[81]	PA-II-SD	PM_1; $PM_{2.5}$; PM_{10}	Laser; 2× PMS5003 (Plantower)	0-500 μg m^{-3}	0-100 μg m^{-3} → ±10 μg m^{-3}; 100-500 μg m^{-3} → ±10%;	T, RH; AQI; GPS; Internal clock	Wi-Fi → cloud (PurpleAir Map/dashboard); Micro SD card logger (32 GB)	Website & API; Data export
PurpleAir[81]	PA-II-Flex	PM_1; $PM_{2.5}$; PM_{10}	Laser; 2× PMS6003 (Plantower)	0-500 μg m^{-3}	0-100 μg m^{-3} → ±10 μg m^{-3}; 100-500 μg m^{-3} → ±10%;	T, RH; AQI; GPS; Internal clock	Wi-Fi → cloud (PurpleAir Map/dashboard); Optional Micro SD (≤ 64 GB); Res: >10 s	Website & API; Data export
PurpleAir[81]	Zen	PM_1; $PM_{2.5}$; PM_{10}	Laser; 2× PMS6003 (Plantower)	0-500 μg m^{-3}	0-100 μg m^{-3} → ±10 μg m^{-3}; 100-500 μg m^{-3} → ±10%;	T, RH; AQI; GPS; Internal clock	Wi-Fi → cloud (PurpleAir Map/dashboard); Optional Micro SD (≤ 64 GB); Res: >10 s	LED ring (AQI); Website & API; Data export

Manufacturer	LCS/Model	Pollutant	Sensor/ Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
PurpleAir[81]	Touch (PA-I)	PM_1; $PM_{2.5}$; PM_{10}	Laser; 1× PMS6003 (Plantower)	0-500 µg m^{-3}	0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%;	T, RH; AQI; GPS; Internal clock	Wi-Fi → cloud (PurpleAir Map/dashboard)	LED ring (AQI); Website & API; Data export
SAF Tehnika[82]	Aranet4	CO_2	NDIR; Sunrise (SenseAir)	0 - 9999 ppm; Res: 1 ppm	0–5000 ppm → ± 30 ppm + 3 % of reading;	T, RH, P; Threshold levels	BLE → Aranet Home App (historical data); Internal storage (30 days at 10 min); Res: 1,2,5, or 10 min	E-ink display; Mobile application
SmartAir[83]	CO_2 Monitor	CO_2	NDIR; (Sensirion)	400~9999 ppm	±15% of m.v.	T, RH; AQ indicator	Wi-Fi/BLE → cloud (Qingping IoT app); Internal storage (2880 sets, 30 days at 15 min)	Onboard display, Mobile application
TSI[84]	Blue Sky 8413	$PM_{2.5}$; PM_{10}	OPC; SPS30 (Sensirion)	0-1000 µg m^{-3}; Res: 1 µg m^{-3}	0-100 µg m^{-3}→ ±10 µg m^{-3} 100-1000 µg m^{-3} → ±10%	T, RH	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB)	Website; SD Export
uRADMonitor[85]	SMOGGIE-PM	PM_1; $PM_{2.5}$; PM_{10}	Laser	0-1000 µg m^{-3}	±5%	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	SMOGGIE-CO_2 4th gen	CO_2	NDIR	0-5000 ppm	±5%	T, RH, P; AQ indicator	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	LED; Website/API; Local access LAN
uRADMonitor[85]	SMOGGIE-Gas	CO	EC	0-200 ppm; Res: 1 ppm	±10%	T, RH, P	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	SMOGGIE-Gas	NO_2	EC	0-10 ppm; Res: 0.1 ppm	±10%	T, RH, P	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	SMOGGIE-Gas	O_3	EC	0-10 ppm; Res: 0.1 ppm	±10%	T, RH, P	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	SMOGGIE-Gas	SO_2	EC	0-20 ppm; Res: 0.1 ppm	±10%	T, RH, P	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	SMOGGIE-Gas	H_2S	EC	0-100 ppm; Res: 0.1 ppm	±10%	T, RH, P	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN

All information is accurate as of June 2024 and is subject to change at any time.

Table 3.3.5. Specifications (a) of multi-pollutant LCS devices for IAQ monitoring.

Manufacturer	LCS/Model	Unit Price	Purchasing	Weight	Dimensions (h × w × d in)	Battery/Power	Resources	Notes
Aethair (formerly AirThinx)[86]	Aethair IAQ	$699	Quote Link	180 g	4.3 × 2.6 × 1.2	Power (micro-USB, 5V DC)	Datasheet	Contract option: $49 for (24-month contract); End-to-end encryption; Built-in sim card
Air Gradient[87]	AirGradient ONE (9th generation)	$195	Buy direct Link	350 g	5.1 × 5.1 × 1.4	Power (USB-C, 5V 2A)	Datasheet	Mount or standalone; open-source data platform
air-Q[88]	Light	$280	Buy direct Link	400 g	4.5 × 5.3 × 1.7	Power (micro-USB and USB-C, 5V 2A)	Datasheet	Replaceable and exchangeable sensors with optional additional sensors
air-Q[88]	Basic	$380	Buy direct Link	400 g	4.5 × 5.3 × 1.7	Power (micro-USB and USB-C, 5V 2A)	Datasheet	Replaceable and exchangeable sensors with optional additional sensors
air-Q[88]	Pro	$565	Buy direct Link	400 g	4.5 × 5.3 × 1.7	Power (micro-USB and USB-C, 5V 2A)	Datasheet	Replaceable and exchangeable sensors with optional additional sensors
AirThings[89]	View Plus	$299	Buy direct Link	360 g	6.7 × 3.5 × 1.3	Battery (6× AA); Power (USB-C)	Datasheet	Compatible with Amazon Alexa; Mountable; Initial calibration time: VOC ~7 days, CO2 ~7 days
AirThings[89]	Wave Plus	$229.99	Buy direct Link	219 g	h 1.4 × d 4.7	Battery (2× AA)	Datasheet	Compatible with Amazon Alexa; Mountable; Initial calibration time: VOC ~7 days, CO2 ~7 days
Amazon[90]	Smart Air Quality Monitor	$69.99	Buy direct Link	120 g	2.6 × 2.6 × 1.8	Power (micro-USB, 5V 1A)	—	Compatible with Amazon Alexa
Atmotech Inc.[91]	Atmotube PRO	$189	Buy direct Link	104 g	3.4 × 2 × 0.9	Battery (rechargeable, 2000 mAh, USB-C)	Datasheet User support	Wearable/portable
Atmotech Inc.[91]	Atmocube	$299	Quote Link	300 g	5 × 5 × 1.5	Power (USB-C or USB-A, 5V 2A); Power over Ethernet	Datasheet User support	Mountable
Awair[92]	Element/2nd edition	$209	Buy direct Link	241 g	3.33 × 6.06 × 1.8	Power (USB-A/USB-C, 5V 2A)	Setup Datasheet	VOC sensor will require 24 to 48 hours to become fully calibrated after initial setup; Can be integrated with Amazon Alexa and Google Home
Awair[92]	Omni	$399	Buy direct Link	220 g	3.85 × 3.85 × 1.35	Battery (2250 mAh, 3.7 V); Power adapter (USB-C, 5V 2A); Power over Ethernet	Setup Datasheet	Standalone or wall mount
Ecowitt[74]	WH45	$159.99	Buy direct Link	—	2.7 × 4 × 2.8	AC power (USB adapter, 5V 1A) or 2× AA 1.5V batteries	User Manual	$29.99 (required Wi-Fi getaway) $22.99 (optional digital LCD display)

Manufacturer	LCS/Model	Unit Price	Purchasing	Weight	Dimensions (h × w × d in)	Battery/Power	Resources	Notes
Edimax[93]	AI-2002W	$199	Buy direct Link	210 g	5.3 × 5.3 × 1.4	Power (12V 1A)	Setup User manual Datasheet	Mount or standalone; recommended to clean the sensors every 3-6 months
Edimax[93]	AI-2003W	$199	Buy direct Link	210 g	5.3 × 5.3 × 1.4	Power (12V 1A)	Setup User manual Datasheet	Mount or standalone; recommended to clean the sensors every 3-6 months
Edimax[93]	AI-2004W	$199	Buy direct Link	210 g	5.3 × 5.3 × 1.4	Power (12V 1A)	Setup User manual Datasheet	Mount or standalone; recommended to clean the sensors every 3-6 months
Elitech[75]	Temtop M10	$95.99	Buy direct Link	200 g	3.2 × 3.2 × 1.2	Li Battery (rechargeable, 2200 mAh, 6 hr, 5V 1A)	User Manual	Life of sensors is estimated at 3 yrs
Elitech[75]	Temtop M10i	$119.99	Buy direct Link	200 g	3.2 × 3.2 × 1.2	Li Battery (rechargeable, 2200 mAh, 6 hr, 5V 1A)	Setup User Manual	Comparison chart of all 19 LCS devices found here
Elitech[75]	Temtop M100	$189.99	Buy direct Link	—	6.9 × 2.6 × 1.2	Li Battery (rechargeable, 4200 mAh; 5V 2A)	User Manual	Comparison chart of all 19 LCS devices found here
Elitech[75]	Temtop P1000	$99.99	Buy direct Link	—	10.2 × 5.5 × 1.3	Li Battery (rechargeable, 3000 mAh, 6-8 hr, 5V 1A)	User Manual	Comparison chart of all 19 LCS devices found here
Elitech[75]	Temtop M2000 2nd gen	$159.99	Buy direct Link	454 g	8.8 × 2.8 × 1.4	Li Battery (rechargeable, 3000 mAh, 6-8 hr, 5V 1A)	User Manual	Comparison chart of all 19 LCS devices found here
Elitech[75]	Temtop M2000C 2nd gen	$165.99	Buy direct Link	454 g	8.8 × 2.8 × 1.4	Li Battery (rechargeable, 3000 mAh, 6-8 hr, 5V 1A)	User Manual	Comparison chart of all 19 LCS devices found here
Elitech[75]	Temtop LKC-1000E	$109.99	Buy direct Link	408 g	7 × 2.6 × 1.3	Li Battery (rechargeable, 3000 mAh, 6-8 hr, 5V 1A)	User Manual	Comparison chart of all 19 LCS devices found here
Elitech[75]	Temtop LKC-1000S+ 2nd gen	$179.99	Buy direct Link	454 g	7 × 2.6 × 1.3	Li Battery (rechargeable, 3000 mAh, 6-8 hr, 5V 1A)	User Manual	Comparison chart of all 19 LCS devices found here
Ikea[94]	Vindstyrka	$49.99	Buy direct Link	—	3.5 × 2 × 2.25	Power (USB-C, 5V 1A)	Setup	USB power adapter sold separately; Connect Vindstyrka to Dirigera hub to see AQ in app; No display of tVOC on device display
IQAir[95]	Air Visual Pro	$299	Buy direct Link	670 g	6.4 × 2.7 × 8	Li Battery (rechargeable, 1900 mAH, 4 hr); Power (micro-USB)	Setup User Manual Datasheet	Personalized recommendations from indoor and outdoor air quality
IQAir[95]	Air Visual Outdoor	$299	Buy direct Link	758 g	6.4 × 2.7 × 8	Power (USB-C, 5.2V 2.3A); Power over Ethernet (48V)	User Manual Datasheet	$99 PM and $149 CO replacement modules; Mountable
Kaiterra[96]	Sensedge	$1500	Quote Link	800 g	1.9 × 5.7 × 7.2	Battery (5200 mAh, 8 hr, 4.2V); Power (USB-C, 5V 1.8A)	Datasheet User guide	Expected 5-7 lifespan; Mountable; Regularly subjected to 3rd party security tests
Kaiterra[96]	Sensedge Mini	$699	Quote Link	370 g	1.3 × 5.1 × 6.1	Power (USB-C, 5V 1.8A); Power (direct wiring, 12-30V); Power over Ethernet	Datasheet User guide	Expected 5-7 lifespan; Mountable; Regularly subjected to 3rd party security tests
Kaiterra[96]	Sensedge Mini Outdoor	—	Quote Link	426 g	6.7 × 3.2 × 7.5	Power (direct wiring, 12-30V); Power over Ethernet	Datasheet	Expected 5-7 lifespan; Mountable; Regularly subjected to 3rd party security tests

Manufacturer	LCS/Model	Unit Price	Purchasing	Weight	Dimensions (h × w × d in)	Battery/Power	Resources	Notes
NuWave Sensors[97]	AirSentric	$683	Buy direct Link	320 g	4 × 6 × 1.8	Power (12 V ±10%, 420 mA); Power over Ethernet (available)	Datasheet	Included GY36 Wireless Gateway; Mountable
Piera Systems[80]	Canārее I5	$349	Buy direct Link	50 g	3.5 × 2.4 × 0.81	Power (USB 5.5V 100-120 mA)	Datasheet User guide	—
Qingping[98]	Air Monitor 2	$149	Buy direct Link	250 g	4.1 × 3.5 × 2.9	Li Battery (rechargeable, 1800 mAh, 3.7V, , 4 hr); Power (USB-C, 5V 1A)	Datasheet	Replaceable PM sensor
Qingping[98]	Air Monitor Lite	$76	Buy direct Link	143 g	2.1 × 2.5 × 1.8	Li Battery (rechargeable, 2000 mAh, 7 hr); Power (USB-C, 5V 1A)	Datasheet User Manual	Apple Home hub required for Apple Home connection
Qingping[98]	CO_2 Monitor	$69.99	Buy direct Link	129 g	3.0 × 3.0 × 1.1	Power (USB-C, 5V 1A); Li Battery (2600 mAh, rechargeable)	Datasheet	Mountable
TSI[84,99]	Blue Sky 8145	—	Quote Link	159 g	6 × 5.5 × 4.5	Power (5V)	Datasheet User Manual	Mountable; replacement sensors; Designed for outdoor use and applicable indoors
TSI[84,99]	AirAssure (8144-2 / 8144-4 / 8144-6)	—	Quote Link	227 g	3.5 × 6.75 × 1.3	Power (USB-C 5V)	Datasheet User manual	Mountable; replacement sensors
uHoo[100]	Smart Air Monitor	$299	Buy direct Link	270 g	h 6.3 × d 3.3	Power (micro-USB, 5V 2A)	Datasheet User Manual	Able to Sync uHoo with other smart home devices
uRADMonitor[85]	Model A3	$589	Buy direct Link	170 g	4.3 × 2.6 × 1.0	Power (6-28 V)	Datasheet User Manual Setup	Mountable; 3 connectivity versions (Wi-Fi, ethernet, LoraWan)
uRADMonitor[85]	Model A4	$440	Buy direct Link	200 g	5.5 × 2.6 × 1.7	Power (USB-C, 5V 500 mA)	Datasheet	Mountable
Wicked Device[101]	Air Quality Egg Indoor V2	$650 (Base)	Buy direct Link	250 g	5.8 × 3.3 × 2.0	Power (USB, 5V)	User Manual Setup	Mix and match sensor types in one device: $168 (PM, CO_2), $365 ($NO_2$, O_3, CO, SO_2, H_2S), $65 (VOC); $70 (GPS), $35 (power bank); Expected life: 3 years
Wicked Device[101]	Air Quality Egg Outdoor V2	$650 (Base)	Buy direct Link	740 g	5.8 × 5.8 × 2.0	Power (USB, 5V)	User Manual Setup	Mix and match sensor types in one device: $168 (PM, CO_2), $365 ($NO_2$, O_3, CO, SO_2, H_2S), $65 (VOC); $70 (GPS), $35 (power bank); Expected life: 3 years

All information is accurate as of June 2024 and is subject to change at any time.

Table 3.3.6. Specifications (b) of multi-pollutant LCS devices for IAQ monitoring.

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Aethair (formerly AirThinx)[86]	Aethair IAQ	PM_1; $PM_{2.5}$; PM_{10}	—	0-500 μg m^{-3}; Res: 1 μg m^{-3}	± 10%	T, RH, P; AQI; GPS	WiFi/Cellular/BLE → cloud (Aethair Environet web console and Aethair App)	Website; Mobile application
Aethair (formerly AirThinx)[86]	Aethair IAQ	CO_2	—	400-5000 ppm; Res: 1 ppm	± 50 ppm + 2%	T, RH, P; AQI; GPS	WiFi/Cellular/BLE → cloud (Aethair Environet web console and Aethair App)	Website; Mobile application
Aethair (formerly AirThinx)[86]	Aethair IAQ	HCHO	—	0-1 mg m^{-3} Res: 0.001 mg m^{-3}	± 5%	T, RH, P; AQI; GPS	WiFi/Cellular/BLE → cloud (Aethair Environet web console and Aethair App)	Website; Mobile application
Aethair (formerly AirThinx)[86]	Aethair IAQ	TVOC	—	0-10 ppm	±15%	T, RH, P; AQI; GPS	WiFi/Cellular/BLE → cloud (Aethair Environet web console and Aethair App)	Website; Mobile application
Air Gradient[87]	AirGradient ONE (9^{th} generation)	PM_1; $PM_{2.5}$; PM_{10}	Laser; PMS5003 (Plantower)	0-500 μg m^{-3}	0-100 μg m^{-3} → ± 10; 100-500 m^{-3} → ±10%	T, RH	Wi-Fi/BLE → cloud (AirGradient Platform)	OLED Display; Website/API
Air Gradient[87]	AirGradient ONE (9^{th} generation)	CO_2	NDIR; S8 (SenseAir)	0-10000 ppm	0-2000 pm → ± 40 ppm ± 3%	T, RH	Wi-Fi/BLE → cloud (AirGradient Platform)	OLED Display; Website/API
Air Gradient[87]	AirGradient ONE (9^{th} generation)	NO_x	MOX; SCP41 (Sensirion)	0-500 NO_x/VOC Index	< ± 50	T, RH	Wi-Fi/BLE → cloud (AirGradient Platform)	OLED Display; Website/API
Air Gradient[87]	AirGradient ONE (9^{th} generation)	TVOC	MOX; SCP41 (Sensirion)	0-500 NO_x/VOC Index	< ± 15	T, RH	Wi-Fi/BLE → cloud (AirGradient Platform)	OLED Display; Website/API
air-Q[88]	Light	CO_2	—	300-5000 ppm; Res: 1 ppm	± 30 ppm, ± 3 % of reading	T, RH; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Light	VOC	—	0 – 60000 ppb; Res: 1 ppb (0 – 2008 ppb), 6 ppb (2008 – 11110 ppb), 32 ppb (11,110 – 60.000 ppb)	± 15 % of reading	T, RH; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Basic	PM_1; $PM_{2.5}$; PM_{10}	—	0 – 1000 μg m^{-3}; Res: 1 μg m^{-3}	± 10 μg/m³, ± 10 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Basic	CO_2	—	300-5000 ppm; Res: 1 ppm	± 30 ppm, ± 3 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
air-Q[88]	Basic	CO	—	0-5700 mg m⁻³ (0-5000 ppm); Res: 0.05 mg m⁻³ (0-180 mg m⁻³), 1.6 mg m⁻³ (>180 mg m⁻³)	± 8 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Basic	VOC	—	0 – 60000 ppb; Res: 1 ppb (0 – 2008 ppb), 6 ppb (2008 – 11110 ppb), 32 ppb (11,110 – 60.000 ppb)	± 15 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	PM_1; $PM_{2.5}$; PM_{10}	—	0 – 1000 µg m⁻³; Res: 1 µg m⁻³	± 10 µg/m³, ± 10 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	CO_2	—	300-5000 ppm; Res: 1 ppm	± 30 ppm, ± 3 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	CO	—	0-5700 mg m⁻³ (0-5000 ppm); Res: 0.05 mg m⁻³ (0-180 mg m⁻³), 1.6 mg m⁻³ (>180 mg m⁻³)	± 8 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	VOC	—	0 – 60000 ppb; Res: 1 ppb (0 – 2008 ppb), 6 ppb (2008 – 11110 ppb), 32 ppb (11,110 – 60.000 ppb)	± 15 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	O_3	—	0-10000 µg m⁻³ (0-5000 ppb) Res: 0.4 µg m⁻³ (0-1100 µg m⁻³), 75 µg m⁻³ (>1100 µg m⁻³)	± 8 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	NO_2	—	0-52000 µg m⁻³; Res: 0.1 µg m⁻³ (0-3000 µg m⁻³), 110 µg m³ (> 3000 µg m⁻³)	± 8 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	H_2S	—	0-70000 µg m⁻³ (0-50 ppm); 0.1 µg/m	± 5 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
air-Q[88]	Pro	Oxygen	—	0-25%; Res: 0.01%	± 2 % of reading	T, RH, P; Noise	Optional Wi-Fi → cloud (air-Q web/app); SD card (16 GB)	Website; Mobile application; Data export
AirThings[89]	View Plus	$PM_{2.5}$	Laser	0-500 µg m⁻³	<150 µg m⁻³ → ±(5 µg m⁻³ + 15%); >150 µg m⁻³ → ±(5 µg m⁻³ + 20%)	T, RH, P; Radon; Color threshold levels	Wi-Fi/BLE/Airthings SmartLink → cloud (Airthings app); Res: 5 min	eInk display; Website; Mobile Application
AirThings[89]	View Plus	CO_2	NDIR	400-5000 ppm	500-2000 ppm → ±50 ppm ±5%	T, RH, P; Radon; Color threshold levels	Wi-Fi/BLE/Airthings SmartLink → cloud (Airthings app); Res: 5 min	eInk display; Website; Mobile Application
AirThings[89]	View Plus	VOC	MOS	0-10000 ppb	—	T, RH, P; Radon; Color threshold levels	Wi-Fi/BLE/Airthings SmartLink → cloud (Airthings app); Res: 5 min	eInk display; Website; Mobile Application

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
AirThings[89]	Wave Plus	CO_2	NDIR	400-5000 ppm	±30 ppm ±3%	T, RH, P; Radon; Color threshold levels	BLE/Airthings SmartLink → cloud (Airthings Wave app); Res: 5 min	eInk display; Website; Mobile Application
AirThings[89]	Wave Plus	TVOC	—	—	—	T, RH, P; Radon; Color threshold levels	BLE/Airthings SmartLink → cloud (Airthings Wave app); Res: 5 min	eInk display; Website; Mobile Application
Amazon[90]	Smart Air Quality Monitor	$PM_{2.5}$	Laser; SEN44 (Sensirion)	0-500 µg m^{-3}	± 20 µg m^{-3} or ±20%, whichever is larger	T, RH; AQ score (color-coded LED)	Wi-Fi → cloud (Alexa app)	Multicolor LED indicator; Mobile application
Amazon[90]	Smart Air Quality Monitor	CO	TGS5141 (Figaro)	0-70 ppm	±5 ppm or ±30%	T, RH; AQ score (color-coded LED)	Wi-Fi → cloud (Alexa app)	Multicolor LED indicator; Mobile application
Amazon[90]	Smart Air Quality Monitor	VOCs	SEN44 (Sensirion)	0-500 points	±10 points or ±10% points	T, RH; AQ score (color-coded LED)	Wi-Fi → cloud (Alexa app)	Multicolor LED indicator; Mobile application
Atmotech Inc.[91]	Atmotube PRO	PM_1; $PM_{2.5}$; PM_{10}	OPC; SPS30 (Sensirion)	0-1000 µg m^{-3}	PM_1, $PM_{2.5}$: 0-100 µg m^{-3} → ± 5 µg m^{-3} + 5%; 100-1000 µg m^{-3} → ±10% PM_{10}: 0-100 µg m^{-3} → ± 25 µg m^{-3}; 100-1000 µg m^{-3} → ±25%	T, RH, P; AQI; GPS; Clock (in app)	Wi-Fi/BLE → cloud (Atmotube PRO app); Internal storage (10 days); Res: 1-15 min	Mobile application; API; Data export
Atmotech Inc.[91]	Atmotube PRO	TVOC	MOS; SGPC3 (Sensirion)	0-60 ppm	± 15%	T, RH, P; AQI; GPS; Clock (in app)	Wi-Fi/BLE → cloud (Atmotube PRO app); Internal storage (10 days); Res: 1-15 min	Mobile application; API; Data export
Atmotech Inc.[91]	Atmocube	PM_1; $PM_{2.5}$; PM_4; PM_{10}	OPC; SPS30 (Sensirion)	0-1000 µg m^{-3}	PM_1, $PM_{2.5}$: 0-100 µg m^{-3} → ± 5 µg m^{-3} + 5%; 100-1000 µg m^{-3} → ±10% PM_4, PM_{10}: 0-100 µg m^{-3} → ± 25 µg m^{-3}; 100-1000 µg m^{-3} → ±25%	T, RH, P; AQI; Light; Noise	Wi-Fi /BLE/Ethernet/ → cloud (Atmocube mobile app and dashboard web app); Internal storage (1 week); Res: 1 min	LED; Mobile application; Website dashboard
Atmotech Inc.[91]	Atmocube	CO_2	NDIR; SCD41 (Sensirion)	0-5000 ppm	400 – 1000 ppm → ± 75 ppm; 1001 – 2000 ppm → ± 40 ppm + 5% of reading	T, RH, P; AQI; Light; Noise	Wi-Fi /BLE/Ethernet/ → cloud (Atmocube mobile app and dashboard web app); Internal storage (1 week); Res: 1 min	LED; Mobile application; Website dashboard

