Guidance: Low-Cost Sensors for Healthier Indoor Air

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Disclaimer

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Foreword

In 2023, the California Air Resources Board (CARB) awarded the University of California, Berkeley (UC Berkeley) a grant to work on a project entitled "Low-Cost Sensors for Healthier Indoor Air Quality in Impacted Communities." This project was intended to provide accessible knowledge for impacted communities to facilitate their use of low-cost sensors (LCS) for monitoring indoor air quality (IAQ).

IAQ is a critical aspect of public health that significantly influences human well-being. People spend over two-thirds of their time at home alone, where indoor air pollutant concentrations are often higher than outdoor conditions when indoor sources are present. Furthermore, exposure to indoor air pollution can be more critical for residents in impacted communities, who not only have increased exposure from outdoor pollution sources such as traffic and industry, but may also be exposed to higher levels of indoor air pollutants due to their smaller unit sizes, higher occupant density, insufficient ventilation, use of gas ovens as heating sources, and limited access to greener products. As a result, low-income communities and communities of color across California and the United States are disproportionately vulnerable to the effects of indoor air pollution due to these societal, financial, and environmental factors. Improving IAQ is therefore crucial for protecting public health and sustaining healthier indoor environments in impacted communities.

The technological advancements of LCS have made it increasingly feasible for individuals and communities to monitor IAQ. LCS provide valuable data that can prompt immediate actions to mitigate indoor pollution in real time. Additionally, LCS are affordable, user-friendly, and have become useful tools for promoting healthier indoor environments. However, understanding the limitations and proper usage of LCS devices is crucial to maximizing their effectiveness and utility for improving IAQ.

This document outlines the importance of IAQ, sources of indoor pollutants, strategies for improving indoor environments, and the application of LCS for IAQ monitoring. By leveraging the capabilities of LCS, individuals and communities can create safer and healthier indoor environments, thereby protecting their health, comfort, and well-being.

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List of Figures and Tables

Glossary of Acronyms

AQI	Air quality index
AQ-SPEC	Air Quality Sensor Performance Evaluation Center
CARB	California Air Resources Board
CO	Carbon monoxide
CO_2	Carbon dioxide
EPA	Environmental Protection Agency
H_2S	Hydrogen sulfide
HCHO	Formaldehyde
IAQ	Indoor air quality
LCS	Low-cost sensors
MAE	Mean absolute error
NASEM	National Academies of Science, Engineering, and Medicine
NO_2	Nitrogen dioxide
NOx	Nitrogen oxides
O_3	Ozone
PM	Particulate matter
PM1	Particles < 1 µm
PM2.5	Fine particulate matter (< 2.5 µm)
PM10	Coarse particles (< 10 µm)
R^2	Coefficient of determination
SCAQMD	South Coast Air Quality Management District
SO_2	Sulfur dioxide
TVOC	Total volatile organic compounds
$\mu g/m^3$	Micrograms per cubic meter
µm	Micrometers
VOCs	Volatile organic compounds

1. Introduction

1.1. Indoor Air Quality

Indoor air quality (IAQ) describes how much air pollution is present in the air we breathe within and around indoor environments (e.g., homes, offices, schools). It indicates whether the air is clean and safe enough to breathe or poses a concern for human health. This is important because people spend the majority (~90%) of their time indoors, mainly at home or at work, [1, 2] where IAQ can significantly influence our well-being and exposure to air pollutants. Additionally, indoor residential air often has an abundance of air pollutants from various sources that usually exceed levels found outdoors. [3] Many research studies have shown the many adverse health effects of exposure to air pollution indoors. These include: eye, nose, and throat irritation; aggravation of respiratory illnesses (e.g., asthma) and cardiovascular diseases; cancers; other chronic conditions; and even premature death. [4-11]

IAQ suffers from a lack of regulations and standards [12] compared to outdoor air pollution. [13] If present, standards would guide adequately estimating exposure risk to air pollutants holistically and sustaining healthier indoor environments. Without proper regulations, assessing the impacts of IAQ on the health and comfort of building occupants can be challenging, potentially leading to prolonged exposure to harmful pollutants and adverse health effects. This is important for populations who may be more susceptible than others to poor IAQ, such as children, the elderly, communities of color, and low-income residents. [4, 14]

Communities of color and low-income neighborhoods are often burdened by poor access to safe and healthy homes, [15-18] and the unequal distribution of outdoor sources of pollution surrounding them. [19, 20] These factors can lead to significant disparities in IAQ and health status for these communities. Additionally, the behavior of impacted populations when indoors (e.g., occupant density, activities, indoor sources, etc.) can also contribute to disparities in IAQ. As a result, assessing IAQ to aid subsequent interventions to improve indoor conditions is crucial for reducing exposure risk to indoor air pollution in impacted communities.

References

1. Klepies et al. (*JESEE*, 2001)
2. Leech et al. (*JESEE*, 2002)
3. Mannan and Al-Ghamdi (*IJERPH*, 2021)
4. US EPA, *Introduction to Air Quality*
5. WHO, *Household Air Pollution*
6. Lee et al. (*Lancet Glob Health*, 2020)
7. Shupler et al. (*Lancet Planet Health*, 2020)
8. Apte and Salvi (*F1000Research*, 2016)
9. Smith et al. (*Annu. Rev. Public Health*, 2014)
10. Cheng et al. (*ERR*, 2021)
11. Allen et al. (*Environ. Health*, 2016)
12. Steinemann et al. (*Build. Environ.*, 2017)
13. Samet et al. (*NEJM*, 2017)
14. US EPA, *Research on Health Effects from Air Pollution*
15. Adamkiewicz et al. (*AJPH*, 2011)
16. Swope and Hernández (*Soc. Sci. Med.*, 2019)
17. Jacobs (*AJPH*, 2011)
18. US HHS, *The Surgeon General's Call to Action to Promote Healthy Homes*
19. Tessum et al. (*Sci. Adv.*, 2021)
20. Mohai et al. (*AJPH*, 2009)

1. Introduction

1.2. Indoor Sources of Pollution

Sources of indoor air pollution can significantly impact air quality, contributing to various health issues and occupant discomfort. Air pollution indoors is a complex mixture of chemicals present as gases or particles. Particle pollution is referred to as particulate matter (PM) with air quality measurements usually focusing on two size ranges – PM2.5 (fine particles; < 2.5 microns or µm in diameter) and PM10 (coarse particles; < 10 microns or µm in diameter) – due to their adverse health effects. [21] Gas pollution consists of multiple chemicals with varying air quality and health impacts. They include gases such as carbon monoxide (CO), nitrogen dioxide (NO2), ozone (O3), radon, and several volatile organic compounds (VOCs), e.g., benzene, formaldehyde (HCHO), some of which act as hazardous air pollutants or air toxics. [22]

Both gas-phase pollutants and PM are directly emitted or released into indoor environments from primary sources. These sources originate either indoors, as a result of occupant activities or the indoor living environment itself, or from outdoor pollution conditions (e.g., traffic, wildfires). [23, 24] In addition to direct emissions, indoor pollution also results from secondary sources such as chemical reactions of VOCs with oxidants to generate ultrafine particles and other pollutants. [24]

Common indoor sources that emit or release pollutants include building materials (e.g., paints, flooring, carpets, wiring, walls), furnishings, consumer products (e.g., printers, personal care products, cleaning products, food packaging), and biological contaminants (e.g., pests, pet dander, microbes, mold).