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Atmotech Inc.[91]	Atmocube	HCHO	EC	0-1 ppm	±20 ppb or ±20% (the larger)	T, RH, P; AQI; Light; Noise	Wi-Fi /BLE/Ethernet/ → cloud (Atmocube mobile app and dashboard web app); Internal storage (1 week); Res: 1 min	LED; Mobile application; Website dashboard
Atmotech Inc.[91]	Atmocube	NO_x/VOC	MOS; SGP41 (Sensirion)	1-500 index points	< ±15 NO_x/VOC Index points or 15% (the larger)	T, RH, P; AQI; Light; Noise	Wi-Fi /BLE/Ethernet/ → cloud (Atmocube mobile app and dashboard web app); Internal storage (1 week); Res: 1 min	LED; Mobile application; Website dashboard
Awair[92]	Element/2nd edition	$PM_{2.5}$	Laser; HPMA115S0 (Honeywell)	0 - 1,000 µg/m^3; Res: 1 µg/m^3	±15 µg/m^3 or 15% (whichever is greater)	T, RH; AQ score	Wi-Fi/BLE → Awair Home App	LED display; Mobile application
Awair[92]	Element/2nd edition	CO_2	NDIR; T6703 (Amphenol-Telaire)	400 - 5,000ppm; Res: 1 ppm	±75 ppm or 10% (whichever is greater)	T, RH; AQ score	Wi-Fi/BLE → Awair Home App	LED display; Mobile application
Awair[92]	Element/2nd edition	TVOCs	MOS; SGP30 (Sensirion)	20 - 36,000ppb; Res: 1 ppb	±15%	T, RH; AQ score	Wi-Fi/BLE → Awair Home App	LED display; Mobile application
Awair[92]	Omni	$PM_{2.5}$	Laser	0 - 1,000 µg/m^3; Res: 1 µg/m^3	±15 µg/m^3 or 15%	T, RH; AQ score; Noise; Light	Wi-Fi/BLE → Awair Business App and dashboard; Ethernet/LTE (optional); Internal memory (11 MB); Res: 10 sec	LED display; Mobile application; Website dashboard; Serial output
Awair[92]	Omni	CO_2	NDIR	400 - 5,000 ppm; Res: 1 ppm	±75 ppm or 10%	T, RH; AQ score; Noise; Light	Wi-Fi/BLE → Awair Business App and dashboard; Ethernet/LTE (optional); Internal memory (11 MB); Res: 10 sec	LED display; Mobile application; Website dashboard; Serial output
Awair[92]	Omni	TVOCs	MOS	0-60000 ppb; Res: 1 ppb	±10%	T, RH; AQ score; Noise; Light	Wi-Fi/BLE → Awair Business App and dashboard; Ethernet/LTE (optional); Internal memory (11 MB); Res: 10 sec	LED display; Mobile application; Website dashboard; Serial output

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Ecowitt[74]	WH45	$PM_{2.5}$, PM_{10}	—	0-999 μg m^{-3} Res: 1 μg m^{-3}	$PM_{2.5}$: 0-100 μg m^{-3} → ±10 μg m^{-3}; 100-1000 μg m^{-3} → ±10%; PM_{10}: 0-100 μg m^{-3} → ±25 μg m^{-3}; 100-1000 μg m^{-3} → ±25%;	T, RH; AQI	Wi-Fi → Wi-Fi Gateway → cloud (WS ViewPlus App); Res: 1 min (AC power), 10 min (battery)	Mobile application; Website
Ecowitt[74]	WH45	CO_2	NDIR	0-40,000 ppm; Res: 1 ppm	400-10000 ppm → ± 30 ppm ± 3%;	T, RH; AQI	Wi-Fi → Wi-Fi Gateway → cloud (WS ViewPlus App); Res: 1 min (AC power), 10 min (battery)	Mobile application; Website
Edimax[93]	Al-2002W	$PM_{2.5}$, PM_{10}	Laser; PMS5003 (Plantower)	0-500 μg m^{-3}	—	T, RH; AQ indicator levels	WiFi → cloud (EdiGreen Home app)	LED color display; Mobile application
Edimax[93]	Al-2002W	CO_2	—	400-2000 ppm	—	T, RH; AQ indicator levels	WiFi → cloud (EdiGreen Home app)	LED color display; Mobile application
Edimax[93]	Al-2002W	HCHO	—	0-1 mg m^{-3}	—	T, RH; AQ indicator levels	WiFi → cloud (EdiGreen Home app)	LED color display; Mobile application
Edimax[93]	Al-2002W	TVOC	—	0-1000 ppb	—	T, RH; AQ indicator levels	WiFi → cloud (EdiGreen Home app)	LED color display; Mobile application
Edimax[93]	Al-2003W	$PM_{2.5}$, PM_{10}	—	0-500 μg m^{-3}	$PM_{2.5}$: <100 μg m^{-3} → ± 15 μg m^{-3}; >100 μg m^{-3} → 20%	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2003W	CO_2	NDIR	0-10,000 ppm	± 30 ppm	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2003W	HCHO	—	0-1 mg m^{-3}	± 10%	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2003W	TVOC	—	0-1000 ppb	± 15%	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2004W	$PM_{2.5}$, PM_{10}	—	0-500 μg m^{-3}	$PM_{2.5}$: <100 μg m^{-3} → ± 15 μg m^{-3}; >100 μg m^{-3} → 20%	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2004W	CO_2	NDIR	0-10,000 ppm	± 30 ppm	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Edimax[93]	Al-2004W	CO	—	0-500 ppm	± 20 ppm	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2004W	HCHO	—	0-1 mg m^{-3}	± 10%	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Edimax[93]	Al-2004W	TVOC	—	0-1000 ppb	± 15%	T, RH; AQ indicator levels	Wi-Fi/RS485 → cloud (EdiGreen Plus app)	OLED data display; Mobile application; Website
Elitech[75]	Temtop M10	$PM_{2.5}$	Laser; $PM_{2.5}$ sensor, 4th-gen (Temtop)	0-999 µg m^{-3} Res: 1 µg m^{-3}	0-100 µg m^{-3} → ± 10 µg m^{-3}; 100-500 µg m^{-3} → ±10%	AQI (LED indicator)	Device continuous monitoring	LCD Screen
Elitech[75]	Temtop M10	HCHO	EC (Dart Sensors)	0-2 mg m^{-3} Res: 0.01 mg m^{-3}	0-0.4 mg m^{-3} → ± 0.04 mg m^{-3}; ≥ 0.4 mg m^{-3} → ± 10%	AQI (LED indicator)	Device continuous monitoring	LCD Screen
Elitech[75]	Temtop M10	TVOC	—	0-5 mg m^{-3} Res: 0.01 mg m^{-3}	—	AQI (LED indicator)	Device continuous monitoring	LCD Screen
Elitech[75]	Temtop M10i	$PM_{2.5}$	Laser; $PM_{2.5}$ sensor, 4th-gen (Temtop)	0-999 µg m^{-3} Res: 1 µg m^{-3}	0-100 µg m^{-3} → ± 10 µg m^{-3}; 100-500 µg m^{-3} → ± 10%	AQI (LED indicator)	Wi-Fi → Temtop app	LCD Screen; Mobile application
Elitech[75]	Temtop M10i	HCHO	EC; HCHO (Dart Sensors)	0-2 mg m^{-3} Res: 0.01 mg m^{-3}	0-0.4 mg m^{-3} → ± 0.04 mg m^{-3}; ≥ 0.4 mg m^{-3} → ± 10%	AQI (LED indicator)	Wi-Fi → Temtop app	LCD Screen; Mobile application
Elitech[75]	Temtop M10i	TVOC	—	0-5 mg m^{-3} Res: 0.01 mg m^{-3}	—	AQI (LED indicator)	Wi-Fi → Temtop app	LCD Screen; Mobile application
Elitech[75]	Temtop M100	$PM_{2.5}$; PM_{10}	Laser; $PM_{2.5}$ sensor, 4th-gen (Temtop)	0-999 µg m^{-3} Res: 0.1 µg m^{-3}	$PM_{2.5}$: 0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%; PM_{10}: 0-100 µg m^{-3} → ±15 µg m^{-3}; 100-500 µg m^{-3} → ±15%	T, RH; AQI	Wi-Fi/BLE → Temtop App	7.8" Touch LCD display; Mobile application
Elitech[75]	Temtop M100	CO_2	NDIR; S8 (SenseAir)	0-5000 ppm; Res: 1 ppm	± 40 ppm ± 3% reading	T, RH; AQI	Wi-Fi/BLE → Temtop App	7.8" Touch LCD display; Mobile application
Elitech[75]	Temtop P1000	$PM_{2.5}$; PM_{10}	Laser	0-999 µg m^{-3}; Res: 0.1 µg m^{-3}	—	T, RH	Device continuous monitoring	LCD screen
Elitech[75]	Temtop P1000	CO_2	NDIR	0-5000 ppm; Res: 1 ppm	—	T, RH	Device continuous monitoring	LCD screen
Elitech[75]	Temtop M2000 2nd gen	$PM_{2.5}$; PM_{10}	Laser; $PM_{2.5}$ sensor, 4th-gen (Temtop)	0-999 µg m^{-3}; Res: 0.1 µg m^{-3}	$PM_{2.5}$: 0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%; PM_{10}: 0-100 µg m^{-3} → ±15 µg m^{-3}; 100-500 µg m^{-3} → ±15%	T, RH; Internal clock	Device → Res: 1-60 min	LCD display; Data export
Elitech[75]	Temtop M2000 2nd gen	CO_2	NDIR; S8 (SenseAir)	0-5000 ppm; Res: 1 ppm	± 50 ppm ± 5% reading	T, RH; Internal clock	Device → Res: 1-60 min	LCD display; Data export

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Elitech[75]	Temtop M2000 2nd gen	HCHO	EC (Dart Sensors)	0-2 mg m^{-3} Limit: 5 mg m^{-3}; Res: 0.001 mg m^{-3}	0-0.3 mg m^{-3} → ± 0.03 mg m^{-3}; 0.3-1 mg m^{-3} → ± 10%	T, RH; Internal clock	Device → Res: 1-60 min	LCD display; Data export
Elitech[75]	Temtop M2000C 2nd gen	$PM_{2.5}$; PM_{10}	Laser; $PM_{2.5}$ sensor, 4th-gen (Temtop)	0-999 µg m^{-3}; Res: 0.1 µg m^{-3}	$PM_{2.5}$: 0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%; PM_{10}: 0-100 µg m^{-3} → ±15 µg m^{-3}; 100-500 µg m^{-3} → ±15%	T, RH; Internal clock	Device → Res: 1-60 min (1, 5, 10, 30, 60)	LCD display; Data export
Elitech[75]	Temtop M2000C 2nd gen	CO_2	NDIR; S8 (SenseAir)	0-5000 ppm; Res: 1 ppm	± 50 ppm ± 5% reading	T, RH; Internal clock	Device → Res: 1-60 min (1, 5, 10, 30, 60)	LCD display; Data export
Elitech[75]	Temtop LKC-1000E	$PM_{2.5}$; PM_{10}	Laser; $PM_{2.5}$ sensor, 3rd-gen (Temtop)	0-999 µg m^{-3}; Res: 0.1 µg m^{-3}	$PM_{2.5}$: 0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%; PM_{10}: 0-100 µg m^{-3} → ±15 µg m^{-3}; 100-500 µg m^{-3} → ±15%	AQI	Device continuous monitoring	LCD display
Elitech[75]	Temtop LKC-1000E	HCHO	EC (Dart Sensors)	0-2 mg m^{-3}; Res: 0.01 mg m^{-3}	0-0.3 mg m^{-3} → ± 0.03 mg m^{-3}; 0.3-2 mg m^{-3} → ± 15%	AQI	Device continuous monitoring	LCD display
Elitech[75]	Temtop LKC-1000S+ 2nd gen	$PM_{2.5}$; PM_{10}	Laser; $PM_{2.5}$ sensor, 3rd-gen (Temtop)	0-999 µg m^{-3}; Res: 0.1 µg m^{-3}	$PM_{2.5}$: 0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10%; PM_{10}: 0-100 µg m^{-3} → ±15 µg m^{-3}; 100-500 µg m^{-3} → ±15%	T, RH; AQI	Device → Res: 1-60 min (1, 5, 10, 30, 60)	LCD display; Data export
Elitech[75]	Temtop LKC-1000S+ 2nd gen	HCHO	EC (Dart Sensors)	0-2 mg m^{-3}; Res: 0.01 mg m^{-3}	0-0.3 mg m^{-3} → ± 0.03 mg m^{-3}; 0.3-2 mg m^{-3} → ± 15%	T, RH; AQI	Device → Res: 1-60 min (1, 5, 10, 30, 60)	LCD display; Data export
Elitech[75]	Temtop LKC-1000S+ 2nd gen	TVOC	—	0-5 mg m^{-3}; Res: 0.01 mg m^{-3}	—	T, RH; AQI	Device → Res: 1-60 min (1, 5, 10, 30, 60)	LCD display; Data export
Ikea[94]	Vindstyrka	$PM_{2.5}$	Laser; SEN54 (Sensirion)	0-1000 µg m^{-3}	±10%	T, RH; AQ Indicator (RYG)	IKEA Home smart app (only with Dirigera hub)	Device display
	Vindstyrka	tVOC	MOX; SEN54 (Sensirion)	Trend arrow (increasing ↑, stable →, and decreasing ↓	±15% m.v.	T, RH; AQ Indicator (RYG)	IKEA Home smart app (only with Dirigera hub)	Device display
IQAir[95]	Air Visual Pro	$PM_{2.5}$	Laser; AVPM25b (IQAir)	—	—	T, RH; AQI; Internal clock	Wi-Fi → cloud (AirVisual app and dashboard); Device (real-time, past 24 hr)	LED display; Mobile application; Website

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
IQAir[95]	Air Visual Pro	CO_2	NDIR; S8 (SenseAir)	400-10000 ppm	—	T, RH; AQI; Internal clock	Wi-Fi → cloud (AirVisual app and dashboard); Device (real-time, past 24 hr)	LED display; Mobile application; Website
IQAir[95]	Air Visual Outdoor	PM_1; $PM_{2.5}$; PM_{10}	Laser	—	—	T, RH; AQI	Wi-Fi/Ethernet → cloud (AirVisual app and dashboard); Cellular (optional)	LED indicator; Mobile application; Website
IQAir[95]	Air Visual Outdoor	CO_2	—	400-10000 ppm	—	T, RH; AQI	Wi-Fi/Ethernet → cloud (AirVisual app and dashboard); Cellular (optional)	LED indicator; Mobile application; Website
Kaiterra[96]	Sensedge	$PM_{2.5}$	Laser	0-1000 µg m^{-3} Res: 1 µg m^{-3}	0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10 %	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal storage (8 GB)	Full color touch display; Website
Kaiterra[96]	Sensedge	CO_2	NDIR	400-2000 ppm (up to 10000 ppm); Res: 1 ppm	± 40 ppm ± 3%	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal storage (8 GB)	Full color touch display; Website
Kaiterra[96]	Sensedge	TVOC	MOx	0 - 60000 ppb; Res: 1 ppb	±15 % ±8 ppb	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal storage (8 GB)	Full color touch display; Website
Kaiterra[96]	Sensedge Mini	PM_1	Laser	0-1000 µg m^{-3} Res: 1 µg m^{-3}	0-100 µg m^{-3} → ±10 µg m^{-3}; 100-500 µg m^{-3} → ±10 %	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal memory (1 hr); Res: 1 min, 1 hr, 1 day	Website; Serial output (RS-485)
Kaiterra[96]	Sensedge Mini	CO_2	NDIR	400-2000 ppm (up to 10000 ppm); Res: 1 ppm	± 40 ppm ± 3%	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal memory (1 hr); Res: 1 min, 1 hr, 1 day	Website; Serial output (RS-485)
Kaiterra[96]	Sensedge Mini	TVOC	MOx	0 - 60000 ppb; Res: 1 ppb	±15 % ±8 ppb	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal memory (1 hr); Res: 1 min, 1 hr, 1 day	Website; Serial output (RS-485)
Kaiterra[96]	Sensedge Mini	O_3 (optional; KM-207 module)	EC	20-2000 ppb; Res: 1 ppb	±10 %	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal memory (1 hr); Res: 1 min, 1 hr, 1 day	Website; Serial output (RS-485)
Kaiterra[96]	Sensedge Mini Outdoor	$PM_{2.5}$	Laser	0-1000 µg m^{-3} Res: 1 µg m^{-3}	0-100 µg m^{-3}→ ±10 µg m^{-3}; 100-500 µg m^{-3}→ ±10 % m.v.	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal memory (1 hr); Res: 1 min, 1 hr, 1 day	Website; Serial output (RS-485)
Kaiterra[96]	Sensedge Mini Outdoor	CO_2	NDIR	400-2000 ppm (up to 10000 ppm); Res: 1 ppm	± 40 ppm ± 3%	T, RH	Wi-Fi/Ethernet → cloud (Kaiterra web app); Internal memory (1 hr); Res: 1 min, 1 hr, 1 day	Website; Serial output (RS-485)

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
NuWave Sensors[97]	AirSentric	PM_1; $PM_{2.5}$; PM_4; PM_{10}	—	0-1000 µg m^{-3}	± 10%	T, RH	Wi-Fi/Cellular/Ethernet → cloud (HEX Software)	Mobile application; website
NuWave Sensors[97]	AirSentric	CO_2	NDIR	0-5000 ppm; 0.04 to 2 % volume CO_2	± 3%	T, RH	Wi-Fi/Cellular/Ethernet → cloud (HEX Software)	Mobile application; website
NuWave Sensors[97]	AirSentric	TVOC	—	0-500 index points; 0-1000 ppb	± 5 VOC index points	T, RH	Wi-Fi/Cellular/Ethernet → cloud (HEX Software)	Mobile application; website
Piera Systems[80]	Canāree I5	PM	OPC; IPS-7100 (Piera)	0-6000 µg m^{-3}; Res: 0.1 µg m^{-3}	$PM_{0.1-2.5}$: 0-50 µg m^{-3} → ± 5 µg m^{-3} >50 µg m^{-3} → ± 10% PM_{5-10}: 0-50 µg m^{-3} → ± 10 µg m^{-3} >50 µg m^{-3} → ± 20%	T, RH, P; IAQ	Wi-Fi/Ethernet/BLE → cloud (SenseiAQ software)	LED AQ indicator Website
Piera Systems[8]	Canāree I5	TVOCs	EC	—	—	T, RH, P; IAQ	Wi-Fi/Ethernet/BLE → cloud (SenseiAQ software)	LED AQ indicator Website
Piera Systems[8]	Canāree I5	eCO_2	EC	—	—	T, RH, P; IAQ	Wi-Fi/Ethernet/BLE → cloud (SenseiAQ software)	LED AQ indicator Website
Qingping[98]	Air Monitor 2	$PM_{2.5}$; PM_{10}	Laser; Grandway PM5500	0~999 µg m^{-3}	—	T, RH; AQ indicator; Noise; Internal clock and alarms	Wi-Fi → cloud (Qingping+ app, 90-day historical data); Device (24 hr and 30-day data); Res: 1 sec	IPS touch display; Mobile application
Qingping[98]	Air Monitor 2	CO_2	Sensirion	400~9999 ppm	±15% m.v.	T, RH; AQ indicator; Noise; Internal clock and alarms	Wi-Fi → cloud (Qingping+ app, 90-day historical data); Device (24 hr and 30-day data); Res: 1 sec	IPS touch display; Mobile application
Qingping[98]	Air Monitor 2	eTVOC	EC; Sensirion	0~500 VOC Index or 0.005~9.999 mg m^{-3}	—	T, RH; AQ indicator; Noise; Internal clock and alarms	Wi-Fi → cloud (Qingping+ app, 90-day historical data); Device (24 hr and 30-day data); Res: 1 sec	IPS touch display; Mobile application
Qingping[98]	Air Monitor Lite	$PM_{2.5}$; PM_{10}	Laser; Grandway	0~500 µg m^{-3}	—	T, RH; AQ indicator	Wi-Fi/BLE → cloud (Qingping+ app, 30-day historical data); Apple HomeKit (available)	OLED display; Mobile application
Qingping[98]	Air Monitor Lite	CO_2	Sensirion	400~9999 ppm	±15% m.v.	T, RH; AQ indicator	Wi-Fi/BLE → cloud (Qingping+ app, 30-day historical data); Apple HomeKit (available)	OLED display; Mobile application