Occupant activities such as cooking, cleaning, smoking, use of gas appliances and fireplaces, and candle/incense burning also generate gases and particles indoors (Figure 1.2.1). Common indoor pollutants, their typical sources, and related health effects are shown in Table 1.2.1. [24-27]

Indoor sources of air pollution can be influenced by different factors in indoor environments. For instance, occupant activities and behaviors will determine the extent to which gas-phase pollutants and PM are emitted indoors, mediated by the duration and frequency of events. Poor ventilation can further worsen the concentrations of these pollutants for occupants. Environmental indoor conditions are also important since high temperature and high humidity (moisture) levels can increase the concentrations of some pollutants. This is often the case for mold and the infestation of pests (roaches, mice).
[18] Entry of outdoor air pollution indoors is influenced by building type and quality (e.g., insulation), natural/mechanical ventilation, and proximity to outdoor pollution sources (e.g., traffic and industrial facilities). Taken together, these factors indicate that indoor air pollution is complex, and with additional contributions from chemical and physical transformations of these pollutants, [24] it is essential to monitor IAQ for occupant comfort and well-being.

References

21. US EPA, *Indoor Particulate Matter*
22. US EPA, *Hazardous Air Pollutants*
23. US EPA, *Introduction to Indoor Air Quality*
24. NASEM 2022, *Why Indoor Chemistry Matters*
25. US EPA, *Indoor Pollutants and Sources*
26. CARB, *Indoor Air Pollution in California*
27. CARB, *Combustion Pollutants & Indoor Air Quality*

1. Introduction

1.2. Indoor Sources of Pollution

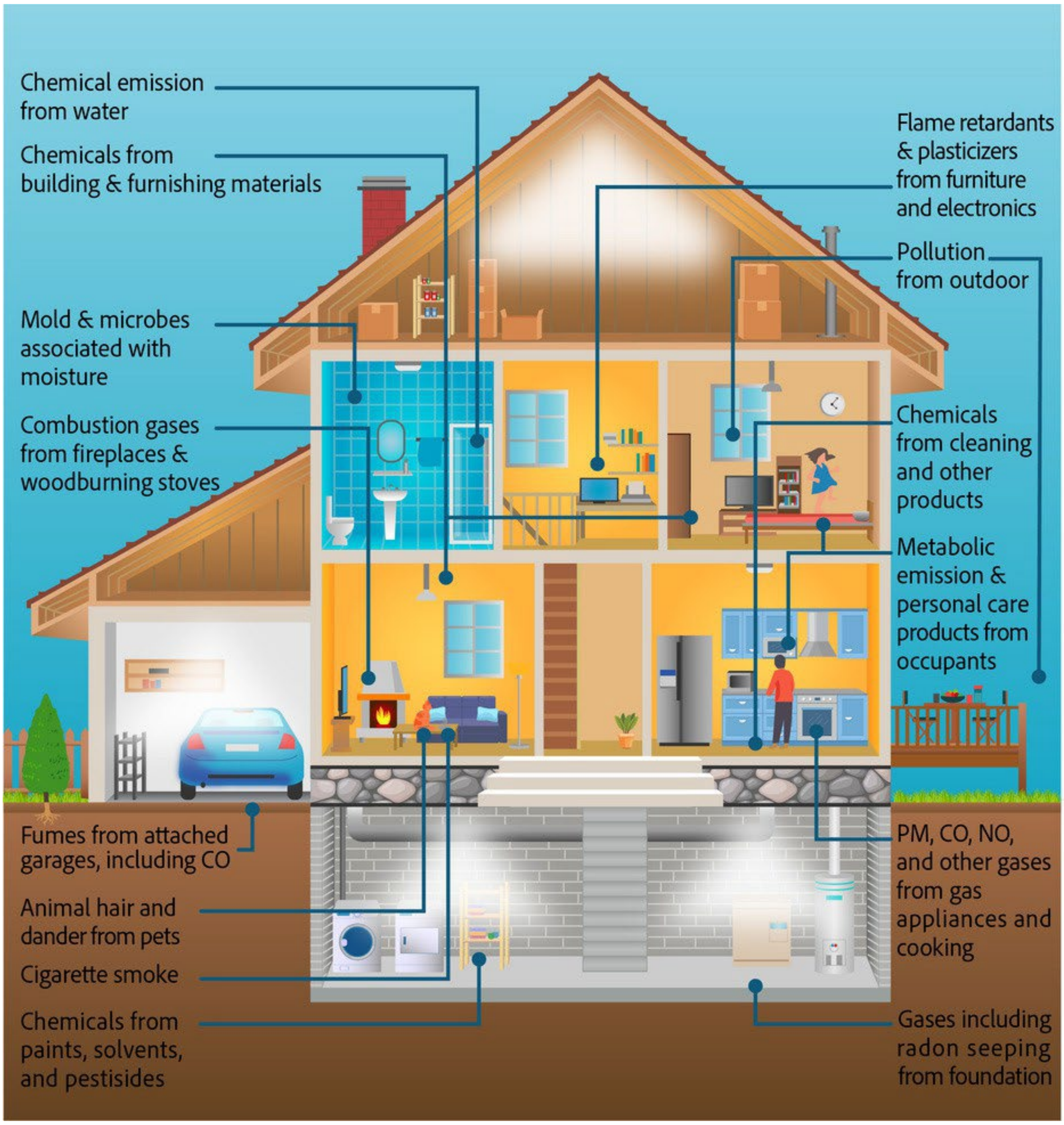

Figure 1.2.1. Chemical emission sources and reservoirs that impact the indoor environment.

Note: CO = carbon monoxide; NO_2 = nitrogen dioxide; PM = particulate matter.

Adapted from Figure 2-1; National Academies of Sciences, Engineering, and Medicine 2022 "Why Indoor Chemistry Matters." [24]

1.2. Indoor Sources of Pollution

Table 1.2.1. Sources and health effects of common indoor air pollutants. [24-27]

Pollutant	Description	Sources	Health Effects
Biological Agents	Fungi, bacteria, viruses, animal dander, house dust mites	House and floor dust, bedding, poorly maintained air conditioners, humidifiers, dehumidifiers, insect infestations, pets	Eye, nose, and throat irritation, allergic reactions, humidifier fever, influenza, other infectious diseases
CO	Colorless, odorless, tasteless gas	Malfunctioning gas appliances, improper use of gas stoves, wood burning, fireplaces, gas heaters, charcoal grills, idling cars in closed garages, outdoor air	Death, headache, fatigue, queasiness, poor vision and concentration, heart pains
NO_2	Colorless, tasteless gas; sharp odor	Gas stoves, malfunctioning gas appliances, wood burning, tobacco smoking, charcoal grills, outdoor air	Lung damage, lung disease, respiratory infections
O_3	Colorless gas, strong odor	Infiltration of outdoor air, electronic air cleaners, consumer products, home appliances	Lung inflammation, aggravated asthma, cough, wheeze, chest pain
PM	Small inhalable particles	PM2.5: Tobacco smoke, wood burning and fireplaces, incense and candle burning, hair styling tools, outdoor air (e.g., wildfires) PM10: vacuuming, house dust and re-suspension, paint chipping, skin flakes, polluted outdoor air	Eye, nose, and throat irritation, allergic reactions, bronchitis, respiratory and ear infections, emphysema, asthma, lung cancer
VOCs	Chemical gases	Cooking, smoking, pesticides, wood burning, building materials, paints, furnishings, office machines, cleaning products, air fresheners, dry-cleaned clothes, electronics, personal care products, outdoor air	Cancer, aggravated asthma, eye, nose, and throat irritation, decreased lung function, liver, brain, and kidney damage
Radon	Colorless, odorless, tasteless gas	Uranium-baring soil/foundation under buildings, groundwater, construction materials	Lung cancer