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Qingping[98]	CO_2 Monitor	CO_2	Sensirion	400~9999 ppm	±15% m.v.	T, RH; AQ indicator	Wi-Fi → cloud (Qingping IoT app or dashboard, 24 hr and 30-day historical data); Internal storage (2880 readings); Res: 1 min	LCD display; Mobile application; Website
TSI[84,99]	Blue Sky 8415	$PM_{2.5}$; PM_{10}	OPC; SPS30 (Sensirion)	0-1000 μg m^{-3}; Res: 1 μg m^{-3}	0-100 μg m^{-3} → ±10 μg m^{-3}; 100-1000 μg m^{-3} → ±10%	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	Blue Sky 8415	CO_2	NDIR	0-10000 ppm; Res: 1 ppm	±30 ppm + 3% of reading	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	Blue Sky 8415	CO	EC	0-20 ppm; Res: 0.001 ppm	0.150 ppm	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	Blue Sky 8415	O_3	EC	0-5000 ppb; Res: 1 ppb	±30 ppb	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	Blue Sky 8415	NO_2	EC	0-5000 ppb; Res: 1 ppb	±30 ppb	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	Blue Sky 8415	SO_2	EC	0-5000 ppb; Res: 1 ppb	±50 ppb	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	PM	Laser	0-1000 µg m^{-3}; Res: 1 µg m^{-3}	0-100 µg m^{-3} → ±10 µg m^{-3}; 100-1000 µg m^{-3} → ±10%	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	CO_2	NDIR	400-10000 ppm; Res: 1 ppm	±3% of reading + 30 ppm	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	CO	EC	0-1000 ppm; Res: 100 ppb	±15% of reading or ±150 ppb (whichever is greater)	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	O_3	EC	0-20 ppm; Res: 1 ppb	—	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	NO_2	EC	0-20 ppm; Res: 1 ppb	±15% of reading or ±15 ppb (whichever is greater)	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	SO_2	EC	0-10 ppm; Res: 1 ppb	—	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	HCHO	EC	0-1000 ppb; Res: 1 ppb	±20% of reading + 20 ppb	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
TSI[84,99]	AirAssure 8144-2 (PM, CO_2, VOCs); 8144-4 (CO_2, CO, HCHO, VOCs); 8144-6 (CO_2, CO, NO_2, O_3, SO_2, VOCs)	tVOC	MOX	0-1885 mg m^{-3}; Res: 0.001 mg m^{-3}	—	T, RH,P	Wi-Fi → cloud (TSI Link™ Solutions); SD card (32 GB, 2 weeks for 15 min data); Res: 1, 5, 10, 15, 30, 60 min	Website; SD Export
uHoo[100]	Smart Air Monitor	$PM_{2.5}$	—	1 - 200 µg m^{-3}; Res: 1 µg m^{-3}	±15 µg m^{-3} or ±10% (whichever is higher)	T, RH, P; AQ indicator	Wi-Fi → cloud (uHoo app);	Mobile Application
uHoo[100]	Smart Air Monitor	CO_2	—	400-10000 ppm; Res: 1 ppm	±50 ppm plus ±3%	T, RH, P; AQ indicator	Wi-Fi → cloud (uHoo app);	Mobile Application
uHoo[100]	Smart Air Monitor	NO_2	—	1-1000 ppb; Res: 1 ppb	±20 ppb or ±10% (whichever is higher)	T, RH, P; AQ indicator	Wi-Fi → cloud (uHoo app);	Mobile Application
uHoo[100]	Smart Air Monitor	CO	—	0 - 1,000 ppm; Res: 0.1 ppm	±2 ppm or ±5% (whichever is higher)	T, RH, P; AQ indicator	Wi-Fi → cloud (uHoo app);	Mobile Application
uHoo[100]	Smart Air Monitor	VOCs	—	0-30000 ppb; Res: 1 ppb	±20 ppb or ±15% (whichever is higher)	T, RH, P; AQ indicator	Wi-Fi → cloud (uHoo app);	Mobile Application
uHoo[100]	Smart Air Monitor	O_3	—	1-1000 ppb; Res: 1 ppb	±20 ppb or ±10% (whichever is higher)	T, RH, P; AQ indicator	Wi-Fi → cloud (uHoo app);	Mobile Application
uRADMonitor[85]	Model A3	PM_1; $PM_{2.5}$; PM_{10}	Laser	0-1000 µg m^{-3}; Res: 1 µg m^{-3}	±15%	T, RH, P; Noise	Wi-Fi /Ethernet/LoRaWAN → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A3	CO_2	NDIR	400-5000 ppm; Res: 1 ppm	±5%	T, RH, P; Noise	Wi-Fi /Ethernet/LoRaWAN → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A3	O_3	EC	0-10 ppm; Res: 10 ppb	±5%	T, RH, P; Noise	Wi-Fi /Ethernet/LoRaWAN → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
uRADMonitor[85]	Model A3	HCHO	EC	0-5 ppm; Res: 10 ppb	±5%	T, RH, P; Noise	Wi-Fi /Ethernet/LoRaWAN → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A3	VOCs	MOX	10-1000 ppm (for alcohol)	±15%	T, RH, P; Noise	Wi-Fi /Ethernet/LoRaWAN → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	PM_1; $PM_{2.5}$; PM_{10}	Laser	0-1000 $\mu g\ m^{-3}$; Res: 1 $\mu g\ m^{-3}$	±15%	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	CO_2	NDIR	400-5000 ppm; Res: 1 ppm	±5%	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	O_3	EC	0-10 ppm; Res: 10 ppb	±5%	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	HCHO	EC	0-5 ppm; Res: 10 ppb	±5%	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	CO	EC	0-500 ppm; Res: 100 ppb	±10%	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	NO_2	Micro-electromechanical	0.1-10 ppm Res: 10 ppb	±0.05 ppm	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
uRADMonitor[85]	Model A4	VOCs	MOX	0-3 AQ score	—	T, RH	Wi-Fi → cloud (uRADMonitor servers); Res: 1 min	Website/API; Local access LAN
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	PM_1; $PM_{2.5}$; PM_{10}	Laser; PMS5003 (Plantower)	Min: 0.3 µm 0-1000 $\mu g\ m^{-3}$	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	CO_2	—	—	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	CO	EC; ZE12A (Winsen)	0-10 ppm; Res: ≤10 ppb	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	O_3	EC; ZE12A (Winsen)	0-1 ppm Res: ≤10ppb	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	NO_2	EC; ZE12A (Winsen)	0-1 ppm Res: ≤10ppb	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export

Manufacturer	LCS/Model	Pollutant	Sensor/Technology	Measurement Range	Accuracy	Other Parameters	Data Storage & Transmission	Data Retrieval/ Visualization
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	SO_2	EC; ZE12A (Winsen)	0-1 ppm Res: ≤10ppb	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	H_2S	EC; ZE12A (Winsen)	0-1 ppm Res: ≤10ppb	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export
Wicked Device[101]	Air Quality Egg Indoor/Outdoor	VOC	—	—	—	T, RH, P; AQI; GPS (optional)	Wi-Fi → cloud (Air Quality Egg Portal); Internal storage	Website; Mobile application; Data export

All information is accurate as of June 2024 and is subject to change at any time.

3.3 Performance Evaluations for LCS Devices

The market availability of several single- and multi-pollutant LCS (Tables 3.3.1 and 3.3.2) provides end users with choices in their selection and needs for IAQ monitoring. The accessibility and ease-of-use of these LCS devices are important, as well as their ability to reliably detect and quantify one or more targeted pollutants. Unlike regulatory or reference monitors, the performance of LCS devices depends on several internal and external factors that influence the reliability and accuracy of associated air quality measurements. These factors include the target pollutant and underlying measurement technology, quality and design of sensor hardware components, environmental conditions, and methods of operation (see Table 3.4.1).[47,49,54,102] Additionally, LCS manufacturers often present their devices as calibrated and ready to use "out of the box" ensuring accurate readings; however, these manufacturers often do not elaborate on their calibration process and conditions, algorithms, and reference instruments used. As a result, it can be challenging for end users to distinguish which LCS provides reasonable reliability and accuracy for pollutants of interest, driving the need for independent assessments of these devices.

The EPA evaluates LCS only in outdoor, ambient conditions ("Air Sensor Toolbox", www.epa.gov/air-sensor-toolbox) while AQ-SPEC (www.aqmd.gov/aq-spec) characterizes LCS performance under ambient (field) and controlled (laboratory) conditions. Researchers also examine the performance of different LCS in a range of environmental settings, including different types of indoor environments (e.g., laboratory, home, office, school)[43,103–105] as well as under ambient outdoor conditions.[45,51,52] While assessing the performance of LCS occur in diverse environments, these evaluations have largely focused on ambient and laboratory conditions with fewer studies focusing on IAQ. Ambient evaluations of LCS often result in sophisticated correction algorithms to account for environmental factors such as humidity and temperature.[106,107] Regardless of the evaluator and environmental conditions, LCS testing is usually conducted alongside or in comparison to reference-grade (EPA FEM/FRM) or research instrumentation to determine LCS data confidence. These reference-grade or research instrumentations are operated and maintained by highly trained technical staff and have known and consistent data quality in a variety of conditions, and thus can serve as reliable references.

The process of selecting LCS for stakeholders depends on the project or application objectives, and striking a balance between maximizing data quality and performance with cost, operation, and maintenance needs. In some cases, having a LCS device provide trends or display qualitative data such as when concentrations are high or low may be sufficient for informing and educating nontechnical end users of air quality in indoor environments, but would be inadequate for LCS applications requiring highly quantitative and precise measurements, in the case of a research field deployment using LCS to supplement regulatory measurements.

Table 3.4.1. Factors that affect LCS performance.

Factors	Characteristics/Properties
Target pollutant(s) and Technology (Section 3.1)	Light-scattering sensors o More reliable for $PM_{2.5}$ than PM_{10} o Sensitive to particle size, composition, and hygroscopicity o Current technology cannot measure smaller particles (< 0.3 µm)[103] o PM build-up in sensor over time can change performance
Target pollutant(s) and Technology (Section 3.1)	EC and MOS/MOX sensors o Performance depends on manufacturer and pollutant gases o Cross-sensitivities and susceptible to interferences from non-target pollutants and environmental parameters o Sensors may lose sensitivity over time and subject to drift
Target pollutant(s) and Technology (Section 3.1)	PID sensors o Does not measure all VOCs and are more sensitive to some VOCs o Sensors are not specific for VOCs when more than one is present o Cross-sensitivities and responds to non-target pollutants and environmental parameters
Target pollutant(s) and Technology (Section 3.1)	NDIR sensors o Reliable and state-of-the-art for CO_2 measurements o Less widely applied to other IR active pollutant gases (e.g., CO, NO_x, SO_2)
Quality and Design of Sensor Hardware	o Ruggedness of sensor enclosure for protecting internal components from external and environmental conditions o Placement of the sensing component inside LCS device and efficiency of the target pollutant reaching it (e.g., air flow placement for PM LCS)
Environmental Conditions and Calibrations	o Environment concentrations of the target pollutant must match LCS capabilities and sensitivities o In outdoor and indoor conditions, sensors can be sensitive to temperature, humidity, and other conditions that can influence measurements or damage internal components o In indoor conditions: ▪ LCS may be consistently overloaded if high pollution events occur frequently and cause drift or aging of the LCS ▪ Occupants' behavior may also impact the performance, e.g., blocking LCS sampling air inlet, causing vibration constantly (high traffic area), and high humidity impacts (placement near bathroom or humidifier) o Manufacturer calibration of LCS may use pollutant sources (e.g., aerosol type) different from target monitoring needs, thus potentially affecting measurement outcomes
Operation	o Siting or placement of sensor in adequate location for best performance (e.g., mounted) o Routine or preventative maintenance of LCS (e.g., cleaning, sensor replacements) o Data transmission (e.g., stable wireless connection)

Table 3.4.2. Performance evaluation considerations for LCS applications.

Factors	Key Questions
Trends	How well do the changes in LCS measurements mimic or track the change in pollutant concentrations that are measured by the reference instrument?
Precision (Intra-model variability)	How consistent are the concentration measurements obtained by LCS of the same make, model, and firmware version that are operated under the same evaluation conditions?
Bias (Accuracy)	How closely do the LCS measurements agree with measurements made by a collocated reference instrument?
Concentration Range	Does the operating range of the LCS cover the range of pollutant concentrations expected at the desired monitoring location or environment?
Meteorology	Is the sensor response affected by meteorological conditions (e.g., RH, T)? Was the LCS evaluation performed in an environment similar to your application of interest?
Specificity	Does the LCS measure the target pollutant? Are the LCS measurements affected by any interferent(s)?
Drift	Is the LCS response to pollutant concentrations stable over time? For how long?

Adapted from EPA's *The Enhanced Air Sensor Guidebook* (Section 4.4)[47]

Table 3.4.3. Examples of suggested performance goals for LCS applications compared to regulatory monitoring.

Application Area	Pollutants	Precision & Bias Error	Data Completeness	Rationale
Education & Information	All	<50%	≥50%	Importance is demonstrating pollutant exists in some wide concentration range.
Hotspot Identification & Characterization	All	<30%	≥75%	Higher data quality needed to ensure concentration close to true value.
Supplemental Monitoring	Criteria pollutants, air toxics	<20%	≥80%	Must be sufficient quality to ensure information is filling in monitoring gaps.
Personal Exposure	All	<30%	≥80%	Error rates higher than these make interpretation of personal exposure data difficult to understand
Regulatory Monitoring	O_3 CO, SO_2 NO_2 $PM_{2.5}$, PM_{10}	<7% <10% <15% <10%	≥75%	Precise measurements needed to ensure high data quality able to meet regulatory requirements

Color gradient indicates increasing importance of performance for AQ measurements.
Adapted from Table 5-1 in EPA's *Air Sensor Guidebook*[108]

EPA's *The Enhanced Air Sensor Guidebook*[47] provides information on factors to consider when reviewing sensor performance evaluation results in the scope of an end-user's planned LCS application (Table 3.4.2). Additional guidance on LCS performance goals for individuals, communities, and other stakeholders have been suggested in an earlier version of EPA's *Air Sensor guidebook*[108] (Table 3.4.3).

Existing performance evaluations for commercially-available single- and multi-pollutant LCS devices suitable for IAQ monitoring (Tables 3.3.1 and 3.3.2) are summarized in Section 3.3.1 for those evaluated by AQ-SPEC and Section 3.3.2 for those reviewed in peer-reviewed and other gray literature. All single- and multi-pollutant LCS with existing validation results from AQ-SPEC and/or research studies are listed in Table 3.4.4. Given that LCS rapidly evolve and newer versions are created every few years by some manufacturers, available evaluations included in Sections 3.3.1 and 3.3.2 cover older versions of current commercially-available LCS for IAQ monitoring if the most recent version or model has not been evaluated.

Table 3.4.4. Single- and multi-pollutant LCS with available performance evaluations from AQ-SPEC and/or peer-reviewed or gray literature.

Manufacturer	**Single**-Pollutant LCS
Davis Instruments	AirLink
Applied Particle Technology	Minima
Dylos Corporation	DC1100
	DC1100 Pro
	DC1700 Battery
	DC1700-PM
Ecowitt	WH41
HabitatMap	Airbeam 3
Netatmo	Smart IAQ Monitor
PurpleAir	PA-II (classic)
	PA-II-Flex
	PA-I
SAF Tehnika	Aranet4
TSI	BlueSky
uRADMonitor	SMOGGIE-PM

Manufacturer	**Multi**-Pollutant LCS
Aethair (formerly AirThinx)	AirThinx IAQ
Atmotech Inc.	Atmotube PRO
Awair	Element
Edimax	AI-2002W
	AI-2003W
Elitech	Temtop M2000 2^{nd} gen
	Temtop LKC-1000S+ 2^{nd} gen
IQAir	Air Visual Pro
	Air Visual Outdoor
Qingping	Air Monitor 2
	Air Monitor Lite
TSI	AirAssure
UHOO	Smart Air Monitor
uRADMonitor	MODEL A3
Wicked Device	Air Quality Egg Indoor
	Air Quality Egg Outdoor

3.3.1 AQ-SPEC Performance Evaluations of LCS Devices

AQ-SPEC was established by South Coast AQMD to evaluate the performance of commercially available LCS and provide guidance on data quality. AQ-SPEC (www.aqmd.gov/aq-spec) performs the most systematic and extensive evaluations of commercially-available LCS using carefully developed methods, protocols, and procedures in the field, under ambient conditions, and in the laboratory under controlled environmental conditions.

In the field, manufacturer-calibrated LCS are evaluated in triplicate (3 units) over a span of approximately two months alongside FEM and FRM AQ instruments under a Field Testing Protocol[109] at the South Coast AQMD Rubidoux stationary ambient air monitoring station. In the laboratory, LCS with nominal field performance are further evaluated with controlled tests in AQ-SPEC specialized chambers under a Laboratory Testing Protocol.[110,111] In AQ-SPEC chambers, controlled artificial aerosol comprising liquid aerosol (salt) and dry dust are used in experiment testing of PM sensors while controlled gaseous atmosphere environments are generated for testing gas sensors.[111] AQ-SPEC makes use of several metrics to report the performance of LCS such as R^2, slope, intra-model variability, and error measures. R^2 calculated from a linear regression indicates the correlation between co-located LCS and FEM/FRM concentration measurements. An R^2 approaching the value of 1 reflects a near perfect correlation with reference instruments, whereas a value of 0 indicates a complete lack of correlation. The slope of the linear regression shows how similar the LCS measurements are to reference measurements, and the closer the slope is to 1, the more the LCS response is like the reference instrument. A slope larger or smaller than 1 represents an over- or underestimation of LCS concentrations when compared to reference instruments. Intra-model variability describes how close together the measurements of three evaluated units of the same LCS are compared to each other. Error calculations show the degree of closeness of LCS measurements to the actual (true) concentration value using FEM/FRM instruments. AQ-SPEC uses mean absolute error (MAE) as an error metric to present the disagreement in pollutant concentrations between co-located LCS and reference instruments. The closer MAE is to 0, the higher the agreement of LCS measurements to reference instruments.

Single- and multi-pollutant LCS (Tables 3.3.1 and 3.3.2) evaluated by AQ-SPEC are summarized in Tables 3.4.5 and 3.4.6 respectively with relevant performance information, including year of evaluation, links to evaluation reports, pollutants evaluated, reference instruments used, R^2, slope, MAE, and other related information. The year of evaluation is important as LCS manufacturers consistently change or improve their devices, releasing newer generations or models every few years. FEM/FRM reference instruments and evaluated LCS use 5-minute resolution data unless otherwise stated in Tables 3.4.5 and 3.4.6. This resolution is selected as some reference instruments used by AQ-SPEC provide data only at a 1-hour resolution in the field, whereas laboratory reference instruments consistently provide data at a 5-minute resolution. To ensure an ideal comparison of performance between field and laboratory evaluations, the 5-minute resolution data was adopted. For slope values resulting from linear regressions, reference instrument data are along the *y*-axis and LCS measurements are on the *x*-axis. Additional notes in Tables 3.4.5 and 3.4.6 include trends of LCS measurements either over- or underestimating reference concentration values as well as LCS data recovery, as reported by AQ-SPEC. Data recovery describes the ratio of valid LCS data points over the total number of data points collected during the testing period,[109] which is important for reliable and representative LCS pollution data. T and RH sensors were present in all evaluated LCS devices, and usually had $R^2 > 0.90$ compared to references.

Table 3.4.5. AQ-SPEC performance evaluations for single-pollutant LCS.

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE (µg m^{-3})	Pollutant Notes	LCS Notes
Applied Particle Technology	Minima	2020[112]	Ambient	PM_1	Teledyne API T640	~ 0.83-0.90	5.0-5.6	Slope = 1.35-1.47 Underestimation	Data recovery: ~100% Intra-model variability: Low
Applied Particle Technology	Minima	2020[112]	Ambient	$PM_{2.5}$	Teledyne API T640	~ 0.86-0.89	5.8-6.5	Slope = 1.0-1.1 Underestimation	Data recovery: ~100% Intra-model variability: Low
Applied Particle Technology	Minima	2020[112]	Ambient	PM_{10}	Teledyne API T640	~ 0.36-0.38	39.4-40.3	Slope = 1.40-1.49 Underestimation	Data recovery: ~100% Intra-model variability: Low
Applied Particle Technology	Minima	2020[112]	Chamber	$PM_{2.5}$	Teledyne API T640x	> 0.99	5.0-8.1	Slope = 1.0 Overestimation	Data recovery: ~100% Intra-model variability: Low
Davis Instruments	AirLink	2021[113]	Ambient	PM_1	GRIMM Teledyne API T640	~ 0.85-0.89	2.2-2.8	Slope = 0.73-0.79 Underestimation	Data recovery: ~100% Intra-model variability: Low
Davis Instruments	AirLink	2021[113]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.73-0.81	4.9-5.9	Slope = 0.50-0.57 Over/underestimation	Data recovery: ~100% Intra-model variability: Low
Davis Instruments	AirLink	2021[113]	Ambient	PM_{10}	GRIMM Teledyne API T640	~ 0.24-0.31	12.1-26.0	Slope = 0.47-0.68 Underestimation	Data recovery: ~100% Intra-model variability: Low
Davis Instruments	AirLink	2021[113]	Chamber	$PM_{2.5}$	Teledyne T640x	> 0.99	4.3-6.6	Slope = 1.1 Overestimation (< 200 µg m^{-3})	Data recovery: ~100% Intra-model variability: Low
Dylos Corporation	DC1100 Pro with PC interface	2014-2015[114]	Ambient	$PM_{0.5\text{-}2.5}$	GRIMM	~ 0.81	4.2	—	Data recovery: ~100% Intra-model variability: Low
Dylos Corporation	DC1700 Battery	2014-2015[114]	Chamber	$PM_{0.5\text{-}2.5}$	GRIMM	~ 0.89	—	Slope = 0.93 Overestimation	Data recovery: ~100% Intra-model variability: Low
Dylos Corporation	DC1700-PM	2018[115]	Ambient	$PM_{2.5}$	GRIMM Teledyne T640	~ 0.58-0.68	24.3-28.5	Slope = 0.15-0.21 Large overestimation	Data recovery: ~100% Intra-model variability: Low
Dylos Corporation	DC1700-PM	2018[115]	Ambient	PM_{10}	GRIMM Teledyne T640	~ 0.15-0.18	43.9-53.8	Slope = 0.19-0.29 Large overestimation	Data recovery: ~100% Intra-model variability: Low
Dylos Corporation	DC1700-PM	2018[115]	Chamber	$PM_{2.5}$	GRIMM	> 0.95	198.3-209.4	Slope = 0.41 Large overestimation	Data recovery: ~100% Intra-model variability: Low
Ecowitt	WH41	2019[116]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.33-0.52	8.2-15.4	Slope = 0.17-0.43 Overestimation	Data recovery: ~92% Intra-model variability: Low
HabitatMap	Airbeam 3	2022[117]	Ambient	PM_1	GRIMM EDM 180 Teledyne API T640	~ 0.94-0.97	1.3-2.6	Slope = 0.76-1.0 Underestimation	Data recovery: > 98% Intra-model variability: Moderate
HabitatMap	Airbeam 3	2022[117]	Ambient	$PM_{2.5}$	GRIMM EDM 180 Teledyne API T640	~ 0.80-0.91	3.6-5.3	Slope = 0.85-1.1 Underestimation	Data recovery: > 98% Intra-model variability: Moderate
HabitatMap	Airbeam 3	2022[117]	Ambient	PM_{10}	GRIMM EDM 180 Teledyne API T640	~ 0.19-0.26	20.4-26.8	Slope = 0.94-1.56 Underestimation	Data recovery: > 98% Intra-model variability: Moderate
HabitatMap	Airbeam 3	2022[117]	Chamber	PM_1	Teledyne T640x	> 0.99	1.5-5.7	Slope = 0.89 Underestimation	Data recovery: > 98% Intra-model variability: Moderate

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE (µg m^{-3})	Pollutant Notes	LCS Notes
HabitatMap	Airbeam 3	2022[117]	Chamber	$PM_{2.5}$	Teledyne T640x	> 0.99	2.6-11.6	Slope = 1.1 Underestimation	Data recovery: > 98% Intra-model variability: Moderate
PurpleAir	PA-II	2016[118]	Ambient	PM_1	GRIMM	~ 0.86-0.98	—	Slope = 0.64-0.83 Overestimation	Data recovery: 95-99% Intra-model variability: Low
PurpleAir	PA-II	2016[118]	Ambient	$PM_{2.5}$	GRIMM	~ 0.90-0.98	—	Slope = 0.51-0.64 Overestimation	Data recovery: 95-99% Intra-model variability: Low
PurpleAir	PA-II	2016[118]	Ambient	PM_{10}	GRIMM	~ 0.66-0.70	—	Slope = 0.53-0.69 Overestimation	Data recovery: 95-99% Intra-model variability: Low
PurpleAir	PA-II	2016[118]	Chamber	PM_1	GRIMM	> 0.99	11.7-15.9	Slope = 1.49 Underestimation 0-175 µg m^{-3}	Data recovery: 95-99% Intra-model variability: Low
PurpleAir	PA-II	2016[118]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	1.7-4.2	Slope = 1.31 Underestimation 0-250 µg m^{-3}	Data recovery: 95-99% Intra-model variability: Low
PurpleAir	PA-II	2016[118]	Chamber	PM_{10}	GRIMM	~ 0.94	15.6-20.5	Slope = 2.38 Large Underestimation 0-200 µg m^{-3}	Data recovery: 95-99% Intra-model variability: Low
PurpleAir	PA-II-Flex	2022[119]	Ambient	PM_1	GRIMM EDM 180 Teledyne API T640	~ 0.90-0.94	1.4-2.2	Slope = 0.74-0.81 Underestimation	Data recovery: ~94% Intra-model variability: Low
PurpleAir	PA-II-Flex	2022[119]	Ambient	$PM_{2.5}$	GRIMM EDM 180 Teledyne API T640	~ 0.77-0.89	3.4-3.8	Slope = 0.62-0.67 Underestimation	Data recovery: ~94% Intra-model variability: Low
PurpleAir	PA-II-Flex	2022[119]	Ambient	PM_{10}	GRIMM EDM 180 Teledyne API T640	~ 0.21-0.39	15.3-24.8	Slope = 0.63-0.91 Underestimation	Data recovery: ~94% Intra-model variability: Low
PurpleAir	PA-II-Flex	2022[119]	Chamber	PM_1	Teledyne T640x	> 0.99	13.5-14.6	Slope = 1.78 Underestimation 0-300 µg m^{-3}	Data recovery: ~100% Intra-model variability: Low
PurpleAir	PA-II-Flex	2022[119]	Chamber	$PM_{2.5}$	Teledyne T640x	> 0.99	1.7-2.2	Slope = 1.16 Underestimation 50-300 µg m^{-3}	Data recovery: ~100% Intra-model variability: Low
PurpleAir	PA-I	2018[120]	Ambient	$PM_{2.5}$	MetOne BAM	~ 0.75-0.76	—	Slope = 0.57-0.59 Overestimation	Data recovery: > 99% Intra-model variability: Low 1-hr data
PurpleAir	PA-I	2018[120]	Ambient	PM_{10}	MetOne BAM	~ 0.36-0.46	—	Slope = 14.7-31.1 Large Underestimation	Data recovery: > 99% Intra-model variability: Low 1-hr data
PurpleAir	PA-I	2018[120]	Chamber	PM_1	GRIMM	> 0.99	5.1-9.5	Slope = 1.17 Underestimation > 50 µg m^{-3}	Data recovery: ~100% Intra-model variability: Low
PurpleAir	PA-I	2018[120]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	18.7-27.7	Slope = 0.73 Overestimation	Data recovery: ~100% Intra-model variability: Low

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE (µg m^{-3})	Pollutant Notes	LCS Notes
PurpleAir	PA-I	2018[120]	Chamber	PM_{10}	GRIMM APS	~ 0.97	4.4-20.4	Slope = 1.83-2.16 Underestimation	Data recovery: ~100% Intra-model variability: Low
TSI	BlueSky	2020[121]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.65-0.76	4.9-5.9	Slope = 0.84-1.29 Underestimation	Data recovery: >80% Intra-model variability: Moderate
TSI	BlueSky	2020[121]	Ambient	PM_{10}	GRIMM Teledyne API T640	~ 0.09-0.21	22.7-26.3	Slope = 1.42-2.25 Underestimation	Data recovery: >80% Intra-model variability: Moderate
TSI	BlueSky	2020[121]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	3.1-6.2	Slope = 0.98 0-250 µg m^{-3}	Data recovery: ~100% Intra-model variability: Moderate
uRADMonitor	SMOGGIE-PM	2020[122]	Ambient	PM_1	GRIMM	~ 0.83-0.85	4.8-5.6	Slope = 1.52-1.65 Underestimation	Data recovery: >78% Intra-model variability: Low
uRADMonitor	SMOGGIE-PM	2020[122]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.60-0.81	2.1-2.8	Slope = 0.62-1.17 Underestimation	Data recovery: >78% Intra-model variability: Low
uRADMonitor	SMOGGIE-PM	2020[122]	Ambient	PM_{10}	GRIMM Teledyne API T640	~ 0.02-0.06	17.5-25.2	Slope = 0.44-1.05 Underestimation	Data recovery: >78% Intra-model variability: Low
uRADMonitor	SMOGGIE-PM	2020[122]	Chamber	PM_1	GRIMM	> 0.99	25.3-26.8	Slope = 4.03 Large Underestimation	Data recovery: ~100% Intra-model variability: Low
uRADMonitor	SMOGGIE-PM	2020[122]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	19.5-22.9	Slope = 2.55 Large Underestimation	Data recovery: ~100% Intra-model variability: Low

Table 3.4.6. AQ-SPEC performance evaluations for multi-pollutant LCS.

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE (µg m^{-3})	Pollutant Notes	LCS Notes
Aethair (formerly AirThinx)	AirThinx IAQ	2018[123]	Ambient	PM_1	GRIMM	~ 0.68-0.71	2.4-2.5	Slope = 0.78-0.82	Data recovery: ~100% Intra-model variability: Low
Aethair (formerly AirThinx)	AirThinx IAQ	2018[123]	Ambient	$PM_{2.5}$	GRIMM	~ 0.54-0.57	4.8-5.0	Slope = 0.51-0.53	Data recovery: ~100% Intra-model variability: Low
Aethair (formerly AirThinx)	AirThinx IAQ	2018[123]	Ambient	PM_{10}	GRIMM	~ 0.04-0.05	19.7-19.8	Slope = 0.49-0.55 Large Underestimation	Data recovery: ~100% Intra-model variability: Low
Atmotech Inc.	Atmotube PRO	2020[124]	Ambient	PM_1	GRIMM	~ 0.90-0.93	3.6-4.6	Slope = 1.03-1.32 Underestimation	Data recovery: > 92% Intra-model variability: Low
Atmotech Inc.	Atmotube PRO	2020[124]	Ambient	$PM_{2.5}$	GRIMM	~ 0.88	4.9-5.9	Slope = 0.98-1.21 Underestimation	Data recovery: > 92% Intra-model variability: Low
Atmotech Inc.	Atmotube PRO	2020[124]	Ambient	PM_{10}	GRIMM	~ 0.22	20.9-22.9	Slope = 0.99-1.18 Underestimation	Data recovery: > 92% Intra-model variability: Low
Atmotech Inc.	Atmotube PRO	2020[124]	Chamber	PM_1	GRIMM	> 0.99	1.9-6.4	Slope = 0.88 0-200 µg m^{-3}	Data recovery: ~ 100% Intra-model variability: Low to moderate
Atmotech Inc.	Atmotube PRO	2020[124]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	2.9-3.8	Slope = 0.94 0-250 µg m^{-3}	Data recovery: ~ 100% Intra-model variability: Low to moderate
Edimax	AI-2002W	2018[125]	Ambient	$PM_{2.5}$	GRIMM	~ 0.82-0.83	3.3-4.4	Slope = 0.60-0.63 Overestimation	Data recovery: > 99% Intra-model variability: Low
Elitech	Temtop M2000 2nd gen	2020[126]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.77-0.82	2.1-3.2	Slope = 0.66-0.99 Underestimation	Data recovery: ~ 100% Intra-model variability: Low
Elitech	Temtop M2000 2nd gen	2020[126]	Ambient	PM_{10}	GRIMM Teledyne API T640	~ 0.18-0.28	12.1-14.1	Slope = 1.01-1.34 Underestimation	Data recovery: ~ 100% Intra-model variability: Low
Elitech	Temtop M2000 2nd gen	2020[126]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	13.3-21.5	Slope = 0.70 Overestimation	Data recovery: ~ 100% Intra-model variability: Low
Elitech	Temtop LKC-1000S+	2020[127]	Ambient	$PM_{2.5}$	GRIMM	~ 0.91-0.92	3.1-3.6	Slope = 0.64-0.73 Overestimation	Data recovery: ~ 100% (1 unit at ~ 78%) Intra-model variability: Low
Elitech	Temtop LKC-1000S+	2020[127]	Ambient	PM_{10}	GRIMM	~ 0.31-0.35	11.7-17.9	Slope = 0.53-0.57 Underestimation	Data recovery: ~ 100% (1 unit at ~ 78%) Intra-model variability: Low
Elitech	Temtop LKC-1000S+	2020[127]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	11.1-21.9	Slope = 0.71 Overestimation	Data recovery: ~ 100% Intra-model variability: Low
IQAir	Air Visual Pro	2018[128]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.63-0.81	3.5-5.5	Slope = 0.83-1.09 Underestimation	Data recovery: > 99% Intra-model variability: Low
IQAir	Air Visual Pro	2018[128]	Chamber	$PM_{2.5}$	GRIMM	0.99	1.8-10.8	Slope = 0.82 Overestimation	Data recovery: > 99% Intra-model variability: Low

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE (µg m^{-3})	Pollutant Notes	LCS Notes
IQAir	Air Visual Outdoor	2022[129]	Ambient	PM_1	GRIMM EDM 180 Teledyne API T640	~ 0.52-0.65	4.5-5.6	Slope = 1.12-1.30 Underestimation	Data recovery: > 99% Intra-model variability: Low
IQAir	Air Visual Outdoor	2022[129]	Ambient	$PM_{2.5}$	GRIMM EDM 180 Teledyne API T640	~ 0.53-0.65	4.4-6.0	Slope = 0.75-0.95 Underestimation	Data recovery: > 99% Intra-model variability: Low
IQAir	Air Visual Outdoor	2022[129]	Ambient	PM_{10}	GRIMM EDM 180 Teledyne API T640	~ 0.38-0.61	10.5-14.4	Slope = 1.06-1.49 Overestimation	Data recovery: > 99% Intra-model variability: Low
Qingping	Air Monitor	2022-2023[130]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.86-0.91	1.8-2.3	Slope = 0.84-0.94 Underestimation	Data recovery: ~ 100% Intra-model variability: Low
Qingping	Air Monitor Lite	2022-2023[131]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640	~ 0.84-0.93	1.8-3.6	Slope = 0.96-1.14 Underestimation	Data recovery: ~ 97% Intra-model variability: Low
Qingping	Air Monitor Lite	2022-2023[131]	Ambient	PM_{10}	GRIMM Teledyne API T640	~ 0.36-0.43	16.2-20.1	Slope = 1.49-1.63 Large Underestimation	Data recovery: ~ 97% Intra-model variability: Low
TSI	AirAssure	2015-2016[132]	Ambient	$PM_{2.5}$	GRIMM	~ 0.81-0.83	—	Slope = 0.67-0.72 Overestimation	Data recovery: > 99% Intra-model variability: Low
TSI	AirAssure	2015-2016[132]	Chamber	$PM_{2.5}$	GRIMM	> 0.99	32.4-55.0	Slope = 0.50 Large Overestimation (0-150 µg m^{-3}) Plateau measurements at 300 µg m^{-3}	Data recovery: > 97% Intra-model variability: Moderate to high
uHOO	Smart Air Monitor	2017[133]	Ambient	$PM_{2.5}$	FEM BAM	< 0.01	9.5-17.8	Slope = 0.02-0.06 No correlation	1-hr data Data recovery: > 95% (1 unit at ~ 88%) Intra-model variability: High
uHOO	Smart Air Monitor	2017[133]	Ambient	CO	FRM CO instrument	0.0	3.6 ppm*	No response	1-hr data Data recovery: > 95% (1 unit at ~ 88%) Intra-model variability: High
uHOO	Smart Air Monitor	2017[133]	Ambient	O_3	FEM O_3 instrument	~ 0.43-0.72	14.5-68.8 ppb*	Slope = 0.21-0.64 Significant Underestimation	1-hr data Data recovery: > 95% (1 unit at ~ 88%) Intra-model variability: High

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE ($\mu g\ m^{-3}$)	Pollutant Notes	LCS Notes
uRADMonitor	MODEL A3	2018-2019[134]	Ambient	PM_1	GRIMM Teledyne API T640 FEM BAM	~ 0.81-0.85	4.0-5.2	Slope = 1.08-1.43 R^2 for > ~10 $\mu g\ m^{-3}$ Underestimation	1-hr data Data recovery: > 99% (1 unit at ~ 82%) Intra-model variability: Moderate
uRADMonitor	MODEL A3	2018-2019[134]	Ambient	$PM_{2.5}$	GRIMM Teledyne API T640 FEM BAM	~ 0.70-0.84	5.2-8.9	Slope = 0.89-1.34 R^2 for > ~10-20 $\mu g\ m^{-3}$ Underestimation	1-hr data Data recovery: > 99% (1 unit at ~ 82%) Intra-model variability: Moderate
uRADMonitor	MODEL A3	2018-2019[134]	Ambient	PM_{10}	GRIMM Teledyne API T640 FEM BAM	~ 0.15-0.41	20.3-29.1	Slope = 0.85-1.39 Underestimation	1-hr data Data recovery: > 99% (1 unit at ~ 82%) Intra-model variability: Moderate
Wicked Device	Air Quality Egg Indoor V2 2015	2016[135]	Ambient	$PM_{2.5}$	GRIMM	~ 0.42-0.84	—	Slope = 0.98-1.01 Lower R^2 from 1/3 units and slope from 2/3 units	Data recovery: ~100% Intra-model variability: Low
Wicked Device	Air Quality Egg Indoor V2 2015	2016[135]	Ambient	PM_{10}	GRIMM	~ 0.10-0.36	—	Large Underestimation	—
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Ambient	PM_1	GRIMM EDM 180 Teledyne API T640	~ 0. 84-0.89	2.9-3.9	Slope = 1.07-1.23 Overestimation	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Ambient	$PM_{2.5}$	GRIMM EDM 180 Teledyne API T640	~ 0.87-0.90	6.0-7.1	Slope = 0.71-0.82 Overestimation	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Ambient	PM_{10}	GRIMM EDM 180 Teledyne API T640	~ 0.29-0.53	18.5-20.8	Slope = 0.66-0.95 Underestimation	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Ambient	CO	Horiba APMA 370	~ 0.60-0.79	0.15-0.21 ppm*	Slope = 0.74-1.50 Overestimation	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Ambient	O_3	Teledyne T400	~ 0.20-0.51	13.2-18.0 ppb*	Slope = 0.94-1.62 Overestimation	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Ambient	NO_2	Teledyne T200	~ 0.38-0.56	20.8-32.0 ppb*	Slope = 0.30-0.51 Overestimation	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Chamber	$PM_{2.5}$	Teledyne T640x	> 0.99	5.0-8.0	Slope = 1.13 Overestimation (< 100 $\mu g\ m^{-3}$)	Data recovery: > 99% Intra-model variability: Low
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Chamber	O_3	Teledyne T400	> 0.98	4.7-21.0 ppb*	Slope = 1.24 Underestimation (~ 30-250 ppb); ~ 3 ppb (1 unit at ~12 ppb) baseline compared to reference (~0.5 ppb); NO_2 interferent	Data recovery: > 99% Intra-model variability: Low

Manufacturer	LCS/Model	Year of Evaluation	Setting	Pollutant	Comparison Instrument	R^2	MAE (μg m^{-3})	Pollutant Notes	LCS Notes
Wicked Device	Air Quality Egg Outdoor V2 2022	2021-2022[136]	Chamber	NO_2	Teledyne T200	0.99	5.5-61.8 ppb*	Slope = 0.97 Overestimation ~ 3 ppb baseline (1 unit at 65 ppb) compared to reference (~0 ppb)	Data recovery: > 98% Intra-model variability: High

* Different units for gas pollutants MAE.

3.3.2 Literature Performance Evaluations of LCS Devices

Performance evaluations of some AQ-SPEC and non-AQ-SPEC validated single- and multi-pollutant LCS are also found in various research studies, providing additional data into the performance of these devices in different settings. Similar to AQ-SPEC tests, evaluation results are summarized only for manufacturer-calibrated LCS with no additional calibration or corrections, which are usually applied subsequently in research studies. These studies and the associated single- or multi-pollutant LCS evaluated are provided in Tables 3.4.7 and 3.4.8. LCS performance characterized in literature are subsequently summarized in Tables 3.4.9 and 3.4.10 with relevant information, including year of evaluation, location and setting, pollutants evaluated, reference instruments used, and performance results – i.e., R^2.

Table 3.4.7. List of single-pollutant LCS performance evaluations in literature.

Manufacturer	LCS/Model	Reference
Applied Particle Technology	Minima	Li et al.[137]
Dylos Corporation	DC1100	Williams et al.,[138] Dacunto et al.,[139] Manikonda et al.,[140] Jiao et al.,[141] Jones et al.,[142] Tan,[143] Feinberg et al.,[144] Collingwood et al.,[145] Hegde et al.,[146] Zou et al.[147]
	DC1700	Holstius et al.,[148] Steinle et al.,[149] Jovašević-Stojanović et al.,[150] Manikonda et al.,[140] Han et al.,[151] Carvlin et al.,[152] Li et al.,[137] Oluwadairo et al.[153]
Habitat Map	AirBeam	Jiao et al.,[141] Mukherjee et al.,[61] Sousan et al.,[154] Hainsworth and Lim,[155] Feinberg et al.,[144]Zou et al.,[147] Huang et al.[156]
Netatmo	Smart IAQ Monitor	Demanega et al.[43]
PurpleAir	PA-II	Li et al.,[137] Sayahi et al.,[157] Kim et al.,[158] Holder et al.,[159] Ardon-Dryer et al.,[160] Magi et al.,[161] Malings et al.,[162] Bi et al.,[163] Barkjohn et al.,[106] Zou et al.,[147] Sankhyan et al.,[164] Koehler et al.,[165]Park et al.,[166] deSouza et al.[167]
	PA-I	Sayahi et al.,[157] Wang et al.,[103] Sankhyan et al.[164]
SAF Tehnika	Aranet4	Villanueva et al.[168]
TSI	BlueSky	Zou et al.[147]

Table 3.4.8. List of multi-pollutant LCS performance evaluations in literature.

Manufacturer	LCS/Model	Reference
Aethair (formerly AirThinx)	AirThinx IAQ	Zamora et al.,[105] Zou et al.[147]
Atmotech Inc.	Atmotube Pro	Zheng et al.[169]
Awair	1st Edition/2nd Edition	Li et al.,[137] Wang et al.,[103] Demanega et al.[43]
Edimax	AI-2003W	Zheng et al.[169]
IQAir	AirVisual Pro (formerly AirVisual Node)	Tan,[143] Li et al.,[137] Wang et al.,[103] He et al.,[170] Zamora et al.,[105] Demanega et al.,[43] Shao et al.,[171] Sankhyan et al.[164]
TSI	AirAssure	Manikonda et al.,[140] Feinberg et al.[144]
uHoo	Smart Air Monitor	Baldelli et al.,[172] Demanega et al.[43]
uRADMonitor	MODEL A3	Shao et al.[171]
Wicked Device	AirQuality Egg	Jiao et al., 2016[141] Wang et al., 2020[103] Manibusan and Mainelis 2020[104]

Table 3.4.9. Summary of single-pollutant LCS performance evaluations in literature.

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
Applied Particle Technology	Minima	Li et al. 2020[137]	Chamber (Arizona dust, sea salt, incense) 2018	$PM_{2.5}$	GRIMM 11C TSI SidePak AM530	~ 0.94-0.99	1 unit 1-min data
Dylos Corportation	DC1100	Williams et al. 2014[138]	Ambient (EPA North Carolina) 2013	$PM_{0.5\text{-}2.5}$	FEM GRIMM EDM180	0.55	1 unit 5-min data
Dylos Corportation	DC1100	Dacunto et al. 2015[139]	Single rooms in 4 indoor environments California (47 experiments with 17 sources like cooking, smoking, incense, candles)	$PM_{2.5}$	TSI SidePak AM510	≥ 0.90	2 units 1-min data
Dylos Corportation	DC1100	Jiao et al. 2016[141]	Ambient (Decatur, Georgia) 2014-2015	$PM_{\geq 1}$	FEM MetOne BAM 1020	0.33	1 unit 12-hr data
Dylos Corportation	DC1100	Jones et al. 2016[142]	Swine farrowing room 2013-2014	$PM_{0.5\text{-}2.5}$	Thermo pDR-1200	0.85	3 units 10-min data
Dylos Corportation	DC1100	Feinberg et al. 2018[144]	Ambient (Denver, Colorado) 2015-2016	$PM_{>1}$	GRIMM EDM 180	0.53	1 unit 1-hr data
Dylos Corportation	DC1100			$PM_{>5}$	GRIMM EDM 180	0.07	1 unit 1-hr data
Dylos Corportation	DC1100 Pro	Manikonda et al. 2016[140]	Laboratory chamber (cigarette smoke, Arizona Test Dust)	$PM_{2.5}$	TSI APS 3321	0.88-0.94	1 unit
Dylos Corportation	DC1100 Pro	Manikonda et al. 2016[140]	Laboratory chamber (cigarette smoke, Arizona Test Dust)	PM_{10}	TSI APS 3321	0.67-0.89	1 unit
Dylos Corportation	DC1100 Pro	Jiao et al. 2016[141]	Ambient (EPA, Decatur, Georgia) 2014-2015	$PM_{\geq 0.5}$	FEM MetOne BAM 1020	0.40-0.45	2 units 12-hr data
Dylos Corportation	DC1100 Pro	Tan 2017[143]	Chamber (road dust and sodium chloride)	$PM_{2.5}$	TSI APS 3321	0.88-0.90	1 unit 1-min data
Dylos Corportation	DC1100 Pro	Tan 2017[143]	Chamber (road dust and sodium chloride)	PM_{10}	TSI APS 3321	0.94	1 unit 1-min data
Dylos Corportation	DC1100 Pro	Feinberg et al. 2018[144]	Ambient (Denver, Colorado) 2015-2016	$PM_{>1}$	GRIMM EDM 180	0.61-0.74	2 units 1-hr data
Dylos Corportation	DC1100 Pro	Collingwood et al. 2019[145]	Carpeted single room (detritus vacuuming)	$PM_{2.5}$	GRIMM 1.109	0.72-0.80	8 units 1-min data
Dylos Corportation	DC1100 Pro	Hegde et al. 2020[146]	2 Homes (indoor activities such as cooking, candle burning) 2016	$PM_{2.5}$	GRIMM 1.109 TSI DustTrak II	0.60-0.99	10 units (Home 1) 4 units (Home 2) 5-min data
Dylos Corportation	DC1100 Pro	Zou et al. 2021[147]	Chamber (incense) 2020	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.48-0.90	3 units 1-min data

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
Dylos Corportation	DC1100 Pro	Zou et al. 2021[147]	Chamber (Burnt toast)	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.54-0.96	3 units 1-min data
Dylos Corportation	DC1700	Holstius et al. 2014[148]	Ambient (West Oakland California) 2013	$PM_{0.5-2.5}$	FEM MetOne BAM 1020	0.58	1 unit 1-hr data
Dylos Corportation	DC1700	Steinle et al. 2015[149]	Ambient (Scotland) 2012-2013	$PM_{0.5-2.5}$	TEOM-FDMS	0.7-0.9	1-hr data
Dylos Corportation	DC1700	Jovašević-Stojanović et al. 2015[150]	Laboratory (no pollution)	$PM_{0.5-2.5}$	TSI OPS 3330	0.95	1-min data
Dylos Corportation	DC1700	Jovašević-Stojanović et al. 2015[150]	Laboratory (no pollution)	$PM_{2.5-10}$	TSI OPS 3330	0.77	1-min data
Dylos Corportation	DC1700	Jovašević-Stojanović et al. 2015[150]	Laboratory (cigarette smoke)	$PM_{0.5-2.5}$	TSI OPS 3330	0.44	1-min data
Dylos Corportation	DC1700	Jovašević-Stojanović et al. 2015[150]	Laboratory (cigarette smoke)	$PM_{2.5-10}$	TSI OPS 3330	< 0.01	1-min data
Dylos Corportation	DC1700	Manikonda et al. 2016[140]	Laboratory chamber (cigarette smoke, Arizona Test Dust)	$PM_{2.5}$	TSI APS 3321	0.87-0.93	1 unit
Dylos Corportation	DC1700	Manikonda et al. 2016[140]	Laboratory chamber (cigarette smoke, Arizona Test Dust)	PM_{10}	TSI APS 3321	0.70-0.85	1 unit
Dylos Corportation	DC1700	Han et al. 2017[151]	Ambient (Houston Texas) 2015-2016	$PM_{2.5}$	GRIMM 11-R	0.78	1 unit 1-min data
Dylos Corportation	DC1700	Han et al. 2017[151]	Ambient (Houston Texas) 2015-2016	$PM_{2.5-10}$	GRIMM 11-R	0.48	1 unit 1-min data
Dylos Corportation	DC1700	Carvlin et al. 2017[152]	Ambient (Imperial California) 2015-2016	$PM_{2.5}$	FEM MetOne BAM 1020	0.78	1 unit 1-hr data
Dylos Corportation	DC1700	Carvlin et al. 2017[152]	Ambient (Imperial California) 2015-2016	PM_{10}	FEM MetOne BAM 1020	0.56	1 unit 1-hr data
Dylos Corportation	DC1700	Li et al. 2020[137]	Chamber (Arizona dust, sea salt, incense) 2018	$PM_{2.5}$	GRIMM 11C TSI SidePak AM530	~0.82-0.97	1 unit 1-min data
Dylos Corportation	DC1700	Oluwadairo et al. 2022[153]	Chamber (sodium chloride) 2019	$PM_{0.5-2.5}$	GRIMM 11R	0.89	1 unit 1-min data
Habitat Map	AirBeam	Jiao et al. 2016[141]	Ambient (Decatur, Georgia) 2014-2015	$PM_{2.5}$	FEM MetOne BAM 1020	0.42-0.43	3 units 12-hr data
Habitat Map	AirBeam	Mukherjee et al. 2017[61]	Ambient (Cuyama, CA) 2016	$PM_{2.5}$	GRIMM 11-R	0.62-0.71	3 units 1-min data Low-intramodel variability Data recovery: > 99%
Habitat Map	AirBeam	Mukherjee et al. 2017[61]	Ambient (Cuyama, CA) 2016	PM_{10}	MetOne BAM 1020	0.21-0.33	1-hr data