1.3. Improving the Indoor Environment

Outdoor air: As pollutants can easily be transported indoors from outside, simple measures such as cleaning or replacing the filters in air conditioners regularly help prevent particles from entering the indoor environment. [28] Using filters labeled "MERV 13" or higher and portable HEPA air cleaners are especially helpful for trapping particles and preventing indoor air pollution. In the event of a wildfire, all exterior doors and windows should remain closed, and the use of indoor combustion sources (e.g., candles, incense), house fans, and swamp coolers with outdoor air intakes should be avoided. Filtered air conditioners can remain on, but fresh air intake should be disabled to ensure that only the indoor air is recirculated and to prevent the introduction of wildfire emissions indoors. Moreover, in the aftermath of a wildfire, using a vacuum with a HEPA filter or misting the floor with water before sweeping gently with a broom or wet mop is recommended. People who don't have access to an air conditioner or purifier should wear N95 masks or they can choose to use a DIY air cleaner (e.g., single 20" × 20" × 1" MERV 13 electrostatic filter taped to a box fan) as a temporary alternative to commercial air cleaners [28, 29]

Indoor combustion: It is also important to make sure that combustion appliances (i.e., stoves, space heaters, clothes dryers) vent towards the outside and to always use them safely as they emit dangerous pollutants such as NO2, CO, and HCHO [30, 31]. Cooking, for example, especially at high temperatures emits harmful pollutants from heating ingredients such as oil and fats. Several steps can be taken to reduce these emissions: (1) turning on range hoods and setting the fans at the highest speed possible, (2) cooking on the back burners as range hoods exhaust these areas more efficiently, (3) using a wall or ceiling exhaust fan while cooking if there is no access to a range hood, (4) opening windows and exterior doors to improve airflow, (5) spacing out the frequency of cooking activities, shortening its duration, or switching between different types of cooking (e.g., boiling vs frying) [31]. It is important to also note that cooking is not the only source of air pollution in kitchens as ovens also emit high levels of pollutants during the self-cleaning process from the combustion of food waste.

Combustion appliances should be inspected annually and used safely to reduce indoor emissions [32]. Safety precautions include never using gas stoves as heat sources indoors as they cause air pollutants to accumulate, never using fuel-powered generators indoors, and using appliances such as charcoal grills outdoors only and away from all windows and doors. Additionally, it is recommended to use zero-emission cooking appliances such as induction or electric stoves, when possible.

Indoor products: Improving IAQ can also be achieved by minimizing the use of strongly scented versions of products such as pesticides, air fresheners, and household cleaning products. Products that have a pine or citrus scent can react chemically with O3 to form additional harmful pollutants. Other consumer products that are used for their stain- and water-repellent or non-stick properties should also be avoided when possible [30, 32]. Using mild soap and water for cleaning and integrated pest management methods are alternatives approved by the EPA [30].

1.3. Improving the Indoor Environment

Ventilating while painting, cleaning, and disinfecting is also recommended.

Other methods that help reduce indoor air pollution include: the use of bathroom exhaust fans while showering, restricting all forms of smoking indoors as well as away from doors and windows, and using dehumidifiers to control moisture and prevent mold. Using medium- or high-efficiency filters in HVAC systems, or using high-efficiency portable air cleaners if there is no access to a central system regularly is also recommended as it is in the case of wildfires and high outdoor pollution events [30, 32]. Additionally, buying furnishing and adhesive products that contain the Carpet and Rug Institute (CRI) Green Label Plus tag, and airing out new carpets and furniture outdoors for as long as possible also helps improve IAQ [32].

In addition to the strategies presented above, a review of published IAQ research findings synthesized similar practical approaches to improve IAQ for both individuals and supportive organizations or communities. [33] The review also assessed their effectiveness and cost-effectiveness. These strategies are summarized in Figure 1.3.1 and include both behavioral and physical interventions.

References

28. SCAQMD, Wildfire Health Information & Smoke Tips
29. US EPA, Wildfires and Indoor Air Quality (IAQ)
30. US EPA, Improving Your Indoor Environment
31. CARB, Indoor Air Pollution from Cooking
32. CARB, Reducing Your Exposure to Indoor Air Pollution
33. Tsoulou et al. (Indoor Air, 2021)

Resources for More Information

The Inside Story: A Guide to Indoor Air Quality, United States Environmental Protection Agency (EPA), last updated on June 16, 2024.

- Comprehensive article on indoor air quality concerns, major indoor air pollutants, and source-specific controls

https://www.epa.gov/indoor-air-quality-iaq/inside- story-guide-indoor-air-quality

Interventions to Improve

Indoors

Behavioral
Residents & Organizations

1) No indoor smoking, smoking education, including on the dangers of secondhand smoke
2) Decreased use of the gas stove, switch to zero- emission cooking appliances, or combined with increased ventilation and education
3) Reductions in cooking time and in frying of food or combined with increased ventilation and associated education
4) Decreased use of candles/incense or combined with increased ventilation
5) Changes in cleaning activities (use of HEPA filters, wet mopping over dry sweeping; in some cases, more frequent cleaning)
6) When pets are present, increased ventilation and more frequent cleaning
7) Increased/regular natural ventilation (window opening) or air cleaner/purifier

Physical
Organizations & Residents

8) Building design/operation of mechanical ventilation/air filtration
9) Implement weatherization practices (reduced air leaks, sealed windows/doors, insulation)
10) Improved cookstove quality (use of exhaust ventilation)
11) Avoidance of carpeted floors
12) No open fireplaces (design) or reduced use (operation)
13) Reduced gas stove use; switching from fuel burning for cooking and heating to cleaner means of cooking and heating, if possible

Outdoors

Physical
Organizations & Residents

14) Promote/retain/maintain tree canopy
15) Planting/maintenance of lower vegetation (shrubs and grass)
16) Construction of green roofs, green/living walls

Figure 1.3.1. Suggested strategies and actionable interventions to improve IAQ. Adapted from Figure 5, Tsoulou et al. (*Indoor Air, 2021*). [33]

1. Introduction

1.4. IAQ Monitoring with Low-Cost Sensors

Given the complexities of IAQ and increasing concern on its impacts on health, efforts to monitor IAQ have evolved over the years. Until recently, monitoring IAQ relied on conventional sampling and analysis, requiring expensive and bulky instruments in laboratory settings or onsite in indoor environments, where they could be disruptive (e.g., noisy). Additionally, these traditional methods often rely on sampling over long time periods (e.g., daily, weekly) to produce averaged pollutant level information, [34, 35] which is inadequate for providing real-time information on short-term changes in IAQ and peak concentrations during pollution events.

Due to these limitations, monitoring IAQ using low-cost air quality sensors emerged as a promising solution for identifying sources of pollution indoors in real time to facilitate effective mitigation and avoid the development of adverse health effects from inhalation. These low-cost sensors (LCS) have rapidly advanced and proliferated in recent years. [36, 37] Continuous research and improvement in the design of sensor components have resulted in the compact, lightweight, and inexpensive air quality assessment options we see today, [35] capable of detecting a range of pollutants, such as PM, VOCs, and CO2.

With the growing availability of LCS, it is now possible for individuals and communities to monitor IAQ more efficiently and at a low cost. This development has important implications for public health, as real-time data can prompt immediate actions to improve IAQ, thereby reducing the risk of respiratory and cardiovascular diseases, and other health issues associated with poor IAQ.