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
Habitat Map	AirBeam	Sousan et al. 2017[154]	Chamber (salt, welding fume, and ARD) 2016	$PM_{2.5}$	TSI APS 3321 GRIMM SMPS-C 5.402 pDR 1500	0.49-0.92	5-min data
Habitat Map	AirBeam 2	Hainsworth and Lim 2018[155]	Chamber (outdoor particles)	PM_1	TSI DustTrak DRX 8533	0.88	1-min data
Habitat Map	AirBeam 2	Hainsworth and Lim 2018[155]	Chamber (outdoor particles)	$PM_{2.5}$	TSI DustTrak DRX 8533	0.89	1-min data
Habitat Map	AirBeam 2	Feinberg et al. 2018[144]	Ambient (Denver, Colorado) 2015-2016	$PM_{2.5}$	GRIMM EDM 180	0.67-0.71	3 units 1-hr data
Habitat Map	AirBeam 2	Zou et al. 2021[147]	Chamber (incense) 2020	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.23-1.00	3 units 1-min data
Habitat Map	AirBeam 2	Zou et al. 2021[147]	Chamber (Burnt toast)	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.70-0.99	3 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Office (Hong Kong) 2021	PM_1	TSI DustTrak DRX 8533	0.71-0.77	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Office (Hong Kong) 2021	$PM_{2.5}$	TSI DustTrak DRX 8533	0.72-0.78	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Office (Hong Kong) 2021	PM_{10}	TSI DustTrak DRX 8533	0.64-0.73	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Train station (platform)	PM_1	TSI DustTrak DRX 8533	0.72-0.78	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Train station (platform)	$PM_{2.5}$	TSI DustTrak DRX 8533	0.71-0.78	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Train station (platform)	PM_{10}	TSI DustTrak DRX 8533	0.57-0.67	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Train station (lobby)	PM_1	TSI DustTrak DRX 8533	0.64-0.71	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Train station (lobby)	$PM_{2.5}$	TSI DustTrak DRX 8533	0.65-0.76	5 units 1-min data
Habitat Map	AirBeam 2	Huang et al. 2022[156]	Train station (lobby)	PM_{10}	TSI DustTrak DRX 8533	0.61-0.69	5 units 1-min data
Netatmo	Smart IAQ Monitor	Demanega et al. 2021[43]	Chamber (CO_2 injection) 2020	CO_2	LI-COR 850	~ 0.66	1 unit 5-min data Delayed response of peak concentration
PurpleAir	PA-I	Sayahi et al. 2019[157]	Ambient (Salt Lake City, UT) 2016-2017	$PM_{2.5}$	FEM TOEM 1405-F	~ 0.87-0.88	2 units 1-hr data Low-intramodel variability
PurpleAir	PA-I	Wang et al. 2020[103]	Laboratory (overnight outdoor air, California) 2018	$PM_{2.5}$	FEM TEOM with FDMS (1405-DF)	~ 0.79	3 units 1-hr data

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
PurpleAir	PA-I	Wang et al. 2020[103]	Laboratory (residential sources – mineral sources, incense and mosquito coil, candles)	$PM_{2.5}$	GRIMM WRAS 1371	> 0.83	5-min data
PurpleAir	PA-I	Sankhyan et al. 2022[164]	Homes (cooking) 2019-2020	$PM_{2.5}$	TSI OPS 3330	0.35-0.38	2 units 1-min data
PurpleAir	PA-I	Sankhyan et al. 2022[164]	Homes (background)	$PM_{2.5}$	TSI OPS 3330	0.76-0.79	2 units 1-min data
PurpleAir	PA-II	Sayahi et al. 2019[157]	Ambient (Salt Lake City, UT) 2016-2017	$PM_{2.5}$	FEM TOEM 1405-F	~ 0.87-0.89	2 units 1-hr data (CF_1 mass concentration algorithm)[173] Low-intramodel variability
PurpleAir	PA-II	Kim et al. 2019[158]	Ambient (Korea) 2018	$PM_{2.5}$	FEM MetOne BAM 1022	0.89	2 units 1-hr data
PurpleAir	PA-II	Ardon-Dryer et al. 2020[160]	Ambient (San Francisco, CA) 2017-2018	$PM_{2.5}$	EPA FRM/FEM AQS	0.58-0.90	8 units 1-hr data (CF_ATM)[173]
PurpleAir	PA-II	Ardon-Dryer et al. 2020[160]	Ambient (Vallejo, CA)	$PM_{2.5}$	EPA FRM/FEM AQS	0.55-0.91	15 units 1-hr data (CF_ATM)[173]
PurpleAir	PA-II	Ardon-Dryer et al. 2020[160]	Ambient (Denver, CO)	$PM_{2.5}$	EPA FRM/FEM AQS	0.53-0.91	8 units 1-hr data (CF_ATM)[173]
PurpleAir	PA-II	Ardon-Dryer et al. 2020[160]	Ambient (, Salt Lake City, UT)	$PM_{2.5}$	EPA FRM/FEM AQS	0.20-0.81	14 units 1-hr data (CF_ATM)[173]
PurpleAir	PA-II	Magi et al. 2020[161]	Ambient (Charlotte, NC) 2017-2018	$PM_{2.5}$	FEM MetOne BAM 1022	0.54	1 unit 1-hr data (CF_ATM)[173]
PurpleAir	PA-II	Malings et al. 2020[162]	Ambient (Pittsburg, PA) 2017-2018	$PM_{2.5}$	FEM MetOne BAM	0.58	9 units 1-h data
PurpleAir	PA-II	Bi et al. 2020[163]	Ambient (California) 2018	$PM_{2.5}$	EPA FRM/FEM AQS	0.74	2090 units 1-hr data
PurpleAir	PA-II	Barkjohn et al. 2021[106]	Ambient (US-wide, 16 states)	$PM_{2.5}$	EPA FRM/FEM AQS	0.78	50 units 24-hr data (CF_1)[173]
PurpleAir	PA-II	Zou et al. 2021[147]	Chamber (incense) 2020	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.60-0.99	3 units 1-min data
PurpleAir	PA-II	Zou et al. 2021[147]	Chamber (Burnt toast)	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.59-0.99	3 units 1-min data

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
PurpleAir	PA-II	Sankhyan et al. 2022[164]	Homes (cooking) 2019-2020	$PM_{2.5}$	TSI OPS 3330	0.31-0.33	2 units 1-min data (CF_1)[173]
PurpleAir	PA-II	Sankhyan et al. 2022[164]	Homes (background)	$PM_{2.5}$	TSI OPS 3330	0.80-0.82	2 units 1-min data (CF_1)[173]
PurpleAir	PA-II	Koehler et al. 2023[165]	Homes (smoking and non-smoking, Maryland)	$PM_{2.5}$	AST UPAS	0.86	1-week data (CF_1)[173]
PurpleAir	PA-II	deSouza et al. 2023[167]	Ambient (US-wide) 2017-2021	$PM_{2.5}$	EPA FRM/FEM AQS	0.69-0.74	151 units 1-hr data (CF_1 and CF_ATM)[173]
PurpleAir	PA-II-SD	Li et al. 2020[137]	Chamber (Arizona dust, sea salt, incense) 2018	$PM_{2.5}$	GRIMM 11C TSI SidePak AM530	~ 0.90-0.98	1 unit 1-min data
PurpleAir	PA-II-SD	Holder et al. 2020[159]	Ambient (EPA RTP, NC) 2018-2019	$PM_{2.5}$	FEM GRIMM EDM180	0.86	2 units 1-hr data (CF_1 and CF_ATM)[173]
PurpleAir	PA-II-SD	Holder et al. 2020[159]	Ambient, smoke impacted (California, North Carolina) 2018-2019	$PM_{2.5}$	FEM GRIMM EDM180 FEM MetOne BAM 1020 MetOne E-BAM	0.62-0.99	1-hr data (CF_1 and CF_ATM)[173]
PurpleAir	PA-II-SD	Park et al. 2023[166]	Chamber (incense)	PM_1	GRIMM 11-A	0.96	6 units 2-min data (CF_1)[173] Low-intramodel variability
PurpleAir	PA-II-SD	Park et al. 2023[166]	Chamber (incense)	$PM_{2.5}$	GRIMM 11-A	0.95	6 units 2-min data (CF_1)[173] Low-intramodel variability
PurpleAir	PA-II-SD	Park et al. 2023[166]	Chamber (incense)	PM_{10}	GRIMM 11-A	0.92	6 units 2-min data (CF_1)[173] Low-intramodel variability
PurpleAir	PA-II-SD	Park et al. 2023[166]	Apartment testbed (incense, frying, outdoor air)	PM_1	GRIMM TSI SidePak	0.90-0.98	1 unit 2-min data (CF_1)[173]
PurpleAir	PA-II-SD	Park et al. 2023[166]	Apartment testbed (incense, frying, outdoor air)	$PM_{2.5}$	GRIMM TSI SidePak	0.89-0.96	1 unit 2-min data (CF_1)[173]
PurpleAir	PA-II-SD	Park et al. 2023[166]	Apartment testbed (incense, frying, outdoor air)	PM_{10}	GRIMM TSI SidePak	0.86-0.95	1 unit 2-min data (CF_1)[173]
SAF Tehnika	Aranet4	Villanueva et al. 2021[168]	2 Classrooms; (Children, Spain) 2020	CO_2	Delta Ohm	~ 0.98	1 unit Low-intramodel variability

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
TSI	BlueSky	Zou et al. 2021[147]	Chamber (incense) 2020	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.21-0.99	2 units 1-min data
TSI	BlueSky	Zou et al. 2021[147]	Chamber (Burnt toast)	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.57-0.99	2 units 1-min data

Table 3.4.10. Summary of multi-pollutant LCS performance evaluations in literature.

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
Aethair (formerly AirThinx)	AirThinx IAQ	Zamora et al. 2020[105]	Home (occupied and non-smoking) 2018-2019	$PM_{2.5}$	Thermo pDR-1200	0.92-0.93	2 units 1-min data
Aethair (formerly AirThinx)	AirThinx IAQ	Zou et al. 2021[147]	Chamber (incense) 2020	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.39-1.00	1 unit 1-min data
Aethair (formerly AirThinx)	AirThinx IAQ	Zou et al. 2021[147]	Chamber (Burnt toast)	$PM_{2.5}$	TSI SMPS 3938 TSI APS 3321	0.18-0.99	1 unit 1-min data
Atmotech Inc.	Atmotube Pro	Zheng et al. 2022[169]	Laboratory chamber (Dutch daycare activities: cleaning)	$PM_{2.5}$	GRIMM 11-D	0.41-0.95	5-min data
Awair	1st Edition/Element	Li et al. 2020[137]	Chamber (Arizona dust, sea salt, incense) 2018	$PM_{2.5}$	GRIMM 11C TSI SidePak AM530	~ 0.78-0.97	1 unit 1-min data
Awair	2nd Edition/Element	Wang et al. 2020[103]	Laboratory (overnight outdoor air, California) 2018	$PM_{2.5}$	FEM TEOM with FDMS (1405-DF)	0.776	3 units 1-hr data
Awair	2nd Edition/Element	Wang et al. 2020[103]	Laboratory (residential sources – mineral sources, incense and mosquito coil, candles)	$PM_{2.5}$	GRIMM WRAS 1371	> 0.83	5-min data
Awair	2nd Edition/Element	Demanega et al. 2021[43]	Chamber (candles, popcorn cooking, mosquito coil, carpet vacuuming, room deodorant) 2020	$PM_{2.5}$	GRIMM miniWRAS 1371	~ 0.44-0.99	1 unit 5-min data
Awair	2nd Edition/Element	Demanega et al. 2021[43]	Chamber (CO_2 injection)	CO_2	LI-COR 850	> 0.99	1 unit 5-min data
Edimax	Al-2003W	Zheng et al. 2022[169]	Laboratory chamber (Dutch daycare activities: cleaning) 2021	$PM_{2.5}$	GRIMM 11-D	0.11-0.63	5-min data
Edimax	Al-2003W	Zheng et al. 2022[169]	Laboratory chamber (Acrylic painting)	CO_2	INNOVA 1512 and 1403	1.00	5-min data

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
IQAir	AirVisual Node	Tan 2017[143]	Indoor/outdoor (3 elementary schools, China)	$PM_{2.5}$	TSI DustTrak II	0.955	1 unit 10-sec data
IQAir	AirVisual Node	Tan 2017[143]	Chamber (road dust and sodium chloride)	$PM_{2.5}$	TSI APS 3321	> 0.99	30-sec data
IQAir	AirVisual Node	Tan 2017[143]	Chamber (road dust and sodium chloride)	PM_{10}	TSI APS 3321	> 0.99	30-sec data
IQAir	AirVisual Node	Li et al. 2020[137]	Chamber (Arizona dust, sea salt, incense) 2018	$PM_{2.5}$	GRIMM 11C TSI SidePak AM530	~ 0.88-0.96	1 unit 1-min data
IQAir	AirVisual Node	He et al. 2020[170]	Chamber (PSL spheres and ARD) 2016	$PM_{2.5}$	TSI DustTrak DRX 8534	0.85-0.98	3 units 5-min data
IQAir	AirVisual Node	He et al. 2020[170]	Laboratory chamber (nanosilver-based surface cleaner)	$PM_{2.5}$	TSI DustTrak DRX 8534	0.30-0.71	3 units 5-min data
IQAir	AirVisual Node	He et al. 2020[170]	Home (Chinese hotpot cooking in closed conditions)	$PM_{2.5}$	TSI DustTrak DRX 8534	0.96-0.97	3 units 5-min data
IQAir	AirVisual Pro	Wang et al. 2020[103]	120 m^3 laboratory (overnight outdoor air, California) 2018	$PM_{2.5}$	FEM TEOM with FDMS (1405-DF)	0.776	3 units 1-hr data
IQAir	AirVisual Pro	Wang et al. 2020[103]	Residential sources (mineral sources, incense and mosquito coil, candles)	$PM_{2.5}$	GRIMM WRAS 1371	> 0.83	5-min data
IQAir	AirVisual Pro	Zamora et al. 2020[105]	Home (occupied and non-smoking) 2018-2019	$PM_{2.5}$	Thermo pDR-1200	0.89 – 0.90	2 units 1-min data
IQAir	AirVisual Pro	Demanega et al. 2021[43]	Chamber (candles, popcorn cooking, mosquito coil, capet vacuuming, room deodorant) 2020	$PM_{2.5}$	GRIMM miniWRAS 1371	~ 0.28-0.99	1 unit 5-min data
IQAir	AirVisual Pro	Demanega et al. 2021[43]	Chamber (CO_2 injection)	CO_2	LI-COR 850	~ 0.95	1 unit 5-min data
IQAir	AirVisual Pro	Shao et al. 2021[171]	Hair salons (hair services and products) 2018-2019	$PM_{2.5}$	TSI DustTrak 8530	0.81-0.98	1 unit 30-minute data
IQAir	AirVisual Pro	Sankhyan et al. 2022[164]	Homes (cooking) 2019-2020	$PM_{2.5}$	TSI OPS 3330	0.50-0.60	2 units 1-min data
IQAir	AirVisual Pro	Sankhyan et al. 2022[164]	Homes (background)	$PM_{2.5}$	TSI OPS 3330	0.88	2 units 1-min data

Manufacturer	LCS/Model	Reference	Setting/Year	Pollutant	Comparison Instrument	R^2	LCS Notes
TSI	AirAssure	Manikonda et al. 2016[140]	Laboratory chamber (cigarette smoke, Arizona Test Dust)	$PM_{2.5}$	TSI APS 3321	0.45-0.99	3 units
TSI	AirAssure	Feinberg et al. 2018[144]	Ambient (Denver, Colorado) 2015-2016	$PM_{2.5}$	GRIMM EDM 180	0.61-0.66	3 units 1-hr data
uHOO	Smart Air Monitor	Baldelli et al. 2021[172]	Laboratory (sodium chloride, sucrose, and potassium iodide aerosols)	$PM_{2.5}$	TSI OPS 3330	0.97-0.98	3 units 30-min data
uHOO	Smart Air Monitor	Baldelli et al. 2021[172]	Laboratory (CO_2 injection)	CO_2	Vaisala GMP222	0.97	3 units 30-min data
uHOO	Smart Air Monitor	Baldelli et al. 2021[172]	Laboratory (O_3 injection)	O_3	Oxidation Technologies UV106L	0.82	3 units 30-min data
uHOO	Smart Air Monitor	Demanega et al. 2021[43]	Chamber (candles, popcorn cooking, mosquito coil, capet vacuuming, room deodorant) 2020	$PM_{2.5}$	GRIMM miniWRAS 1371	~ 0.08-0.92	1 unit 5-min data
uHOO	Smart Air Monitor	Demanega et al. 2021[43]	Chamber (CO_2 injection)	CO_2	LI-COR 850	~ 0.99	1 unit 5-min data
uRADMonitor	MODEL A3	Shao et al. 2021[171]	Hair salons (hair services and products) 2018-2019	$PM_{2.5}$	TSI DustTrak 8530	0.92-0.98	1 unit 8-hr
Wicked Device	Air Quality Egg 2015	Jiao et al. 2016[141]	Ambient (Decatur, Georgia) 2014-2015	$PM_{2.5}$	MetOne BAM	< 0.16	3 units 12-hr data
Wicked Device	Air Quality Egg 2015	Jiao et al. 2016[141]	Ambient (Decatur, Georgia) 2014-2015	NO_2	Thermo 42I	< 0.1	1-hr data
Wicked Device	Air Quality Egg 2015	Jiao et al. 2016[141]	Ambient (Decatur, Georgia) 2014-2015	CO	Thermo 48C	— No response	1-hr data
Wicked Device	Air Quality Egg 2015	Manibusan and Mainelis 2020[104]	3 Residences (normal indoor activities; no pets and non-smoking) 2016	$PM_{2.5}$	TSI DustTrak DRX 8534 Thermo pDR-1000	0.10-0.81	1 unit 1-hr data
Wicked Device	Air Quality Egg 2018	Wang et al. 2020[103]	Laboratory (overnight outdoor air, California) 2018	$PM_{2.5}$	FEM TEOM with FDMS (1405-DF)	0.785	3 units 1-hr data
Wicked Device	Air Quality Egg 2018	Wang et al. 2020[103]	Laboratory (residential sources – mineral sources, incense and mosquito coil, candles)	$PM_{2.5}$	GRIMM WRAS 1371	> 0.83	5-min data

3.3.3 Summary of Performance Evaluations of LCS

Performance evaluations of commercially-available LCS ensure that they can provide accurate and reliable data while understanding their limitations, guiding best practices and end-user decision making, and informing future improvements in sensor technology. AQ-SPEC and literature derived evaluation results summarized in Tables 3.4.5-3.4.6 and 3.4.9-3.4.10 show varying degrees of confidence for LCS devices suitable for IAQ monitoring in detecting and quantifying PM and other air pollutants. These differences are largely driven by the manufacturer and sourced internal components of LCS devices as well as external factors such as the target pollutant (e.g., particle size distribution for PM) and environmental factors (e.g., humidity). Generally, evaluations show that LCS tended to perform better in indoor settings (e.g., laboratory, chamber, home) than in outdoor ambient conditions. It is worth noting that while LCS calibrated in laboratory settings tend to be the conventional approach, as with AQ-SPEC evaluations and similar research studies, these evaluations may not often overlap with the full range of sources and conditions encountered in an indoor environment (e.g., homes, offices, schools).[48]

Consistent across the majority of LCS validated, is the overwhelming evaluation of PM in single- and multi-pollutant LCS alongside reference instruments in ambient, laboratory, and indoor settings. This reflects the prevalence and public awareness of $PM_{2.5}$ and PM_{10} pollution (e.g., vehicle emissions, industries, wildfires), and their significant health effects.[1,2,4] The technological and financial feasibility of developing sensors for PM compared to other air pollutants is also a factor as optical sensors detecting PM with light scattering technology can be easily miniaturized and produced at low cost.