The ongoing advancements in sensor technology continue to enhance the precision and reliability of these devices, making them an essential tool in the effort to maintain healthier indoor environments. Their adoption for a variety of applications, from residential settings to schools, hospitals, and workplaces, is fostering greater public awareness about the importance of IAQ, encouraging individuals and communities to prioritize air quality as a key aspect of overall health and well- being.

LCS represent a leap forward in efforts to monitor and improve IAQ. Their ability to provide real-time data as well as affordability and accessibility make them a valuable tool for addressing IAQ challenges.

References

34. Rudel et al. (*ES&T*, 2010)
35. Kumar et al. (*Sci. Tot. Environ.*, 2016)
36. Chojer et al. (*Sci. Tot. Environ.*, 2020)
37. Sá et al. (*Environ. Technol. Innov.*, 2022)

2. Low-Cost Sensors (LCS)

2.1. LCS Basics and Components

LCS are integrated or packaged devices of hardware and software, including several components necessary to measure one or more air pollutants and/or environmental parameters. These devices also report the levels of measured pollutants through a readable output. LCS devices considered here are those that are commercially available and can be used straight "out of the box." LCS may also be referred to as air sensors, air quality sensors, air quality monitors, air quality detectors, or air pollutant monitors.

The sensing components within LCS devices physically or chemically interact with their target pollutant(s) and/or environmental parameter(s) to produce a signal. Most LCS also include other internal components: a microprocessor, communications chip (e.g., Wi-Fi, Bluetooth), and power source (see Figure 2.1.1). Air quality data from the sensing components of the LCS are sent to either a screen display or indicator on the device itself, or to cloud servers that store, process, and provide access to data through a website or application.

LCS are non-regulatory air pollutant technologies that are considered to provide informational monitoring (e.g., indoor hotspot detection, daily trends, and education) for end-users. These devices differ from regulatory monitors and reference-grade designations, which are the "gold standard" in air pollutant monitoring, according to the US EPA. [38] LCS are lower in cost, portable, low-power consuming, and quiet, with ease-of-use features compared to regulatory and reference-grade instruments. A comparison of the differences between low-cost air quality sensors and regulatory instruments is shown in Table 2.1.1. [38, 39]

The range of common indoor air pollutants measured within LCS often include PM (e.g., PM1, PM2.5, PM10), NOx, O3, CO, carbon dioxide (CO2), HCHO, VOCs, and radon. Environmental parameters like temperature and relative humidity are also commonly measured within LCS.

The detection of pollutants with LCS are typically translated into concentrations to describe pollutant levels in an environment. For indoor environments, it is important to understand that there are currently no widely accepted air concentration limits for most air pollutants. Therefore, indoor pollutant levels that trigger an alert for a potential air quality problem are typically determined by the LCS manufacturer. [38]

Generally, LCS manufacturers try to employ air quality index (AQI) limits for poor air quality conditions, pulling from US EPA's AQI reporting limits. [40] The EPA divides the AQI into six color-coded categories for air quality conditions: green (good), yellow (moderate), orange (unhealthy for sensitive groups), red (unhealthy), purple (very unhealthy), and maroon (hazardous). Ideally, all monitors would adopt the same AQI color scheme for direct comparison, but LCS manufacturers often use their own categories. [41] Nonetheless, if provided by the LCS, AQI information is valuable for end-users to alert them to IAQ issues and prompt remedial actions.

References

38. US EPA, *The Enhanced Air Sensor Guidebook*
39. Ródenas et al. (*Appl. Spectrosc. Rev.*, 2022)
40. US EPA, *U.S. Air Quality Index* (AQI)
41. Li et al. (*AAQR*, 2020)
42. SCAQMD, *Community in Action: A Comprehensive Guidebook on Air Quality Sensors*

2. Low-Cost Sensors (LCS)

2.1. LCS Basics and Components

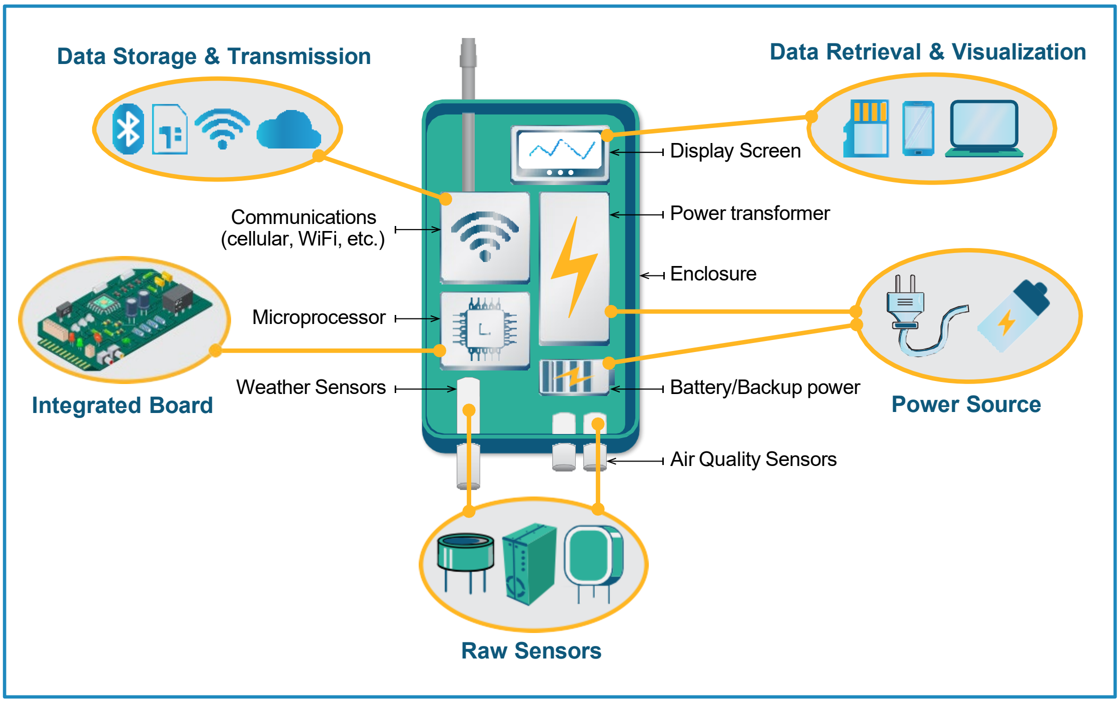

Figure 2.1.1. Basic LCS Components.

Adapted from Figure 1-1; EPA 2022 *"The Enhanced Air Sensor Guidebook."*[38]

Table 2.1.1. Comparison Between LCS and Regulatory Monitors.

Features	Low-Cost Sensors	Regulatory/Reference-Grade Instrument
Applications	Many (e.g., IAQ, personal monitoring, education, research)	Compliance with the National Ambient Air Quality Standards (NAAQS)
End-User	Anyone	Regulatory, Government, Researchers
Cost	$100 – $2,500	$15,000 – $40,000
Operation cost	Relatively inexpensive (routine maintenance, sensor replacement)	Expensive (shelter, technical staff, maintenance, repair, quality assurance)
Expertise/Training	Little to no training (user guide/manual)	Highly trained technical staff
Location	Portable or fixed (self-contained)	Fixed (infrastructure needed)
Area Coverage	High	Low
Data Quality and Selectivity	Variable, unknown, and may suffer from interferences	High, known, and stable
Data Accessibility	Real-time	Real-time (monitor) and offline (instruments)
Lifetime	1–3 years + drift	> 10 years

Adapted from US EPA "*The Enhanced Air Sensor Guidebook*"[38] and literature analysis [35-37, 39].

2. Low-Cost Sensors (LCS)

2.1. LCS Basics and Components

Resources for More Information

Low-Cost Air Pollution Monitors and Indoor Air Quality, United States Environmental Protection Agency (EPA), last updated January 3, 2024.

- Guidance article that aims to increase consumer understanding of the use, benefits, and limitations of low-cost indoor air monitors.

https://www.epa.gov/indoor-air-quality-iaq/low-cost- air-pollution-monitors-and-indoor-air-quality

Community in Action: A Comprehensive Guidebook on Air Quality Sensors, Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District (SCAQMD), September 2021.

- Guidebook for community planning that educates on the appropriate selection, use, and maintenance of air quality sensors; performance evaluations of commercially-available low-cost sensors; and data collection, interpretation, and communication.

https://www.aqmd.gov/aq-spec/special-projects/star- grant

The Enhanced Air Sensor Guidebook, Office of Research and Development, Center for Environmental Measurement and Modeling, United States Environmental Protection Agency (EPA), September 2022.

- Guidebook provides information on air quality and pollution monitoring, sensor selection for various applications; data analysis, interpretation, communication, and sensor performance.

https://www.epa.gov/air-sensor-toolbox/how-use-air- sensors-air-sensor-guidebook

Air Quality Sensors: Policy Options to Help Address Implementation Challenges, United States Government Accountability Office (GAO), March 2024.

- Report describing air quality monitor technologies, the benefits and uses of monitors; performance evaluations of monitors; limitations; and options for policymakers to address challenges.

https://www.gao.gov/products/gao-24-106393

Guidebook for Developing a Community Air Monitoring Network, Tracking California, October 2018.

- A guidebook educating on community engagement, sensor selection, quality control and assurance, site selection for monitor installation, data analysis and interpretation, and community monitoring network sustainability.

https://trackingcalifornia.org/images/uploads/imperia l-air-guidebook.pdf

Integrating Low-cost Sensor Systems and Networks to Enhance Air Quality Applications, World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), International Global Atmospheric Chemistry project (IGAC), June 2024

- This document is a resource for utilizing LCS data for air quality applications

https://library.wmo.int/records/item/68924-integrating-low-cost-sensor-systems-and-networks-to- enhance-air-quality-applications

2.2. Considerations for using LCS for IAQ Monitoring

LCS provides end-users interested in IAQ monitoring with a tool that facilitates enhancing overall health indoors. By using real-time data on indoor air pollutants, LCS users can improve IAQ and reduce potential exposure impacts. LCS affordability and ease of use have contributed to growing popularity among individuals, residents, communities, and the broader sensor user base. However, there are important considerations to keep in mind when deciding whether to purchase and utilize an LCS in indoor environments.

The best LCS choice will depend on one's specific needs, such as pollutants of concern, budget, and LCS features (e.g., portability). End-users should also be mindful of the limitations of LCS and proper usage practices to maximize benefits.

The state of LCS remains an emerging market, with current research [38] showing there are still improvements needed to enhance the accuracy and overall design of these devices. In particular, the cost of LCS reflects the number of sensing components included in the device as well as design and additional features such as display quality, power source, connectivity, data processing, and retrieval methods.

LCS cost does not necessarily indicate how well it will perform, as several factors affect LCS performance and data quality (see Chapter 3). Hence, when deciding to purchase a LCS, a balance between cost and other factors such as monitoring objectives and the pollutant(s) of interest should be considered. Table 2.2.1 outlines important questions and considerations to facilitate decision-making for acquiring LCS for IAQ monitoring.

After moving forward with purchasing a LCS, considerations for the deployment, setup, and maintenance of the device indoors should be adopted to maximize its effectiveness in maintaining a healthy indoor environment (see Table 2.2.2).

Understanding the information from LCS is also important for end-users who may be new to using LCS for IAQ monitoring. A key factor is the user's comfort level with technology. LCS users should gradually familiarize themselves with LCS applications and related software. If needed, LCS users can seek additional assistance from more technologically savvy individuals or available resources. These include user manuals of LCS, assistance from local air district staff, and LCS guidance from air quality agencies like the EPA (see Table 2.2.3). Utilizing these resources will enhance understanding and interpretation of LCS data.

End-users should also be adept at identifying trends and patterns in LCS data to understand changes in IAQ over time due to their activities and other environmental factors indoors. LCS apps or device displays may also provide explanations (e.g., AQI) and health recommendations based on the detected air quality conditions. Utilizing these features, if available, along with understanding air pollutant readings and acceptable air quality thresholds, will encourage informed and corrective actions when LCS indicates poor air quality indoors. For example, suppose the LCS detects high levels of PM2.5 during cooking. In that case, end-users might consider operating the rangehood above the cooking source, opening windows for better ventilation, using an air purifier, or shortening the cooking duration to improve IAQ.

2.2. Considerations for using LCS for IAQ Monitoring

Table 2.2.1. Questions and Considerations for Buying LCS for IAQ Monitoring.

Question	Consideration
What is the purpose?	• Education and information • IAQ Hotspot identification • Personal exposure and health • Participatory science
What pollutant(s) do you want to measure indoors?	• Particulate matter (e.g., PM2.5, PM10) • Gases (e.g., O_3, NOx, VOCs)
How much do LCS typically cost and what aligns with your budget?	• $75 – $500 (1 pollutant) • $500 – $1,500 (1-2 pollutants) • > $1,500 (3 or more pollutants)
What are some of the features you should consider?	• Ease of use and setup (e.g., plug and play) • Size, weight, and portability • Performance in the real-world (e.g., response time) • Power source and connectivity • Storage capacity and data accessibility • Maintenance requirements and cost • Expected manufacturer lifetime of LCS
How can you check the performance of your LCS?	• Conduct periodic quality control checks (e.g., timely signal detection from pollution events, firmware and software updates for optimal performance) • Compare results to a nearby regulatory monitor or other LCS in network Periodically review and evaluate data for errors or problems • Check environmental conditions that may impact performance (e.g., high humidity or moisture indoors)
What should you look for in a user manual?	• Type of pollutants measured and detection range • General operating instructions • How to store and recover data conditions of operation • Expected performance • Customer service support

Analysis of EPA's *The Enhanced Air Sensor Guidebook* [38] (Chapter 3, Section 3.4 and Appendix C1-C3); SCAQMD's Community in Action: A Comprehensive Guidebook on Air Quality Sensors [42] (Chapter 2, pages 20-21); literature [35-37, 39].

2. Low-Cost Sensors (LCS)

2.1. Considerations for Using LCS for IAQ Monitoring

Table 2.2.2. Additional Considerations after Buying LCS for IAQ Monitoring.

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

2.2. Considerations for using LCS for IAQ Monitoring

Table 2.2.3. Data Handling and Interpretation Resources.