AQ-SPEC and literature evaluations show that many single- and multi-pollutant LCS devices with PM sensors maintain moderate to strong correlations ($R^2 > 0.5$) of PM_1 and $PM_{2.5}$ data with reference instruments, while PM_{10} measurements often suffer from unresponsiveness and low agreement. Research studies suggest this behavior stems from the inability of optical PM sensors to detect particles in certain size ranges,[55,174] which not only affects the response of larger particles, i.e., PM_{10}[166], but also very small particles (< 0.3 µm) produced by activities such as cooking indoors.[103,170,175] Additionally, while the linearity and relatively high R^2 values of PM_1 and $PM_{2.5}$ from some LCS (Tables 3.4.5-3.4.6 and 3.4.9-3.4.10) show their utility in detecting pollution source events and tracking trends, these devices can also vary in quantitative agreement with reference instruments, often under- or over-reporting particle mass concentrations depending on the particle source[43,103,137,176] and environmental conditions.[147]

AQ-SPEC evaluations (Tables 3.4.5 and 3.4.6) highlight when LCS are under- or over-estimating air pollutant concentrations in ambient and chamber conditions compared to reference instruments. For instance, the Minima (Applied Particle Technology) and AirVisual Pro (IQAir) underestimated ambient $PM_{2.5}$ concentrations while overestimating them subsequently in chamber tests (see Section 3.3.1). Conversely, the PA-II, PA-I (PurpleAir), and AirQuality Egg Outdoor (WickedDevice) overestimated ambient $PM_{2.5}$ concentrations while having varying responses in the chamber tests. In research studies evaluating LCS in laboratory/chamber settings, the quantitative agreement of these devices varied across sources also, sometimes with relatively large differences up to two orders of magnitude. LCS tended to over-report $PM_{2.5}$ emissions from incense burning detected by PA-II, PA-I, Minima, AirVisual Pro, AirQuality Egg, and Element/2nd edition (Awair).[103,137,166] For candle burning and cooking (boiling) sources, LCS tended to under-report $PM_{2.5}$ concentrations seen with PA-I, AirVisual Pro, AirQuality Egg, and Element/2nd edition.[103,170] Similar under-reporting occurred for test dust sources with PA-II, PA-I, Minima, AirVisual Pro, and AirQuality Egg.[103,137,143,170] The different responses of LCS to different particle pollution sources show the dependence on the particle size distribution, due to limitations in their detection mechanisms and sampling efficiency. For incense, particles are most concentrated in the 0.1-1 μm range,[177] allowing LCS to capture a much larger fraction of mass in the optical sensing range for $PM_{2.5}$. For candle burning and cooking without frying (boiling), $PM_{2.5}$ mass is largely present in particles <0.3 μm that are invisible to PM optical sensors as a current limitation, impacting LCS performance and source response.[103,175] Measurements in dusty conditions are also impacted by the particle size response in LCS devices as most of the $PM_{2.5}$ mass in dust are larger supermicron particles (>1 μm), which has been shown to have decreasing quantitative agreement compared to smaller particles.[55]

PurpleAir PA-II has been widely shown to overestimate $PM_{2.5}$ concentrations by up to 40-50%, resulting in the development of calibration or correction factors to increase the accuracy of these sensors to references.[106,161,162,165,178] These corrections also incorporate a relative humidity (RH) factor because of its documented influence on increasing particle size and thus decreased accuracy of LCS detection.[147,162,179] At higher RH, typically >50%, LCS become less accurate compared to reference instruments and overestimate PM mass concentrations.[147,162,178,179] RH impacts are apparent in ambient conditions, as they depend on climate and vary throughout the year. In indoor environments, the influence of RH can be less significant since the ranges are typically smaller. However, RH can still fluctuate over time in residential buildings and other indoor settings to ensure occupant comfort, such as using humidifiers. These fluctuations can lead to increased RH indoors, potentially affecting the performance of LCS as discussed. The internal PM sensors within the PurpleAir PA-II are in the series of PM sensors from Plantower.[63] This series of PM sensors is also present in other LCS devices (e.g., AirLink, Airbeam 3, AirQuality Egg, AirGradient One, Edimax Al-2002W), suggesting likely similar behavior of detecting PM concentrations.[55,179,180]

The Dylos DC1100 and DC1700 LCS were among the earliest developed and studied PM LCS in the early 2010s. Performance evaluations from AQ-SPEC and various research studies have shown that these LCS behave somewhat differently from other LCS. Specifically, they tend to exhibit a non-linear relationship, indicating that a linear regression against reference instruments may not always be suitable or optimal.[139,140,148,153,181] This non-linear response occurs as PM concentration increases, with the LCS becoming less responsive at higher PM levels due to what appears to be sensor saturation. This behavior results in increased bias and decreased accuracy of Dylos LCS compared to reference instruments. For indoor environments, particularly residences with high pollution activities and limited mitigation, this characteristic of Dylos LCS may affect data interpretation without further calibrations or corrections with reference instruments.

For gas pollutants (e.g., CO, NO_2, O_3, TVOC/VOCs), performance evaluations of single- and multi-pollutant LCS are limited in both gray and peer-reviewed literature (Tables 3.4.5-3.4.6 and 3.4.9-3.4.10). Individual pollutant sensors (see Section 3.1) were more likely to have performance evaluations in various field and laboratory settings compared to packaged LCS devices (Tables 3.3.1 and 3.3.2).[50,52] Despite this difference, fewer gas pollutants are evaluated compared to PM and associated LCS, which could be related to the measurement complexity of pollutant gases.[50] From the limited LCS performance data available for gas pollutants, AQ-SPEC's evaluation of AirQuality Egg Outdoor (Table 3.4.6) showed that O_3 and NO_2 exhibited weak to moderate linear response ($0.20 < R^2 < 0.56$) under ambient conditions and higher limits of detection of several ppb in the chamber when compared to reference data. O_3 measurements were further influenced by interference from NO_2 concentrations during chamber evaluations. For some gas pollutants, e.g., NO_2 and VOCs, the lack of LCS specificity and sensitivity[50,182] can limit their utility for IAQ management and ability to provide actionable information in indoor environments (see Section 3.5). The few studies with LCS performance evaluations for gas pollutants were conducted largely for CO_2 against reference instruments in laboratory/chamber conditions (Tables 3.4.9 and 3.4.10). Several LCS (Awair 2nd edition, Edimax Al-2003W, AirVisual Pro, and uHoo) showed strong correlations ($R^2 > 0.95$) with reference instruments, whereas the Netatmo LCS displayed a moderate response ($R^2 \sim 0.66$) due to a delayed response in recording peak concentrations.[43]

Overall, the performance of commercially-available LCS demonstrated expected variability when evaluated across different settings, pollutant sources, and environmental parameters (Table 3.4.1). These findings highlight the need for greater transparency from manufacturers, standardization of data analysis procedures from researchers,[183] and established performance standards for evaluating LCS for different pollutants in diverse environments. An example of such an existing standard is the ASTM D8405-21 for evaluating $PM_{2.5}$ sensors in indoor environments developed by AQ-SPEC in coordination with the American Society for Testing and Materials (ASTM) International.[184,185] Despite these limitations, LCS remain a valuable tool for indoor exposure assessments, particularly for individuals who are concerned about their IAQ and its impacts, but may not have access to more expensive, reference-grade or research instruments. A key advantage of LCS is the ability to provide real-time data on indoor pollutant levels, allowing users to track trends and identify pollution sources while prompting corrective actions to improve IAQ. While regular end-users may not incorporate calibrations and technical corrections to LCS to improve data quality, as is done extensively in research studies, the utility of LCS effectively detecting pollution source events and maintaining strong correlations with reference data remains. This has been shown in the fair number of evaluations presented for several single- and multi-pollutant LCS from AQ-SPEC and several other studies (Tables 3.4.5-3.4.6 and 3.4.9-3.4.10). Furthermore, the increasing number of evaluations and studies supporting the efficacy of LCS underscores their potential for widespread use in IAQ management and suitability for sustaining healthier IAQ.

3.4 Questions and Considerations for IAQ Monitoring with LCS

EPA's *The Enhanced Air Sensor Guidebook*[47] (Chapter 3, Section 3.4) and the South Coast AQMD's *Community in Action: A Comprehensive Guidebook on Air Quality Sensors*[54] (Chapter 2, pages 20-21) provide guidance on selecting an air quality sensor with relevant questions to consider before purchasing one. For IAQ applications specifically, additional important factors to consider for monitoring with LCS include detection range, response time, ease of use, interference from environmental factors, and expected lifetimes. Table 3.5.1 outlines the important questions to facilitate decision-making for acquiring LCS that align with the needs of the targeted applications indoors.

The **detection range** of LCS is important when deciding to deploy these devices for IAQ monitoring. Ensuring that the target LCS can detect the relevant range of pollutant concentrations typically found in indoor environments is necessary for obtaining useful information. A major challenge for some LCS is their ability to detect sufficiently low concentrations of pollutants when measuring indoors.[50,182] While some indoor activities can generate high levels of pollution sufficient for PM and other pollutant LCS, this is not always the case. For instance, most VOCs found indoors are often at relatively low concentrations, while a few of these compounds (e.g., benzene and formaldehyde) remain toxic even at low concentrations.[182] Therefore, given that VOC LCS are not selective for specific compounds (Table 3.4.1) and current LCS require technology improvements to better understand air quality data,[183] it is important for the end-user to check detection range and the targeted concentration when considering LCS options.

Response time, time resolution, or sampling rate of LCS is important for detecting and managing episodic indoor pollution sources such as cooking, smoking, or ventilation changes (e.g., infiltration of outdoor pollutants). Fast-response LCS (pollutant sensitivity is also important; see Section 3.3.3) can quickly detect pollutant spikes and relay data to the LCS display or platform, allowing users to take immediate action, such as increasing ventilation, adjusting air purifiers, or directly managing the pollution source. The sampling frequency of LCS, set by manufacturers' algorithms, determines how data is averaged and reported (e.g., every 1, 5, or 10 minutes). While some LCS like PurpleAir collect pollutant data every second and provide real-time samples at a minimum of two-minute intervals,[186] other LCS may have shorter or longer reporting intervals, potentially delaying air quality alerts to facilitate informed decision-making. Evaluating LCS options holistically while considering manufacturer-defined response times and recognizing that many packaged LCS share similar internal sensors (Section 3.1 and Table 3.2.2) may offer better insights for selecting the most suitable option for improving IAQ.

Ease of use of LCS ensures that the device is user-friendly, provides easy access to real-time data, and offers information that is easily interpretable by non-expert end-users in residential or commercial indoor settings. This is important because researchers and technical experts can invest time in operating, wrangling, and modifying data from certain LCS that would otherwise be inaccessible to the broader LCS community.[183] Therefore, selecting a LCS that is easily deployed, operated, and maintained, while allowing for quick and easy access to pollutant data enhances their utility and overall impact for effectively managing IAQ. An example of easy data interpretation would be the AQI color indicator feature that is common in several LCS displays or data viewing platforms (Table 3.3.4 and 3.3.6), and used to communicate the hazardous level of pollutant concentrations. The EPA divides the AQI into six categories, each designated by a specific color: green–good, yellow–moderate, orange–unhealthy for sensitive groups, red–unhealthy, purple–very unhealthy, and maroon–hazardous. Ideally, all LCS would adopt the same AQI color scheme for direct comparison; however, commercially-available LCS often use their own color assignment categories.[137] Nonetheless, AQI information provided by LCS remains valuable for end users, alerting them to IAQ degradation and suggesting potential remedial actions.

Interference from environmental factors such as humidity and temperature can impact LCS readings indoors (Section 3.3.3), even though indoor conditions are often more controlled and stable compared to outdoor settings. Understanding these influences is crucial when considering the use of LCS. For instance, consistent moisture levels or high temperatures in a home should be taken into account when deciding to deploy LCS for IAQ monitoring. Understanding the **expected lifetimes** of LCS is also important when deciding to deploy these devices indoors. Manufacturers often provide varying estimates for LCS lifetimes, if available, that range from as short as two years to more optimistic claims exceeding five years. However, these estimates can be uncertain and depend heavily on the use cases, maintenance routine, quality of sensor components, and the specific environmental conditions in which LCS are deployed in long term (Table 3.4.1). In indoor environments, high levels of PM and other pollutants can accelerate the aging of LCS, leading to a shorter operational life. For PM LCS specifically, dust accumulation and degradation of electrical components can cause performance issues like measurement drift that results in less reliable measurements and a shortened lifetime.[167,187] Similar issues are present during the life of other pollutant LCS.[49,183] Ensuring proper maintenance like cleaning the sensors in PM LCS devices or even replacing them over time for those with a replacement feature can help extend the lifetime of these devices. Overall, end-users should consider the lifetime and long-term costs associated with potential sensor maintenance and replacement for LCS devices when evaluating the total investment in LCS for IAQ monitoring.

After acquiring a LCS device taking all these factors into context for the targeted IAQ application or deployment, additional considerations for setup, deployment, and maintenance can help maximize the benefits and effectiveness of the LCS (see Table 3.5.2).

Table 3.5.1. Questions and considerations for buying a LCS for IAQ monitoring.

Question	Consideration
What is the purpose?	o Education and information o IAQ Hotspot identification o Personal exposure and health o Participatory science
What pollutant(s) do you want to measure indoors?	o Particulate matter (e.g., $PM_{2.5}$, PM_{10}) o Gases (e.g., O_3, NO_x, VOCs)
How much do LCS typically cost and what aligns with your budget?	o \$75 – \$500 (1 pollutant) o \$500-\$1,500 (1-2 pollutants) o > \$1,500 (3 or more pollutants)
What are some of the features you should consider?	o Ease of use and setup (e.g., plug and play) o Size, weight, and portability o Performance in the real world (e.g., response time) o Power source and connectivity o Storage capacity and data accessibility o Maintenance requirements and cost o Expected lifetime of LCS
How can you check the performance of your LCS?	o Conduct periodic quality control checks (e.g., timely signal detection from pollution events, firmware and software updates for optimal performance) o Compare results to a nearby regulatory monitor or other LCS in network o Periodically review and evaluate data for errors or problems o Check environmental conditions that may impact performance (e.g., high humidity or moisture indoors)
What should you look for in a user manual?	o Type of pollutants measured and detection range o General operating instructions o How to store and recover data conditions of operation o Expected performance o Customer service support

Analysis of EPA's *The Enhanced Air Sensor Guidebook*[47] (Chapter 3, Section 3.4 and Appendix C1-C3); South Coast AQMD's *Community in Action: A Comprehensive Guidebook on Air Quality Sensors*[54] (Chapter 2, pages 20-21); and literature.[44,49,50,182]

Table 3.5.2. Additional considerations after buying a LCS for IAQ monitoring.

Consideration	Option
Setup	o Proper positioning allows the LCS to accurately represent the general air quality of the indoor environment. o Place the LCS in an open area to ensure adequate airflow through the internal sensing components. o Position the LCS away from walls, furniture, and other obstructions that could block airflow and interfere with measurements. o Avoid placing the LCS directly near pollution sources (e.g., cooking, stoves, ovens, smoking) to prevent overloading the sensing components and skewing readings. o Avoid areas with drastic temperature changes or high humidity (e.g., bathrooms, near windows, heaters, or fireplaces). o Follow manufacturer's instructions for initial setup or calibration.
Deployment	Power Source o Ensure the LCS is powered to an electric outlet with minimal disruptions or low usage to avoid interruptions in IAQ data. o For battery-operated LCS, regularly check and recharge or replace batteries as needed. Connectivity o Ensure stable Wi-Fi or other network connectivity for uninterrupted data access. This is important for real-time alerts of air quality conditions. o Routinely check LCS data history for any gaps in data readings for troubleshooting connectivity issues
Maintenance	o Follow the manufacturer's instructions for cleaning and routine maintenance o Clean the internal and external surfaces and components to prevent buildup. Particularly important for the fans and inlets of PM sensors, as dust accumulation impacts data quality and causes drift. o Periodically check for and install firmware and software updates from the manufacturer, as these can improve LCS functionality. o Replace failed sensor components for LCS with available capability o Routinely inspect LCS data for changes such as response to source events or a high baseline when no source is present. This indicates a potential LCS malfunction or a need for additional maintenance. o End-users should take into account additional costs for maintenance in the overall costs for purchasing and deploying a LCS indoors

4 Evidence of IAQ Assessment Efforts using LCS

4.1 Overview

IAQ continues to garner interest given the significant amounts of time people spend across indoor microenvironments.[6] The use of LCS for IAQ monitoring has also grown in recent years,[44] driven by their ability to provide real-time concentration data on pollution hotspots, sources, and related indoor activities. LCS devices are valuable for generating air quality metrics for common indoor air pollutants such as $PM_{2.5}$, CO, NO_2, and VOCs and offering a qualitative and cost-effective approach for IAQ management.[49] Additionally, LCS are particularly beneficial for certain populations seeking to correlate health concerns with the quality of their living environment.

LCS empowers citizens and communities to monitor their local air quality, which often impacts their daily lives and well-being.[31] As a result, marginalized communities, often facing environmental injustices, have begun to adopt LCS for air quality monitoring. LCS air quality monitoring at the community level has primarily focused on tracking outdoor or ambient levels of pollution[35,188,189] due to the unequal distribution of degraded air quality in communities of color and low-income areas.[17,18,190,191] Using air pollution data from LCS, these communities are able to identify air quality issues, develop community-based strategies to address or reduce pollution, and advocate for policy changes at the local, state, or federal level.[192]

More recently, monitoring IAQ has become increasingly important in communities to reduce indoor exposure to air pollutants and toxic chemicals for health concerns (e.g., asthma), and enable informed behavioral choices (e.g., not smoking indoors) to adequately manage and control IAQ. Although the use of LCS for assessing IAQ is relatively new,[44] several studies have pursued characterizing IAQ across different indoor environments. This section presents evidence of IAQ assessments using LCS, with a total of 31 studies identified through a literature review (Section 2.3 and Figure 2.3.1). Tables 4.1.1 and 4.1.2 outline the 31 studies identified from the literature review, including relevant elements such as study locations, communities and participants involved, LCS used, pollutants measured, and the goals of IAQ monitoring.

Given the significance of IAQ for impacted populations, exploring studies performed in impacted communities and those with actionable behavioral changes to modify IAQ were prioritized. Section 4.2 focuses on these studies, examining characteristics, participant behaviors, challenges faced during IAQ monitoring, and necessary steps to narrow the gaps and improve IAQ in these communities. Findings from these studies as well as future-facing considerations for LCS users, community groups, air quality agencies, researchers, and policymakers are also outlined.

Table 4.1.1. Studies characterizing IAQ using LCS.

Reference	Location & Timeline	Community	Participant(s)	Setting	Goal	LCS/Model	Pollutant(s)
Matz et al. 2017[193]	Southwest Pennsylvania (2014)	Environmental Health Project	Households in the Marcellus region	Residences (3-4 wks)	○ To use low-cost ways to understand exposures to air emissions associated with unconventional natural gas development	Speck	$PM_{2.5}$
Wong-Parodi et al. 2018[194]	Pittsburg, PA (Spring-Summer 2016)	City of Pittsburg	276 Pittsburgh residents; Participant-led LCS use and monitoring	Residences (up to 3 weeks)	○ Assess whether using LCS changes what people know and do about indoor air pollution.	Speck	$PM_{2.5}$
Casey et al. 2018[195]	Navajo Nation Southwestern US (February-April 2014)	Tsaile, Arizona; Shiprock, New Mexico	Diné College students or faculty	Tribal residences (41 homes, 2-3 days each)	○ Help inform households on the Navajo Nation about how home heating practices could be impacting air quality (CO) in their homes	U-Pod: (Alphasense CO-B4)	CO
Moore et al. 2018[196]	Salt Lake City, UT (2017-2018)	University of Utah asthma study	Families/households	Residences (6 Homes, 20-47 weeks)	○ To capture the added value for residents from an air quality monitoring system that collects data from multiple monitors, supports proactive annotations, and presents real-time data interactively	Dylos	$PM_{2.5}$
Shrestha et al. 2019[25]	Colorado (1 year) Wildfire seasons (August-October 2016) (June-September 2017)	Denver; Colorado northern front range	Low-income residents	Residences (28 homes, 2-7 days each)	○ To understand how IAQ in low-income homes is affected by (1) outdoor air pollutants during wildfire seasons and (2) the role of home characteristics and occupant behavior in worsening or mitigating impacts	Dylos DC1700, Aethlabs, AE51	$PM_{2.5}$, BC
Kaduwela et. 2019[197]	Albany Middle School, CA CAMP Fire (November 2018)	School community	High school students (AQ club)	1 Classroom (~2 months)	○ Compare and contrast air quality observations made before and during the wildfire in school	LCS package (Plantower PMS7003, Winsen MH-Z19)	$PM_{>0.3}$ CO_2
Gaskins and Hart 2019[198]	Massachusetts General Hospital (2018); Nationwide (2019)	Epidemiology cohorts	Women fertility participants; Men reproductive participants	Residences and wearable (Women, 3 days) (Men, 90 days)	○ To provide an overview of the unique challenges and opportunities that arise when measuring acute exposure to air pollution in two ongoing reproductive epidemiology studies	AirBeam2; emmET: (Alphasense OPC-N3 and NO2B43F, Netatmo)	PM_{10}; $PM_{2.5}$, NO_2, CO_2
Rickenbacker et al. 2020[199]	Pittsburg, PA (1 year) 2016-2017 (November-April) (May-September)	Greater Pittsburgh region	Local residents in single-family homes	Residences (13 homes, 7-31 days each)	○ To examine the relationship between the built environment, IAQ, and quality of life	Graywolf 3016, GraywolfFM801, AethLab, AE51, AirThings, Corentium, Dylos	CO_2; $PM_{(0.3-10)}$; BC; Radon; HCHO; Total VOCs
Singer et al. 2020[200]	San Franscico Bay Area, Southern California (2016-2018)	Owner-occupied, detached California houses	California residents	Residences (70 Homes, ~7 days)	○ To assess the impacts of ventilation and emission standards on IAQ	Met One BT-645, Extech SD-800, Aeroqual S500, GraywolfFM801	$PM_{2.5}$, CO_2, NO_2

Reference	Location & Timeline	Community	Participant(s)	Setting	Goal	LCS/Model	Pollutant(s)
Shao et al. 2021[171]	Maryland/Washington DC 2018-2019 (December-July)	Center for Assisting Families; Health Advocates In-Reach and Research campaign network	Black/Latino Hair salon workers and clients	6 Hair salons (3 days)	○ To fill critical data gaps by characterizing IAQ and PM concentrations in hair salons predominantly serving clients of Black African/Latino descent	uRAD Model A3; AirVisual Pro; PlumeLabs Flow	$PM_{2.5}$, RPM
Webb et al. 2021[201]	Mountain West Region (March/April 2018) (November 2018)	Two (2) frontier reservations in the Rocky Mountain West	Tribe members	Tribal housing (19 homes, 6-8 days)	○ To assess local IAQ, and inform the tribal communities of any concerning levels in need of mitigation ○ To establish recommendations for future assessments	AirU: (PMS3330, Plantower); Passive radon test kits	$PM_{2.5}$, Radon
Do et al. 2021[21]	Southern California (March-April 2019)	Inland Empire	18 Inland Empire residents (5 cities)	Personal monitoring (GPS for participant locations including in homes)	○ To characterize $PM_{2.5}$ exposure variability for individuals from different inland Southern California cities and socioeconomic status neighborhoods ○ To understand which microenvironments pose the greatest exposure risk in region	Applied Particle Technology Minima	$PM_{2.5}$
Collier-Oxandale et al. 2022[53]	California (2016-2022)	14 communities (Southern, central, and northern California)	350 community members	Single- and multi-family homes (up to 3 yrs.)	○ To facilitate successful LCS use by citizen scientists and how to appropriately engage, educate, and empower emerging community air monitoring networks.	PurpleAir PA-II	$PM_{2.5}$
Kang et al. 2022[202]	Chicago (2017-2020)	Chicago Bungalow Association	Occupant-owned households	Residences (40 homes, >2 years)	○ To evaluate the impacts of three types of residential mechanical ventilation system retrofits on reducing indoor pollutants, maintaining IAQ, and improving adult asthma outcomes in Chicago homes	MetOne GT-526; Aeroqual SM-50 and Series 500; Extech SD800; Lascar EL-USB-CO; GrayWolf FM-801	PM_1, $PM_{2.5}$, PM_{10}, O_3, NO_2, CO_2, CO, HCHO
Fritz et al. 2022[203]	Austin, TX (2020)	University of Texas	University students	Residences (20 Homes, 77 days)	○ To address the effect of IAQ on sleep quality	Sensirion SPS30, SCD30, and SGP30; SPEC DGS-CO	CO_2, CO, PM, TVOCs
Masri et al. 2022[204]	Santa Ana, CA (August 2021)	Local community	Factory employees	Industrial facility (3 days)	○ To address worker concerns in an industrial facility by characterizing indoor $PM_{2.5}$ and heat exposure over an 8-h workday	AtmoTube Pro	$PM_{2.5}$
Connolly et al. 2022[27]	Los Angeles, CA (December 2017-June 2019)	UCLA university village housing community	Graduate students with families	Residences (18 apartments, 1.5 years)	○ To evaluate long-term LCS performance and explore the potential applications of PA-II devices in a community residential setting	PurpleAir PA-II	$PM_{2.5}$

Reference	Location & Timeline	Community	Participant(s)	Setting	Goal	LCS/Model	Pollutant(s)
He et al. 2022[205]	Seatle, WA Wildfire season (September 2020)	University of Washington; Urban Seattle	Seattle Residents and research staff	Residences, 2 offices (5 homes, 20 days)	○ To evaluate the effectiveness of intervention strategies on $PM_{2.5}$ during wildfire and estimate personal exposure	Plantower PMSA003	$PM_{2.5}$
Anastasiou et al. 2023[206]	New York City (2018-2021)	NYC Housing Authority	244 Black and Hispanic nonsmoking households	High-rise building (21 apartments, 3 years)	○ To evaluate the impact of smoke-free housing policy on secondhand smoke exposure and health outcomes	AirBeam	$PM_{2.5}$
Walker et al. 2023[207]	Missoula, MT Wildfire season (June -October 2022)	Local climate advocacy organization	Nonsmoking households	Residences paired with outdoors (20 homes, 4 months)	○ To better understand what household and behavioral characteristics impact particle infiltration and indoor exposures during wildfire events	PurpleAir PA-II-SD	$PM_{2.5}$
Gerding et al. 2023[208]	Cincinnati, OH (January-March 2023)	Local home healthcare agencies	12 nonsmoking status female home healthcare workers	Work locations and client residences (during work weeks)	○ To assess the association between occupational stress and salivary cortisol levels among home healthcare workers and the influence of personal air pollution exposure on cortisol fluctuations	PlumeLabs Flow-2	PM_1, $PM_{2.5}$, PM_{10}, NO_2, VOCs
Masri et al. 2023[209]	Santa Ana, CA (June-July 2022)	Green Madison Park Neighborhood Association	Community volunteers; Crowdsourced data	Residences paired with outdoors (10 homes, 22 days); 6 Southern most CA counties for crowdsourced data	○ To characterize July 4th firework-related air pollution using LCS both indoors and outdoors at the neighborhood level in Santa Ana, CA and at the city level throughout southern California	AtmoTube Pro; PurpleAir monitors	$PM_{2.5}$
Pei et al. 2023[210]	Philadelphia, PA (July 2018–January 2019)	N/A	2 office occupants	Office; Ventilation system of 2-story building	○ To examine the potential application of low-cost particle sensors for monitoring particle removal performance of the mechanical ventilation system	IC Sentinel LCS	$PM_{0.5-1}$, PM_{1-5}, $PM_{>5}$
Wenner et al. 2024[211]	Chicago, IL (April-May 2023)	N/A	Volunteering office occupants	11-floor office building paired with outdoors (floor 1, 4, 6, 9)	○ To increase our understanding about vertical variations in $PM_{2.5}$ in urban areas	PurpleAir PA-II and Touch	$PM_{2.5}$
Prathibha et al. 2024[212]	Northwest California, Humboldt County (September-October 2021) (January-March 2022)	Hoopa Valley Tribe Land Management and Tribal EPA	Tribe members and non-smoking households	Tribal housing paired with outdoors (12 homes, four 1-2-week phases)	○ To evaluate DIY portable air cleaner (PAC) effectiveness in an underserved community with a history of extreme smoke impacts ○ To evaluate whether a real-time air quality display (LCS) affected PAC usage	PurpleAir PA-II-SD Kaiterra Laser Egg	$PM_{2.5}$

Table 4.1.2. Crowdsourced studies characterizing IAQ using LCS.

Reference	Location & Timeline	Community	Participant(s)	Setting	Goal	LCS/Model	Pollutant(s)
May et al. 2021[39]	Western USA 2020 Wildfires (September 2020)	PurpleAir LCS users	Crowdsourced data with occupant selected case studies with filtration	Residences, schools, commercial buildings paired with outdoors	○ Evaluate the infiltration of smoke in different building types and the impact of interventions to improve IAQ ○ Evaluate a low-cost $PM_{2.5}$ filtration method that might be able to significantly improve IAQ during smoke events	PurpleAir monitors	$PM_{2.5}$
Liang et al. 2021[21]	San Fransisco Bay Area and Los Angeles Area 2018 & 2020 Wildfires (November 2018) (August-September 2020)	PurpleAir LCS users	Crowdsourced data	Residences paired with outdoors	○ Characterize how IAQ during wildfire episodes is affected by buildings and their occupants	PurpleAir monitors	$PM_{2.5}$
Krebs et al. 2021[213]	California (2019)	PurpleAir LCS users	Crowdsourced data	Indoor environments paired with outdoors	○ Explore the dynamic relationship between indoor and outdoor PM concentrations of various particle sizes across time of day, seasons, and locations	PurpleAir monitors	$PM_{(0.3\text{-}0.5), (0.5\text{-}1), (1\text{-}2.5), (2.5\text{-}5), (5\text{-}10)}$
Mousavi and Wu 2021[214]	Southern and Northen California Pre- and Post-COVID (2019-2020)	PurpleAir LCS users	Crowdsourced data	Residences, offices, schools paired with outdoors	○ Understand the influence of stay-at-home COVID orders on both indoor and outdoor air quality across location, type of building, and proximity to road emissions	PurpleAir monitors	$PM_{2.5}$
O'Dell et al. 2022[215]	Six western US cities: San Francisco, Los Angeles, Salt Lake City, Denver, Seattle, Portland (2020)	PurpleAir LCS users	Crowdsourced data	Indoor environments paired with outdoors	○ Quantify $PM_{2.5}$ exposures indoors and outdoors during smoke-free and smoke-impacted periods ○ Evaluate census-tract level socioeconomic representation of co-located indoor and outdoor LCS	PurpleAir monitors	$PM_{2.5}$
Kramer et al. 2023[216]	San Fransisco Bay Area and Los Angeles Area 2020 Wildfires (August-December 2020)	PurpleAir LCS users	Crowdsourced data	Indoor environments paired with outdoors	○ Evaluate indoor and outdoor $PM_{2.5}$ concentrations during 2020 California wildfires and characterize associated public health and equity implications	PurpleAir monitors	$PM_{2.5}$

4.2 Studies on LCS for IAQ Monitoring in Impacted Communities

This section discusses IAQ monitoring studies conducted in impacted communities using LCS. Nine (9) studies from the literature review (Tables 4.1.1 and 4.1.2) focused on indoor deployments of LCS in low-income communities and communities of color to assess the impact of LCS monitoring on IAQ and the occupants themselves. These studies include Matz et al. 2017,[193] Casey et al. 2018,[195] Shrestha et al. 2021,[25] Shao et al. 2021,[171] Webb et al. 2021,[201] Do et al. 2021,[26] Masri et al. 2022,[204] Masri et al. 2023,[209] and Prathibha et al. 2024.[212] These studies cover a range of settings, including unconventional natural gas development impacted areas in Pennsylvania, Native American reservations, and industrialized regions in Southern California. They also highlight different sources of indoor air pollution, such as household heating, outdoor pollution impacts on IAQ, occupational exposures, and wildfire smoke infiltration.

A common theme across these studies is the shared motivation for IAQ monitoring, with emphasis on the significant health risks associated with poor IAQ, including respiratory issues (e.g., asthma), cardiovascular diseases, and other adverse health effects linked to specific pollutants like $PM_{2.5}$, CO, and VOCs. Additionally, impacted communities included in the studies, namely low-income households, communities of color, and indigenous populations, were disproportionately affected due to their proximity to pollution sources, limited access to cleaner energy alternatives, and inadequate housing conditions.

LCS deployments in the studied impacted communities were often facilitated by community-academic or community-agency partnerships and revealed high levels of indoor air pollution. In some cases, these levels exceeded both prior findings in other homes and established air quality guidelines. Casey et al.[195] showed Navajo homes using wood and coal for heating had CO levels exceeding World Health Organization guidelines, with peak CO concentrations in some homes being higher than those recorded in other parts of the United States and Canada. Shao et al.[171] reported high respirable PM levels in Latino/Dominican salons, with one salon's 95th percentile PM concentration exceeding OSHA's action level. Masri et al.[204] observed significantly higher $PM_{2.5}$ levels indoors in two industrial buildings compared to outdoor conditions, with Latino workers, especially those engaged in sanding and welding, exposed to AQI-defined unhealthy air quality for most of their 8-hour shifts. Webb et al.[201] found some Native American homes in the US Mountain West region experienced $PM_{2.5}$ levels significantly above EPA's daily limit for several days, along with radon concentrations in many homes also exceeding EPA's action level.

LCS monitoring of IAQ in impacted communities also revealed variability in pollution concentrations across different homes and reference points within studies, highlighting how socioeconomic status, residential location, building quality, and occupant activities or behaviors could influence exposures. Casey et al.[195] observed a wide variation in air exchange rates across Navajo homes, of which 23% were below ASHRAE ventilation standards, indicating a higher potential for harmful CO accumulation from home heating practices. Shrestha et al.[25] showed indoor CO levels were three to five times higher than outdoor levels in some low-income homes, potentially due to standing pilot lights in combustion devices present. Additionally, low-income homes with exhaust hoods effectively reduced indoor air pollutant concentrations more than recirculating hoods and no installed stove hoods in other homes. Shao et al.[171] showed that although Black/African American and Latino/Dominican hair salons had elevated respirable PM concentrations (median 299 $\mu g\ m^{-3}$), higher levels were observed in Dominican salons, likely due to the more frequent use of blow drying and flat ironing documented in participant surveys.

Webb et al.[201] monitored IAQ in two Mountain West Native American Tribes, recording notably high but distinct peak $PM_{2.5}$ concentrations for Tribe A (463 $\mu g\ m^{-3}$) and Tribe B (896 $\mu g\ m^{-3}$), indicating a myriad of potential sources, including woodburning stoves and smoking. This study also highlighted housing inequality and an uneven distribution of exposure risks across tribal housing due to the consistent presence of radon in both Tribes A and B homes. Do et al.[26] characterized personal $PM_{2.5}$ exposure across five inland Southern California cities and found that participants from San Bernardino, the lowest socioeconomic status community, experienced higher home exposures over consecutive 24-hour monitoring periods. With participants also spending ~70% of their time at home, those in San Bernardino were more likely to face greater exposure to elevated $PM_{2.5}$, despite high participant mobility and relatively stable ambient $PM_{2.5}$ levels. Masri et al.[204] found that Latino workers in "sanding and welding" roles experienced the highest mean $PM_{2.5}$ concentration (167.6 $\mu g\ m^{-3}$) at an industrial facility, followed by strictly "welders" (111.7 $\mu g\ m^{-3}$). These concentrations were 2 to 5 times greater (33.5-68.1 $\mu g/m^3$) than those observed in the other three occupational categories, sheet metal folding, assembly working, and oversight.

Masri et al.[209] investigated firework-related personal $PM_{2.5}$ exposure in Santa Ana, CA during the 4^{th} of July celebration. Indoor-outdoor $PM_{2.5}$ ratios for disadvantaged homes in the area varied widely, influenced by building characteristics, holiday behaviors (e.g., windows open or closed), and other indoor activities. The study also found that race and ethnicity were leading predictors of July 4th-related $PM_{2.5}$ pollution in Southern California, with higher pollution levels in areas with greater proportions of Hispanic residents such as in Santa Ana. Prathibha et al.[212] explored the use of DIY and commercial portable air cleaners for reducing smoke exposure in underserved Native American homes in the Hoopa Valley Reservation. Study findings showed varied reductions in $PM_{2.5}$ levels across homes due to usage behavior from occupants impacting air cleaner efficacy.

Across the nine studies using LCS in impacted communities, various engagement levels and behaviors in response to IAQ monitoring were observed. Many residents actively used LCS to validate exposure, understand pollution sources, and take immediate action, such as improving ventilation or using air cleaners (Matz et al.,[193] Prathibha et al.[212]). Some participants engaged less frequently with LCS, often due to technical complexity or feeling overwhelmed by ongoing environmental health concerns (Matz et al.[193]) while other participants' behavior suggested a decline in interventions over time without regular external reminders (Prathibha et al.[212]). IAQ monitoring in disadvantaged homes showed that staying indoors during firework episodes effectively reduces $PM_{2.5}$ exposure, and even more so when combined with an indoor air purifier (Masri et al.[209]). In industrial settings, workers used LCS data to advocate for better workplace conditions and protective measures for basic air quality control, such as adequate ventilation systems and high-efficiency particulate air filters (Masri et al.[204]). Similarly, in Native American homes, IAQ monitoring prompted recommendations for immediate radon remediation (Webb et al.[201]) and the installation of CO monitors in homes heated with solid fuels (Casey et al.[195]).

However, despite strong motivations to better understand IAQ in impacted communities, often with successful indoor LCS deployments, several challenges emerged across studies. These included technical and data issues with LCS during deployment by academic or agency partners, as well as barriers faced by impacted communities related to improving IAQ. Issues such as LCS malfunction, lack of user-friendly interfaces, difficulties in data interpretation, and low LCS performance were present (Casey et al.,[195] Shrestha et al.,[25] Shao et al.,[171] Webb et al.[201]). For the participants engaged, high costs and limited access to effective air cleaning technologies were significant barriers, especially in low-income communities (Shrestha et al.,[25] Prathibha et al. 2024[212]). Additionally, continuous and effective use of IAQ monitoring and mitigation devices was influenced by factors like noise levels, ease of use, and indoor comfort (Matz et al.,[193] Casey et al.,[195] Shao et al.,[171] Webb et al.,[201] Prathibha et al.[212]).

The studies suggest that improving IAQ in impacted communities can leverage various opportunities facilitated by LCS, including community engagement and education, affordable tools and solutions, policy and advocacy, and technical improvements. **Community engagement and education:** continued engagement with residents, workers, and other populations in impacted communities to educate them about IAQ risks and mitigation strategies is crucial. Providing simple, actionable information can empower communities to take effective measures (Matz et al.,[193] Masri et al.,[204] Prathibha et al.,[212]). **Affordable tools and solutions:** the promotion of low-cost, effective solutions like DIY air cleaners can be helpful in mitigating exposure in economically disadvantaged communities. It is important to note that support for maintenance and replacement of parts is essential for sustained usage of these tools and solutions in impacted communities (Prathibha et al.[212]). **Policy and advocacy:** strengthening regulations and increasing inspections in workplaces and residential areas can help ensure better IAQ and enforcement of air quality standards for already overburdened communities. Given the propensity of inadequate housing conditions, smaller unit sizes, lack of cleaner heating fuels, and energy insecurity for low-income communities and communities of color, having community air quality data indoors and outdoors is a powerful tool in advocating for change (Masri et al.[204]). **Technical improvements:** developing more robust, user-friendly, and accurate LCS with validated performance testing will enhance data reliability and usability. Accessible training and support for users from LCS manufacturers to interpret and act on the data are also important (Casey et al.,[195] Webb et al.[201]).

Insights from IAQ monitoring studies in impacted communities also suggest several future-facing considerations on LCS utility. **Longitudinal studies** for IAQ monitoring are recommended to capture chronic exposure and seasonal variations that can provide a deeper understanding of health impacts and the effectiveness of interventions (Masri et al.,[204] Webb et al.,[201] Prathibha et al.[212]). Additionally, the continual **integration of mobile applications, wearables, and other digital tools** with LCS, which can be easily accessed and used even for less technologically savvy users, is essential for adapting LCS into daily life for IAQ monitoring and facilitating real-time data knowledge, engagement, and responsiveness (Matz et al.,[193] Shao et al.,[171] Prathibha et al.[212]). **Scaling up** successful models of community-facing engagement and low-cost monitoring to more communities can also help address widespread IAQ issues and promote environmental justice for impacted populations (Webb et al.,[201] Prathibha et al.[212]). Likewise, individual, crowdsourced, or community-led monitoring of IAQ in impacted communities can influence local and national policies to drive systemic changes to improve air quality in these communities. Overall, by addressing challenges in IAQ monitoring and building on the strengths of LCS technologies, significant improvements in IAQ and public health can be achieved, particularly in marginalized and vulnerable communities.

5 Insights from Stakeholder Interviews on LCS for IAQ Monitoring

5.1 Overview

Stakeholder interviews were conducted in accordance with the goals specified in Task 3 (Section 2.4). Interviewees were recruited from the four stakeholder groups: IAQ researchers, LCS manufacturers, members of impacted communities, and LCS users. Interview questions were co-designed with CARB staff and tailored to each stakeholder group. The detailed summaries that follow are organized by stakeholder group, and insights gained from each interview are organized into five themes. These themes include best practices, benefits, caveats, unique experiences, and recommendations. Best practices describe activities that are commonly carried out to improve the indoor air monitoring experience. Benefits describe the positive aspects associated with LCS monitoring for IAQ. Caveats describe aspects of using LCS for IAQ monitoring that users should be aware of, whether based on expert knowledge or whether the knowledge was gained from a negative or challenging experience. Unique experiences include specific recollections of past occurrences from the interviewee regarding IAQ monitoring, exposures, and mitigation approaches. Recommendations include advice from interviewees for future monitoring efforts, science communication, and indoor air pollution mitigation.

A total of 10 individuals were interviewed, and the length of the sessions ranged from 20 to 45 minutes. Specifically, interviewees included one sensor manufacturer, two members from impacted communities, three IAQ researchers, and four sensor users. Interviews were digitally recorded and transcribed to retain the original meaning of interviewees' spoken words. Following transcription, interview content was then sorted into the aforementioned themes and summarized for readability. It is important to note that some themes were not reflected in certain interviews. Section 5.3 collates and combines the unique experiences from stakeholder groups when using LCS for IAQ monitoring as outlined in Tables 5.3.1-5.3.3 while Section 5.4 highlights best practices (Table 5.4.1), identifies key caveats (Table 5.4.2), and presents recommendations (Table 5.4.3) shared from the diverse experiences of the interviewed stakeholders. Together, these insights offer practical guidance for implementing LCS in a variety of contexts, addressing technical, educational, and operational aspects.

5.2 Highlights and Implications of Interview Insights

Interviews were very insightful in gaining an understanding of the experience of multiple stakeholders after using LCS for a variety of applications. All researchers and the manufacturer recommend calibration or comparison to reference grade instrumentation, and this comparison should occur intermittently for longer-term applications. Impacted community members and sensor users appreciate qualitative groupings of data into easily interpretable colors, but researchers warn against inconsistencies in groupings across manufacturers. Sensor users greatly benefited from having access to monitors and were able to make impactful changes to their indoor behavior. However, these changes can be slow for community members with deeply embedded cultural practices that lead to indoor emissions. Impacted communities are presently suffering from low-quality housing that sometimes does not have windows or air conditioning. Tensions and fears surrounding eviction can hamper the willingness of a renter to advocate for healthy household interventions for better IAQ, such as electric stoves and air filtration. The majority of stakeholders cite $PM_{2.5}$ and CO_2 LCS as having reliable data, but would like to see the same for other pollutants. Total VOCs and NO_2 were cited as being not as reliable.

The public would benefit from targeted educational campaigns about IAQ, LCS monitoring indoors, LCS data, data interpretation, indoor air pollution sources, and mitigation strategies. Providing succinct guidance in multiple languages in digital video format, TV and radio announcements, or billboards would promote IAQ education and awareness.

5.3 Unique Experiences of Stakeholders

Table 5.3.1. Unique experiences of **impacted community members**.

Summary of Insights	
Indoor Pollutants & Unhealthy Indoor Conditions	○ Indoor pollution sources include air fresheners, pet dander, rugs, cooking, gas stoves, and air fryers. ○ Bleach, Febreze, and other cleaners are asthma triggers, and were especially noticeable during the height of the COVID-19 pandemic. ○ Old buildings lead to unfavorable indoor conditions as well as overcrowded housing, lack of windows, and limited ventilation. ○ There was an aversion to opening windows during winter. ○ Proximity to freeways and high-traffic roadways worsens IAQ. ○ Asthma and eczema cited as health effects worsened by poor IAQ.
LCS Purchase & Use for IAQ Monitoring	○ Manufacturer recommended purchasing an ultra-low-cost sensor ($75-100) due to their budget constraints. ○ Community member has not purchased their own sensors directly due to cost constraints. ○ Experienced difficultly when setting up monitors and reading and understanding measurements in real time. ○ A small, tube-shaped, portable monitor was used for a youth engagement project. Monitors were lightweight, transmitted data to an app without a hotspot, and stayed charged for up to seven days. However, there was limited accessibility to the app's data due to the lack of an online dashboard. ○ A wearable $PM_{2.5}$ monitor was liked for its real-time data transmission and ability to record measurements while mobile. However, the alarm system was too loud in a school environment. ○ Future purchases will include solar-powered, cellular-enabled $PM_{2.5}$ monitors. ○ Community member is now using air filters in their workplace due to IAQ monitoring indoors. ○ In another community household, they decided to vape outside instead of indoors as a mitigation strategy for indoor air pollution. ○ There is no clean IAQ baseline to compare to in the community.
Behavioral Changes to Improve IAQ	○ Learned how to use filters in window air conditioning units. ○ Changed the time of using their built-in oven to only being used in the morning. ○ Taping up windows during wildfire smoke events suppresses infiltration. ○ Uses Google, AQ-SPEC, Home Depot, and Amazon as resources to learn about IAQ monitoring. ○ Community member would like to purchase an electric convection oven while renting to improve IAQ and then put the original gas oven back after the lease ends.
Obstacles for Improving IAQ	○ Stagnant ambient conditions (e.g., strong marine layer) allowed emissions from a neighbor's fireplace to infiltrate their home. ○ Window air conditioning units were ineffective during Northern California wildfires, prompting temporary displacement to get relief from smoke impacts. ○ Air conditioning alone on a summer day doesn't remove indoor pollutants as effectively as expected when using a built-in oven.

Summary of Insights	
Obstacles for Improving IAQ	○ Tensions with landlords may arise when advocating for cleaner indoor air. Before a 2024 California provision for tenant protection was put in place, landlords could evict when tenants complained. ○ Lack of public awareness about IAQ in a non-residential location (e.g., gym class) led to higher exposure risks. ○ For some communities, behaviors don't change overnight, and so funding for IAQ monitoring and education needs to be available for five or more years. ○ In some cases, it takes time to find community-driven solutions and to change behaviors. So, changes shouldn't be expected in as few as 3-6 months.

Table 5.3.2. Unique experiences of **IAQ researchers**.

Summary of Insights	
Feedback on Sensors	○ For tVOC sensors, a unique application has recently been developed where the sensors are used to understand indoor mixing and timing to disperse across a space, but this may not be useful for a community organization. ○ Low-cost ultrafine particle sensors are emerging that perform well compared to scanning mobility particle sizers (SMPS). ○ IQAir has a nice monitor for $PM_{2.5}$ and CO because there is no Wi-Fi requirement, but battery issues have been experienced. ○ A multi-pollutant indoor monitor is useful for its ability to switch out sensors. A homeowner may only be interested in short-term monitoring, but these are good in the long-term because sensors can be switched out.
Lessons from Residential IAQ Monitoring	○ Researcher unknowingly installed a well-known $PM_{2.5}$ monitor at their home residence near a water heater vent and saw spikes at regular intervals. This was caused by small amounts of particles that are emitted from natural gas combustion. ○ Wildfires are a big motivation for using LCS. ○ There is not always a paid incentive for community studies, and payments depend on the application. Project implementers are usually paid. ○ In an indoor monitoring effort with a Tribal community, 50 homes were assessed for IAQ using low-cost monitors for $PM_{2.5}$, tVOC, CO, CO_2, temperature, and relative humidity. Community members kept activity diaries, and then had a chance to follow up with researchers for one hour to discuss findings. Then, monitoring continued for two additional weeks. The education and capacity building that emerged from this study were then used to leverage ongoing ambient monitoring efforts.
Lessons from IAQ Monitoring in Schools	○ Sometimes schools may not want to buy something deemed “low-cost” because they are concerned about liability and quality when communicating findings with parents. ○ Parents were eager to get access to the data. There was some pressure to release high-quality data (e.g., remove poorly performing sensors).

Table 5.3.3. Unique experiences of **LCS users**.