Method	Resources
Use Available Resources	• Refer to user manuals, guidance documents, and best practices from LCS manufacturers, environmental agencies, public health organizations, and research experts. • Explore publicly available resources for LCS information and data interpretation, such as EPA's Air Sensor Toolbox and SCAQMD's AQ-SPEC.
Collaborate with Air Quality Agencies & Regulatory Bodies	• Contact your local air district for support on LCS data collection, validation, and interpretation. • Seek assistance from agency staff and agency-funded technical assistance centers for LCS technical support.
Leverage Academic Resources	• Collaborate with local universities, environmental research centers, or student-led initiatives for technical support.
Seek Community Support	• Engage with community-led air monitoring projects that guide data handling and LCS air quality interpretation. • Consult other local technical and community experts for assistance in data handling and interpretation. • Seek out other community-driven resources focused on LCS monitoring.
Hire Professional Support	• Engage a qualified contractor or consultant to analyze and interpret LCS monitoring data.

2.3. Commercially Available LCS for IAQ Monitoring

LCS continue to evolve as an emerging technology, [35, 36, 39] with manufacturers contributing their various integrated devices to the market. This expanding LCS market offers a wide range of LCS options for consumers based on their specific needs and applications. Some LCS devices are ruggedly designed with protective covers for outdoor pollution measurements in cities. Others can be used both indoors and outdoors, or are specifically tailored for IAQ monitoring. As IAQ influences our overall health, LCS designed for indoor conditions are optimal for IAQ monitoring.

To conduct an extensive market survey of LCS for IAQ monitoring, various sources were used. These include: guidance from the EPA [37] and the South Coast Air Quality Management District (SCAQMD) Air Quality Sensor Performance Evaluation Center (AQ-SPEC) [41], and information from relevant research studies, air quality forums, and popular internet marketplaces.

This market survey resulted in a total of 72 commercially-available LCS devices from 31 different manufacturers. These devices provide real-time or near real-time measurements of air pollutants and are categorized into single- and multi-pollutant LCS. Single-pollutant LCS devices are priced at ≤ \$500, while multi-pollutant LCS devices are ≤ \$2500.

Tables 2.3.1 and 2.3.2 include information on the manufacturer, model, unit price, pollutants measured, power needs, data access, and data storage of the 30 single-pollutant and 42 multi-pollutant LCS devices surveyed. *All included LCS information is accurate as of June 2024 and is subject to change at any time.*

Resources for More Information

Air Sensor Toolbox, United States Environmental Protection Agency (EPA)
https://www.epa.gov/air-sensor-toolbox

US EPA, Air Sensor Technology and IAQ, United States Environmental Protection Agency (EPA)
https://www.epa.gov/indoor-air-quality-iaq/air- sensor-technology-and-indoor-air-quality

Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District
http://www.aqmd.gov/aq-spec

Table 2.3.1. Specifications of **single**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
AirValent	Wireless CO_2 Monitor	$190	CO_2	Battery (rechargeable)	Mobile app; Internal storage	Display; Mobile app
Applied Particle Technology	Minima		PM1; PM2.5; PM10	Battery (rechargeable)	Cloud	Website
Davis Instruments	AirLink	$215	PM1; PM2.5; PM10	Electrical outlet	Cloud	Website; Mobile app
Dylos Corporation	DC1100	$199.99	Particles (>1 μm; >5 μm)	Electrical outlet	Device (30 days)	Display
	DC1100-PC	$239.99				Display; Serial output
	DC1100 Pro	$260.99	Particles (> 0.5 μm; >2.5 μm)			Display
	DC1100 Pro-PC	$289.99				Display; Serial output
	DC1700 Battery	$425		Electrical outlet; Battery (rechargeable)	Device (10,000 samples)	Display
	DC1700-PM	$475	PM2.5; PM10; Particles (>0.5 μm; >2.5 μm)			Display; Serial output

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

Table 2.3.1 (cont'd). Specifications of **single**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Ecowitt	WH41	$71.99	PM2.5	Battery (rechargeable)	Mobile app	Website; Mobile app
	WH43	$65.99		Electrical outlet; Battery (replaceable)	Mobile app	Website; Mobiel app
Elitech	Temtop P600	$65.99	$PM_{2.5}$; PM10	Battery (rechargeable)	Device	Display
	Temtop P100	$159.99			Mobile app	Display; Mobile app
Eve	Eve Room	$99.95	VOCs	Battery (rechargeable)	Cloud	Display; Mobile app
HabitatMap	AirBeam3	$249	PM2.5; PM10	Electrical outlet; Battery (rechargeable)	Cloud; SD card	Website; Mobile app; Serial output
InkBird	IAM-T1 CO_2 Monitor	$129.99	CO_2	Battery (replaceable)	Mobile app; Internal storage	Display
Netatmo	Smart IAQ Monitor	$119.99	CO_2	Electrical outlet	Cloud	Mobile app
SAF Tehnika	Aranet4	$249	CO_2	Battery (replaceable)	Mobile app; Internal storage	Display; Mobile app
SmartAir	CO_2 Monitor	$69.99	CO_2	Battery (rechargeable)	Cloud; Internal storage	Display: Mobile app

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

Table 2.3.1 (cont'd). Specifications of **single**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
TSI	BlueSky 8413		PM2.5; PM10	Electrical outlet	Cloud; SD card	Website; SD export
Piera Systems	Canaree A1	\$219	PM0.1 - PM10	Electrical outlet	Cloud	Indicator; Website
	Canaree I1	\$269				
Purple Air	PA-II w/ SD	\$259	PM1; PM2.5; PM10	Electrical outlet	Cloud	Website & API
	PA-II (classic)	\$229			Cloud; SD card	Website & API; SD card
	PA-II-Flex	\$289				
	Zen	\$299				Display; Website & API; SD export
	Touch (PA-I)	\$209			Cloud	
uRADMonitor	SMOOGIE-PM	\$199	PM1; PM2.5; PM10	Electrical Outlet	Cloud	Website & API; Local access LAN
	SMOOGIE-CO_2	\$199	CO_2			Display; Website & API: Local access LAN
	SMOOGIE-Gas	\$389	CO; NO_2; O_3; SO_2; H_2S			Website & API: Local access LAN

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

Table 2.3.2. Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Aethair	Aethair IAQ		PM1; PM2.5; PM10; CO_2; HCHO; TVOC	Electrical outlet	Cloud	Website; Mobile app
Air Gradient	AirGradient ONE	$195	PM1; PM2.5; PM10; CO_2; NOx; TVOC	Electrical outlet	Cloud	Display; Website & API
AirThings	View Plus	$299	PM2.5; CO2; VOC	Electrical outlet; Battery (replaceable)	Cloud	Display; Website; Mobile app
	Wave Plus	$229.99	CO_2; TVOC	Battery (replaceable)		
air-Q	Light	$280	CO_2; VOC	Electrical outlet	Cloud; SD card	Website; Mobile App; SD export

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
air-Q	Basic	$380	PM1; PM2.5; PM10; CO_2; CO; VOC	Electrical outlet	Cloud; SD card	Website; Mobile App; SD export
	Pro	$565	PM1; PM2.5; PM10; CO_2; CO; O_3; NO_2; H_2S; VOC; O_2			
Amazon	Smart Air Quality Monitor	$69.99	PM2.5; CO; VOC	Electrical outlet	Cloud	Indicator; Mobile app
Atmotech Inc.	Atmotube PRO	$189	PM1; PM2.5; PM10; VOC	Battery (rechargeable)	Cloud; Internal storage	Mobile app; Cloud API; Bluetooth API

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Atmotech Inc.	Atmocube		PM1; PM2.5; PM4; PM10; CO_2; HCHO; NOx; VOC	Electrical outlet	Cloud; Internal storage	Display; Mobile app; Website
Awair	Element	$209	PM2.5; CO_2; TVOC	Electrical outlet	Mobile app	Display; Mobile app
	Omni	$399		Electrical outlet; Battery (rechargeable)	Mobile app; Internal memory	Display; Mobile app; Website
Ecowitt	WH45	$159.99	PM2.5; PM10; CO_2	Electrical outlet; Battery (replaceable)	Cloud	Website; Mobile App
Edimax	AI-2002W	$199	PM2.5; PM10; CO_2; HCHO; TVOC	Electrical outlet	Cloud	Display; Website; Mobile app

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Edimax	AI-2004W	$199	PM2.5; PM10; CO_2; CO; HCHO; TVOC	Electrical outlet	Cloud	Display; Website; Mobile app
Elitech	Temtop M10	$95.99	PM2.5; HCHO; TVOC	Battery (rechargeable)	Device	Display
	Temtop M10i	$119.99			Mobile app	Display; Mobile app
	Temtop M100	$189.99	PM2.5; PM10; CO_2;			
	Temtop P1000	$99.99			Device	Display
	Temtop M2000 2nd gen	$159.99	PM2.5; PM10; CO_2; HCHO			Display; SD export
	Temtop M2000C 2nd gen	$165.99	PM2.5; PM10; CO_2;			

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Elitech	Temtop LKC-1000E	$109.99	PM2.5; PM10; HCHO	Battery (rechargeable)	Device	Display
	Temtop LKC-1000S+ 2nd gen	$179.99	PM2.5; PM10; HCHO; TVOC			Display; SD export
Ikea	Vindstyrka	$49.99	PM2.5; TVOC	Electrical outlet	Mobile app	Display
IQAir	AirVisual Pro	$299	PM2.5; CO_2	Electrical outlet	Cloud	Display; Mobile app; Website
	AirVisual Outdoor	$299	PM1; PM2.5; PM10; CO_2	Electrical outlet; Battery (rechargeable)		Indicator; Mobile app; Website

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Kaiterra	Sensedge		PM2.5; CO_2; TVOC	Electric outlet; Battery (rechargeable)	Cloud; Internal storage	Display; Website
	Sensedge Mini		PM1; CO_2; TVOC; O3	Electrical outlet	Cloud; Internal memory	Website; Serial output
	Sensedge Mini Outdoor		PM2.5; CO_2			
NuWave Sensors	AirSentric	$683	PM1; PM2.5; PM4; PM10; CO_2; TVOC	Electrical outlet	Cloud	Website; Mobile app
Piera Systems	Canaree I5	$349	PM; TVOC; CO_2	Electrical outlet	Cloud	Indicator; Website

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
Qingping	Air Monitor Gen 2	$149	PM2.5; PM10; CO_2; TVOC	Electrical outlet; Battery (rechargeable)	Cloud; Device	Display; Mobile app
	Air Monitor Lite	$76	PM2.5; PM10; CO_2		Cloud; Mobile app	
	CO2 Monitor	$69.99	CO_2		Cloud; Internal storage	Display; Mobile app; Website
TSI	Blue Sky 8145		PM2.5; PM10; CO_2; CO; O_3; NO_2; SO_2	Electric outlet	Cloud; SD card	Website; SD export
	AirAssure 8144-2		PM; CO_2; TVOC			

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
TSI	AirAssure 8144-4		PM; CO_2; CO; VOC; HCHO	Electric outlet	Cloud; SD card	Website; SD export
	AirAssure 8144-6		PM; CO_2; CO; O_3; NO_2; SO_2; VOC			
uHoo	Smart Air Monitor	$299	PM2.5; CO_2; CO; NO_2; VOC; O_3	Electrical outlet	Cloud	Mobile app

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

Table 2.3.2 (cont'd). Specifications of **multi**-pollutant LCS for IAQ monitoring.

Manufacturer	Model	Unit Price	Pollutant(s)	Power Source	Data Storage	Data Visualization & Retrieval
uRADMonitor	Model A3	$589	PM1; PM2.5; CO_2; O_3; VOC; HCHO	Electrical outlet	Cloud	Website & API; Local access LAN
	Model A4	$440	PM1; PM2.5; CO_2; CO; O_3; NO_2; VOC; HCHO			
Wicked Device	Air Quality Egg Indoor/Outdoor	$650 (base)	PM1; PM2.5; PM10; CO_2; CO; O_3; NO_2; SO_2; H_2S; VOC	Electrical outlet	Cloud; Internal Storage	Website; Mobiel app; SD export

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

3. LCS Performance

3.1. Factors Affecting LCS Performance

The selection of LCS for individuals and other stakeholders depends on the project's objectives. It requires balancing data quality and performance with cost, operation, and maintenance needs. In some cases, an LCS that provides trends or qualitative data (e.g., indicating high or low concentrations) may be sufficient for informing and educating non-technical end users about IAQ. However, such LCS would be inadequate for applications requiring highly quantitative and precise measurements, such as research field deployments supplementing regulatory measurements.

LCS manufacturers often market their devices as calibrated and ready to use "out of the box," promising accurate readings. However, they frequently do not provide detailed information on their calibration processes, algorithms, and reference instruments used. This lack of transparency makes it challenging for end users to determine which LCS offers reasonable reliability and accuracy for specific pollutants, balanced with costs and other considerations. Therefore, independent assessments of these devices are needed.

The performance of LCS devices depends on several internal and external factors influencing the reliability and accuracy of air quality measurements, unlike regulatory or reference monitors. These factors include the target pollutant and underlying measurement technology, the quality and design of sensor hardware components, environmental conditions, and methods of operation. [38, 39, 42] Explanation of these common performance factors influencing LCS is illustrated in Table 3.1.1.

Resources for More Information

Community in Action: A Comprehensive Guidebook on Air Quality Sensors, Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District (SCAQMD), September 2021.
https://www.aqmd.gov/aq-spec/special-projects/star-grant

The Enhanced Air Sensor Guidebook, Office of Research and Development, Center for Environmental Measurement and Modeling, United States Environmental Protection Agency (EPA), September 2022.
https://www.epa.gov/air-sensor-toolbox/how-use-air- sensors-air-sensor-guidebook

Air Quality Sensors: Policy Options to Help Address Implementation Challenges, United States Government Accountability Office (GAO), March 2024.
https://www.gao.gov/products/gao-24-106393

Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District
http://www.aqmd.gov/aq-spec

3. LCS Performance

3.1. Factors Affecting LCS Performance

Table 3.1.1. Factors that affect LCS performance.

Category	**Factor**
Target pollutant(s) and Technology	PM Sensors • More reliable for PM2.5 (e.g., smoking) • Most cannot reliably measure PM10 (e.g., dust) • Current technology cannot measure smaller particles (< 0.3 μm) • Sensitive to particle size, composition, and hygroscopicity • PM build up in sensor over time can change performance • No measurement of particle chemical composition Gas Sensors • Performance depends on manufacturer and pollutant gases • Responds to non-target pollutants and environmental parameters • Signal readings in the absence of target pollutant (i.e., cross-sensitivity) • Sensors may lose sensitivity over time and are subject to drift
Quality and Design of Sensor Hardware	• Ruggedness of sensor enclosure for protecting internal components from external and environmental conditions • Placement of the sensing component inside the LCS device and the efficiency of the target pollutant reaching it (e.g., air flow placement for PM LCS)
Environmental Conditions and Calibrations	• Environment concentrations of the target pollutant must match LCS capabilities and sensitivities • In indoor conditions, LCS may be consistently overloaded if high pollution events occur frequently and cause drift or aging of the LCS • Manufacturer calibration of LCS may use pollutant sources (e.g., aerosol type) different from target monitoring needs, thus, this may potentially affect measurements when deployed
Operation	• Sitting or placement of the LCS in an adequate location is best for optimal performance (e.g., mounted) • Routine or preventative maintenance of LCS (e.g., cleaning, sensor replacements) • Data transmission (e.g., stable wireless connection)

3. LCS Performance

3.2. AQ-SPEC Performance Evaluations for LCS

SCAQMD established AQ-SPEC to evaluate 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 is frequently consulted for information on the accuracy and reliability of LCS on the market.