Summary of Insights	
Indoor Pollutants & Associated Health Effects	o Users identified cigarette smoke, cooking, off-gassing from carpet and furniture, improper filtration, wildfire smoke, proximity to roadways, and outdoor sources as threats to human health indoors. o One user identifies the length of exposure as a determinant of the severity of subsequent health effects, e.g., skin issues, respiratory issues, and certain kinds of cancers. o There are difficulties in establishing causation because of the many chemicals that are in the air. The user recognizes correlational evidence of exposure and adverse health.
Feedback on Sensors	o For personal purchases, the user would choose a well-known $PM_{2.5}$ monitor for its affordability, popularity in the neighborhood, and product familiarity. o A small, tube-shaped monitor was portable but had to be charged often, and the connectivity was inconsistent. It was also responsive to turning on a gas stove, but searing meat led to a spike. o User was motivated to use two popular sensors at home due to exceptional events (e.g., wildfires). The setup was easy, but the charging cycle was inconvenient. o Some monitors are better for research applications, and others are more suitable for the public due their user-friendly design and operation. o User cites a solar-powered, cellular enabled $PM_{2.5}$ monitor as their monitor of choice. o Sensor user has experience with deploying solar-powered, cellular-enabled $PM_{2.5}$ monitors indoors in a school along with CO_2 sensors in partnership with a state agency. One sensor model was chosen based on an existing collaborative relationship with a vendor. The other sensor model was acquired through a partnership with the state agency, which purchased the sensors. o User found the setup process for a popular $PM_{2.5}$ monitor to be easy and found the website for data access to be convenient. o User took advice from a friend on Twitter to use the small, tube-shaped monitor. Purchasing and setup was easy, but they experienced lack of connectivity and didn't like the charging cycle. User does not see spikes when smelling combustion exhaust.
LCS Deployment and Public Engagement	o User's experience with deployment is different depending on who they are engaging with, e.g., a business owner, residential locations, or a city staff member. Questions and responses will be different from stakeholder to stakeholder. o Sensor manufacturer provided advice on where to site monitors and what to look out for. o In a school application, it wasn't realistic to give teachers direct access to the LCS dashboard without a customized guidance document, so one was created. o Outreach to find deployment locations has been challenging for an ambient monitoring effort, because air monitoring is not a priority for everyone or it is difficult to get in contact with building owners. o In a multi-stakeholder collaborative monitoring project, some communities needed workshops on how to file a complaint; some needed better air filtration in schools; and some wanted to know how the regulatory system works so they can be better advocates for air quality.

Summary of Insights	
Behavioral Changes and Associated Improvements in IAQ	o User worked with DIY air cleaners and used LCS to understand how well the cleaners worked in their bedroom. User saw significant reductions in pollutant levels after 15-20 minutes of use. o User experienced an immediate behavior change when cooking as a result of indoor monitoring at home. User now opens a window when cooking because there is no range hood available. o Having additional information about in-home placement of sensors and how to act on the data helps to change behavior and make better decisions about mitigation. o In an IAQ assessment in a school, even when provided with air filters along with monitors, sometimes air filters were never turned on. o COVID-19 was a major driver for the indoor monitoring efforts in one local school district. These efforts also coincided with a district-wide HVAC system upgrade. o User has enjoyed having a popular and commonly used monitor to see which activities increase indoor $PM_{2.5}$ levels. User also enjoys learning how long it takes to mitigate indoor pollution by opening windows or turning on an air filter to return to baseline levels. Having the indoor $PM_{2.5}$ data allows for informed decision-making around the house. User hasn't experienced any significant issues with the popular $PM_{2.5}$ monitor in four years. o User is more conscious of indoor sources as a result of the monitoring, and now opens windows, if the weather allows, or turns on the exhaust fan when cooking. o User likes being able to see the gradient from outside to inside during smoky days. One popular $PM_{2.5}$ monitor is in the living room and one is in the backyard. o Commercial air filters didn't work as well during smoky days due to having an older, leaky house. So, the user decided to spend time in one closed-off room with the air filter. User concluded that controlling a smaller environment and spending more time there was more useful during smoky days. User noticed that even with windows closed, indoor air quickly rose to outdoor levels during smoky days without air filtration. o User was inspired to better understand IAQ dynamics due to a childhood asthma diagnosis. o User would not have purchased a popular $PM_{2.5}$ monitor before their work program offered them due to cost. After experiencing their benefits, they would replace the sensors on their own. If the user didn't have their monitor, they would infer their ambient pollutant levels from a neighbor's monitor. o User is borrowing a well-known multi-pollutant monitor as a loaner from work. The CO_2 readings led to them opening their windows, but $PM_{2.5}$ readings didn't have much variation. o User identifies CO_2 as an indoor pollutant of importance because of the monitor they have access to. o Seeing the numbers on the monitor change as a result of their indoor activities prompted a change in their habits, such as opening the window during data spikes. o Opening two windows and using an industrial fan lowers CO2 levels. o The well-known multi-pollutant monitor emits a light at 8 AM, so the user took the monitor out of their bedroom. o After observing patterns and changing behaviors, there wasn't much additional information needed from the sensors. o User would not have appreciated how much air quality degraded during cooking without having access to the data. o Personalized air pollution information is helpful, especially when outside of the home or when visiting a new location.

Summary of Insights	
Lingering Concerns	o After $PM_{2.5}$ monitoring, the user is still interested and concerned about levels of other indoor pollutants, mold, and pollen. o User still needs ventilation infrastructure to be installed (e.g., range hood), so the need wasn't immediately met as a result of monitoring. o As a higher-income household that is susceptible to higher levels of indoor pollution due to leaky seals, the pollution levels could be similar to those in an AB 617 household. However, more income leads to the ability to deploy more resources to manage IAQ. o User is experiencing a leaky home even after updated duct work and an upgraded furnace being installed within the last 10 years. o User would be interested in sensors for other pollutants if they are as reliable as the popular and commonly used $PM_{2.5}$ monitors o User would not be interested in invasive equipment (e.g., very big, large power requirement, or noisy).

5.4 Best Practices, Caveats, and Recommendations for LCS

Table 5.4.1. Best practices from all interviewees.

Summary of Insights	
Sensor Manufacturer	o Lauds small mobile monitors as being advantageous for monitoring in indoor environments. o Referencing the South Coast AQMD's AQ-SPEC testing results is a good reference point for evaluating monitor performance. o $PM_{2.5}$ LCS should be evaluated against Arizona road dust. This is an indicator of good quality assurance practices. o For a quick check of sensor performance, taking the sensor outside and comparing the values to the nearest reference monitor may be a good check, unless the home is downwind of a strong source. o If a user is seeing a "zero" reading indoors, this could be due to high detection limits, i.e., the sensor doesn't read very low values and measurements are rounded to zero for low values. o $PM_{2.5}$ sensors should show high readings during cooking activities.
Members of Impacted Communities	o Going door-to-door for community outreach and creating personal connections is best for promoting behavior change for indoor exposure mitigation because it takes time to change behaviors. o It is helpful to hear IAQ education from multiple sources over time. o For someone who is initiating community monitoring, it is best to first start talking to community members about air quality. o It is important to understand the occupant density of a household. o Community members need to understand LCS capabilities, e.g., they are not calibrated to measure specific source impacts, like smoke.

Summary of Insights	
IAQ Researchers	o For PurpleAir monitors, the data should not be used if A and B channels diverge significantly. o It is helpful to compare sensor data to measurements from nearby EPA/reference monitors. o When a house is well-ventilated, indoor concentration measurements are similar to outdoor measurements. o Community-based organizations need guidance on how to implement LCS, and they need plain language explanations of the value and limitations of the monitoring. o Always calibrate sensors with research-grade instrumentation. This should be done intermittently for longer-term studies. o It is best to compensate community assistants for their time when working on these monitoring efforts. o The most typical use of LCS was for mitigation of indoor exposure. For example, the researcher could demonstrate how pollutant levels increased in response to cooking without an exhaust fan, and then make recommendations for mitigation. They were not attempting to provide exact exposure estimates. o Co-location in an environment with the target source is a standard practice. For instance, if traffic is expected to be the dominant source, then sensors are co-located in a near-road environment. o Co-location is sometimes carried out at a federal monitoring site. o LCS that are drifting or malfunctioning should be replaced. o For sensor recommendations, it is good practice to reference LCS evaluations on the AQ-SPEC website. o CO_2 sensors have been reliable, but calibration is manufacturer-specific, so they always check performance against research-grade instruments. o Community monitoring efforts are most successful when they are internally motivated by the impacted groups.
LCS Users	o Public resources that are commonly used include the EPA sensor guidance document, AQ-SPEC website, manufacturer websites, wildfire guidance documents, and fact sheets. o Other sources of useful information include blogs, customer reviews, and tailored webinars. o Oftentimes, users will ask questions to researchers and colleagues who work directly with LCS professionally. o It is good for people to think about where in the home the major sources are and where most of the time is spent to determine in-home sensor placement. o Knowledge is power and having IAQ data can help make informed decisions. o Having colors associated with pollutant levels is an accessible way to interpret the data.

Table 5.4.2. Caveats from all interviewees.

Summary of Insights	
Sensor Manufacturer	o Although, some sensors may be manufactured for ambient use, they can also be used indoors. o A "zero" value that is observed outside may be a sign that the sensor is not working. o Some sensors are targeted for industrial applications and enterprise-scale monitoring and therefore may not be very user-friendly. o Be mindful that manufacturers haven't necessarily provided direct information to be included in EPA or AQ-SPEC evaluations. These evaluations are conducted independent of input from manufacturers.
IAQ Researchers	o Be mindful of where LCS are installed at a residence to avoid placement near sources. o The current distribution of a popular $PM_{2.5}$ monitor doesn't represent low-income communities very well. o LCS are not usually high-quality. o There may need to be different duration (time scale) and threshold considerations for community/residential vs. commercial building applications of LCS use in IAQ monitoring. o IAQ in commercial buildings may need longer-term measurements, which may be longer than the optimal lifetime of LCS. o Community organizations and homeowners may have different IAQ goals, so separating the advice for those groups could be useful. o Community organizations may need similar advice to what is useful for school applications. o It is up to the manufacturer to decide how high quality their sensor-provided information is. Since there isn't a standard, this creates inconsistencies, which is not the best of circumstances. o The public generally relies on [qualitative] IAQ groupings (colors) and not numbers (concentration or numerical values), and these groupings can vary across manufacturer. o Community groups may not know what to look for in terms of data quality or accuracy with respect to research-grade measurements (i.e., when comparing LCS to reference values). o For schools and community organizations, a challenge may arise with deciding who owns the data that are collected, as well as accessing those data. So, with organizational-level networks, there may be challenges with data ownership. o Long-term planning can be challenging because organizations may not have a good sense of what to do after 5-10 years, e.g., how to maintain equipment, how to update or repair equipment, and where funding for maintenance comes from. o Community organizations and schools may not be interested in raw data, so access to quality-screened data may be most useful and would need to be easily accessible. o LCS have difficulty detecting ultrafine particles, which will be a challenge in capturing accurate impacts when sampling near activities with lots of fresh emissions, such as cooking. o Research has observed lots of drift for NO_2 sensors. o Regarding accuracy, depending on the pollutant source, the sensors may be measuring something different than what we think they are measuring. For example, indoor combustion sources are not measured well by low-cost $PM_{2.5}$ sensors. o CO and CO_2 sensors perform reasonably well. VOC sensors are not particularly well performing either, in terms of specificity. o The full extent of major sources won't be captured with $PM_{2.5}$ LCS due to size range limitations. o It can be challenging to manage large volumes of LCS data.

Summary of Insights	
LCS Users	o It can be difficult to connect Wi-Fi dependent sensors to a protected Wi-Fi network. It may be best to use personal hotspots. o There is a high occurrence of trial and error when siting sensors, and lessons get learned along the way. On site, finding the place to mount the sensor can be unpredictable. o When engaging with the public and trying to generate interest in air monitoring, socioeconomic or psycho-social challenges may take precedence over air quality concerns. o If users knew the challenges with siting, they may be deterred from purchasing certain ambient sensors.

Table 5.4.3. Recommendations from all interviewees.

Summary of Insights	
Sensor Manufacturer	o If consumers want to use industrial sensors, they should reference their user manuals as well as EPA and AQ-SPEC documents for additional information on operation, evaluation, and quality control.
Members of Impacted Communities	o We need to clearly educate the community about the sources of poor IAQ. o Regarding cultural practices that involve candle burning, we should start educating the community about how to specifically manage candle pollution when the smoke is black, such as extinguishing outside. Other solutions could be for community members to use battery-powered or electric candles. o Community IAQ could be improved by providing air filters, which could also address the high prevalence of pulmonary diseases. o Since community members live in homes with low-bandwidth Wi-Fi or no Wi-Fi, LCS should have an app that makes the data more accessible. Without internet, it is hard to have a clear picture of what is going on in the home. o Having a sensor that indicates that air is good, okay, or poor would be helpful. o For improved community education, having public announcements on TV or radio would be helpful, e.g., a 30-second clip that explains the color-based indicators of poor AQ. o Use of self-contained monitors with their own power source and data transmission is recommended for low-income communities. o Landlords need to be held responsible for supporting home improvements for IAQ, e.g., switching to electric ranges, regularly changing air filters, and upgrading air conditioning systems. o Landlord business license renewal could be tied to their commitment to providing safe and healthy housing for tenants. o A community IAQ campaign would be helpful for raising awareness among families (e.g., informational billboards). o There should be increased awareness raised about exposures in hazardous jobs (e.g., stone countertop artisans, carpet layers, etc.). o Having a dedicated technical expert to work with would facilitate community monitoring efforts.

Summary of Insights	
IAQ Researchers	o Create targeted indoor air regulation that is focused on human health. o Consumer concerns around air quality, particularly wildfire smoke, led to increases in PurpleAir purchases. Such sensors can be useful for climate adaptation planning purposes. o We could propose through new legislation that sensors, like CO detectors, not only report threshold breaches, but also continuously measure and then report those measurements in an accessible central database. o Deployment of affordable sensor packages that include CO, CO_2, NO_x, $PM_{2.5}$, and ozone to have measurements across many residential and business environments is useful. o Sensors need to be foolproof to install. o Having a broader array of multi-pollutant sensors where data are publicly available allows people to put what they are measuring in their own homes into context. o To overcome the income discrepancy of indoor LCS use, they should be given away for free. o The 2021 ASTM standard for low-cost $PM_{2.5}$ LCS evaluation will help to standardize IAQ thresholds for this measurement across manufacturers. o We should probably refer to LCS as consumer-grade sensors because low-cost means something different to everyone. Usually, manufacturers don't use the term low-cost. o Sensors themselves need to be certified in a standardized way, similar to how ASTM standardizes the performance evaluation. o Guidance documents should include some things that community organizations can easily check to evaluate data quality. o There is high value in the research space to make calibration information more usable (or accessible). o Different levels of access to online data interfaces for different roles are useful for community organizations and schools for accessibility. The different roles could include: administrator, analyst, user, public; and the different interfaces on a sensor's online dashboard could be public map only, raw data access, and the administrator setup for sensors. o It is difficult for community organizations to figure everything out on their own, so it may be useful to have an email address where people can actively seek and receive help. o Community-academic partnerships are helpful to provide technical assistance for low-cost monitoring. o We need to think about the case of portfolio-level monitoring, when someone is managing hundreds of buildings, and how to make the data most valuable (e.g., visual presentation). o Having access to a nice dashboard facilitates data management. o There should always be a discussion of sensor limitations for community applications, such as not being able to capture the full magnitude of combustion impacts. o It would be helpful to have more manufacturer guidance on the length of useful life for sensors and their parts. o There should be a clear replacement system in place for sensors and parts (in reference to LCS vendors or manufacturers). o For lender programs (e.g., sensor loans from libraries), there should be simple guidance on how to access the data and what to do with the information.

Summary of Insights	
LCS Users	o Having a device with a cellular plan is recommended to avoid Wi-Fi availability challenges. o Having a device with solar power to keep them charged is also helpful, especially for field work. o It would be helpful to have technical support at multiple levels, such as from the manufacturer, from the user's job, and from a technically trained help desk employee (sometimes they don't have real-world experience). Larger companies may have more capacity to handle technical support. o It is very important that communities can get in contact with technical support quickly, whether it is a state or local entity. Having ready access to technical expertise is important. o When recommending sensors to others, user would recommend a popular and commonly used $PM_{2.5}$ monitor to more technical people and for ambient applications. o For indoor applications and people with less technical experience, a popular multi-pollutant indoor monitor or a comparable device is recommended. o User would recommend a lower-cost $PM_{2.5}$ monitor for more research-leaning applications for its robustness, solar power capability, cellular connection, and back-end support. o It is best to use a sensor with a plug-and-play setup and with a graphical interface that makes the data easy to read. o Having adequate in-house staff support for outreach related to sensor siting is key for the success of monitoring efforts. o Guidance on siting efficiently is greatly needed for end users that facilitate projects who may be interfacing with unfamiliar communities. o It is important to note that improving air pollution disparities requires an interdisciplinary solution, one that doesn't solely rely on monitoring or technical solutions. o User would like a more personalized app to connect to the LCS or an LED display that shows green, yellow, or red based on IAQ. User would rather not be required to always check the status on the website. o User would recommend a popular and commonly used $PM_{2.5}$ monitor to others. o User would like information upfront about where to place sensors in the home. o User recommends information on how to interpret spikes in the data. o It would be useful to have access to short (~3 min) videos about each sensor to explain what the values mean (i.e., an accessible video library). This may be more desirable than attending a 1.5-hour webinar. o Comparing local exposures to those outside of California could be an interesting reference point for people. o Using sensors for one month provides time to understand the link between activities and pollution levels, so that is the recommended time for using the sensors and calibrating behavior.

6 Recommendations on LCS for Sustaining Healthier IAQ

LCS for IAQ monitoring play a crucial role in sustaining healthier indoor environments by providing accessible and affordable means to track pollutants. Insights from market surveys on LCS, reviews of IAQ monitoring studies, and stakeholder interviews reveal that LCS are effective tools for identifying and mitigating exposure to harmful air pollutants, particularly in impacted communities. These contributions highlight the importance of user-friendly interfaces, reliable data, and continuous community engagement to maximize the benefits of LCS. By addressing technical challenges and ensuring equitable access to these technologies, LCS can significantly improve public health outcomes and environmental justice for vulnerable populations.

To reduce barriers to IAQ monitoring with LCS in impacted communities and promote healthy IAQ, several actions can be undertaken by various stakeholders, including LCS manufacturers, researchers, community groups, air quality agencies, policymakers, and LCS users. Broadly, LCS manufacturers can enhance device reliability, user-friendliness, and affordability, while researchers can focus on continuous validation of LCS performance and exploring innovative applications. Community groups can facilitate education and engagement, helping residents understand and utilize LCS effectively. Air quality agencies can support regulatory frameworks and provide technical assistance, while policymakers can advocate for funding and policies that promote equitable access to IAQ monitoring tools. LCS users, including residents and workers in impacted communities, can actively participate by learning about IAQ and using LCS devices to monitor their environments to advocate for healthier indoor conditions. Recommendations for these stakeholders, without a detailed assessment of their implications, are provided in Sections 6.1-6.5.

6.1 Recommendations for Community Groups and Air Quality Agencies

Recommendations for community groups and air quality agencies to facilitate LCS use for IAQ monitoring in impacted communities are as follows:

(1) Provide accessible training programs and workshops on IAQ, including the use and maintenance of LCS, and offer community forums and question and answer sessions to address concerns and provide guidance.

(2) Distribute multilingual educational materials on IAQ health risks, data interpretation, and mitigation strategies or solutions.

(3) Subsidize the cost of LCS for low-income households and impacted communities, and facilitate bulk purchasing or subsidies to lower costs for community members.

(4) Promote and distribute low-cost, effective solutions like DIY air cleaners.

(5) Encourage community-led monitoring projects and citizen science initiatives, and create a local network of volunteers to assist with IAQ monitoring efforts.

(6) Collect and share success stories and case studies to motivate others and demonstrate the benefits of IAQ monitoring.

(7) Tailor IAQ monitoring and mitigation strategies to address specific local sources of pollution, promoting sustainable practices like cleaner cooking and heating methods.

(8) Develop community-led reports and presentations to highlight IAQ concerns and propose solutions.

(9) Partner with policymakers to address systemic IAQ issues in impacted communities.

6.2 Recommendations for Researchers

Recommendations for researchers to facilitate LCS use for IAQ monitoring in impacted communities are as follows:

(1) Scale up successful community engagement models to more areas, leveraging community-led LCS monitoring to influence policies and improve IAQ locally.

(2) Conduct long-term studies with LCS to understand chronic exposure and seasonal variations in IAQ, monitoring the sustained impact of interventions over time.

(3) Incorporate insights from public health, engineering, and social sciences for a comprehensive approach to IAQ.

(4) Ensure IAQ LCS data is accessible, transparent, and easily interpretable for non-experts, while protecting the privacy and ownership of community members' data.

(5) Offer workshops and seminars to disseminate research findings, best practices, and health resources based on IAQ data.

(6) Involve community members in decision-making processes to ensure the relevance and applicability of LCS monitoring and IAQ interventions.

(7) Seek funding opportunities to support community-based research and collaborate with local organizations.

(8) Advocate for increased research funding focused on marginalized and vulnerable communities.

(9) Test LCS technologies tailored to community needs, continuing to validate their performance for accuracy and reliability.

(10) Expand efforts for performance evaluation studies on gas-pollutant LCS and to advance LCS technology, particularly for small particles and gas pollutants with lower data quality.

6.3 Recommendations for LCS Manufacturers

Recommendations for LCS manufacturers to facilitate LCS use for IAQ monitoring in impacted communities are as follows:

(1) Offer discounts, subsidies, or donations of LCS units to schools, clinics, and community centers in underserved areas.

(2) Participate in initiatives to support IAQ improvement projects in vulnerable communities.

(3) Develop user-friendly LCS with simple interfaces, clear instructions, and multilingual support, ensuring accessibility across technological skill levels.

(4) Create mobile applications for real-time monitoring and alerts that integrate seamlessly with LCS.

(5) Enhance LCS accuracy and reliability through rigorous performance testing, ensuring devices are durable and require minimal maintenance.

(6) Establish robust support services for troubleshooting, data interpretation, and continuous technical assistance, including extended warranties.

(7) Implement feedback loops for community reporting and timely responses, using this feedback to improve LCS technology and IAQ programs.

(8) Engage in community-academic partnerships to build credibility and trust.

(9) Invest in research and development to advance LCS technology, staying updated on emerging IAQ issues and trends to adapt features accordingly.

6.4 Recommendations for Policymakers

Recommendations for policymakers to facilitate LCS use for IAQ monitoring in impacted communities are as follows:

(1) Establish and enforce technical standards for LCS performance in indoor environments (e.g., ASTM D8405-21[184]) to ensure reliable data.

(2) Allocate and increase funding for the distribution of LCS and IAQ initiatives in low-income communities and communities of color – e.g., CARB programs: Community Air Grants and Supplemental Environmental Projects.[217,218]

(3) Support LCS studies on the long-term health impacts of poor IAQ and the effectiveness of various interventions.

(4) Facilitate collaboration between health services and IAQ monitoring to link LCS data with health outcomes in impacted communities (dependent on the formation of LCS standards).

(5) Offer incentives for adopting LCS IAQ monitoring, clean air technologies, and energy-efficient appliances, such as tax credits.

(6) Encourage businesses and industries to implement monitoring with LCS and additional IAQ improvement measures through regulatory support and incentives.

6.5 Recommendations for LCS Users

Recommendations for LCS users to facilitate LCS use for IAQ monitoring in impacted communities are as follows:

(1) Educate yourself on air pollutants (e.g., $PM_{2.5}$, CO, NO_2, VOCs), their health impacts, and safe versus hazardous levels with resources from AQ agencies (e.g., the EPA).[219–224]

(2) Utilize available resources like online guidebooks, tutorials, community workshops, and user manuals to improve LCS understanding and data interpretation.[47,54]

(3) Join or form local IAQ-focused groups to share experiences, solutions, and resources.

(4) Inform family members and neighbors about the importance of IAQ and the use of LCS.

(5) Engage with policymakers and community leaders to advocate for IAQ improvements and the benefits of using LCS for indoor monitoring.

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