AQ-SPEC performs the most systematic and extensive evaluations of LCS in both field and laboratory settings using carefully developed protocols and procedures. In the field, manufacturer-calibrated LCS are evaluated in triplicate (3 units) alongside regulatory or reference-grade instruments over approximately two months in outdoor Southern California conditions. If the LCS performs well in the field, they are subsequently evaluated in the laboratory under controlled environmental conditions in specialized chambers.

AQ-SPEC uses several metrics to report LCS performance. Single- and multi-pollutant LCS evaluated by AQ-SPEC are summarized in Tables 3.2.1 and 3.2.2, including the year of evaluation, coefficient of determination (R^2), mean absolute error (MAE), and the intra-model variability.

The year of evaluation is important as LCS manufacturers consistently change or improve their devices, releasing newer generations or models every few years. The R2 value indicates how well a LCS agrees with reference measurements. An R^2 close to 1 shows that there is a good agreement between the evaluated LCS and reference instruments. An R2 closer to 0 indicates poor performance of the LCS for air quality measurements compared to the reference instrument used.

MAE shows how much the actual pollutant concentrations are different between a LCS and a reference instrument. MAEs closer to 0 indicate that the LCS has measurements similar to the actual (true) concentration of the pollutants being measured by the reference instrument.

Intra-model variability represents how consistent measurements are under the same conditions for different units of the same LCS model. Low intra-model variability indicates similar performance across units, reflecting reliability and good quality control from manufacturers. High intra-model variability shows the opposite with different units of the same LCS having significant measurement differences. Lower intra-model variability is preferable, as it ensures users can trust the LCS performance regardless of the specific unit they receive.

Resources for More Information

Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District
http://www.aqmd.gov/aq-spec

AQ-SPEC Field Testing Protocol, South Coast Air Quality Management District, January 2017
https://www.aqmd.gov/docs/default-source/aq- spec/protocols/sensors-field-testing-protocol.pdf? sfvrsn=0

AQ-SPEC Laboratory Testing Protocol, South Coast Air Quality Management District, August 2016
https://www.aqmd.gov/docs/default-source/aq- spec/protocols/sensors-lab-testing-protocol6087afefc2b66f27bf6fff00004a91a9.pdf

Table 3.2.1. AQ-SPEC performance evaluations for single-pollutant LCS.

Manufacturer	**Model**	**Year of Evaluation**	**Setting**	**Pollutant(s)**	**R^2**	**MAE (μg/m³)**	Intramodel Variability
Applied Particle Technology	Minima	2020	Ambient	PM1	0.83-0.90	5.0-5.6	Low
				PM2.5	0.86-0.89	5.8-6.5	
				PM10	0.36-0.38	39.4-40.3	
			Chamber	PM2.5	> 0.99	5.0-8.1	
Davis Instruments	AirLink	2021	Ambient	PM1	0.85-0.89	2.2-2.8	Low
				PM2.5	0.73-0.81	4.9-5.9	
				PM10	0.24-0.31	12.1-26.0	
			Chamber	PM2.5	> 0.99	4.3-6.6	
Dylos Corporation	DC1100 Pro-PC	2014-2015	Ambient	PM0.5-PM2.5	0.81	4.2	Low
	DC1700 Battery		Chamber		0.89		
	DC1700-PM	2018	Ambient	PM2.5	0.58-0.68	24.3-28.5	
				PM10	0.15-0.18	43.9-53.8	
			Chamber	PM2.5	> 0.95	198.3-209.4	
Ecowitt	WH41	2019	Ambient	PM2.5	0.33-0.52	8.2-15.4	Low

Table 3.2.1 (cont'd). AQ-SPEC performance evaluations for single-pollutant LCS.

Manufacturer	Model	Year of Evaluation	Setting	Pollutant(s)	R^2	MAE (µg/m³)	Intramodel Variability
Habitat Map	AirBeam3	2022	Ambient	PM1	0.94-0.97	1.3-2.6	Moderate
				PM2.5	0.80-0.91	3.6-5.3	
				PM10	0.19-0.26	20.4-26.8	
			Chamber	PM1	> 0.99	1.5-5.7	
				PM2.5		2.6-11.6	
Purple Air	PA-II (classic)	2016	Ambient	PM1	0.86-0.98		Low
				PM2.5	0.90-0.98		
				PM10	0.66-0.70		
			Chamber	PM1	> 0.99	11.7-15.9	
				PM2.5		1.7-4.2	
				PM10	0.94	15.6-20.5	
	PA-II-Flex	2022	Ambient	PM1	0.90-0.94	1.4-2.2	
				PM2.5	0.77-0.89	3.4-3.8	
				PM10	0.21-0.39	15.3-24.8	
			Chamber	PM1	> 0.99	13.5-14.6	
				PM2.5		1.7-2.2	

Table 3.2.1 (cont'd). AQ-SPEC performance evaluations for single-pollutant LCS.

Manufacturer	Model	Year of Evaluation	Setting	Pollutant(s)	R^2	MAE (µg/m³)	Intramodel Variability
Purple Air	Touch (PA-I)	2018	Ambient	PM2.5	0.75-0.76		Low
				PM10	0.36-0.46		
			Chamber	PM1	> 0.99	5.1-9.5	
				PM2.5		18.7-27.7	
				PM10	0.97	4.4-20.4	
TSI	BlueSky 8413	2020	Ambient	PM2.5	0.65-0.76	4.9-5.9	Moderate
				PM10	0.09-0.21	22.7-26.3	
			Chamber	PM2.5	>0.99	31.-6.2	
uRADMonitor	SMOOGIE-PM	2020	Ambient	PM1	0.83-0.85	4.8-5.6	Low
				PM2.5	0.60-0.81	2.1-2.8	
				PM10	0.02-0.06	17.5-25.2	
			Chamber	PM1	> 0.99	25.3-26.8	
				PM2.5		19.5-22.9	

Table 3.2.2. AQ-SPEC performance evaluations for **multi**-pollutant LCS.

Manufacturer	Model	Year of Evaluation	Setting	Pollutant(s)	R^2	MAE (µg/m³)	Intramodel Variability
Aethair (formerly AirThinx)	Aethair IAQ	2018	Ambient	PM1	0.68-0.71	2.4-2.5	Low
				PM2.5	0.54-0.57	4.8-5.0	
				PM10	0.04-0.05	19.7-19.8	
Atmotech Inc.	Atmotube PRO	2020	Ambient	PM1	0.90-0.93	3.6-4.6	Low
				PM2.5	0.88	4.9-5.9	
				PM10	0.22	20.9-22.9	
			Chamber	PM1	> 0.99	1.9-6.4	Low to moderate
				PM2.5		2.9-3.8	
Edimax	AI-2002W	2018	Ambient	PM2.5	0.82-0.83	3.3-4.4	Low
Elitech	Temtop M2000 2nd gen	2020	Ambient	PM2.5	0.77-0.82	2.1-3.2	Low
				PM10	0.18-0.28	12.1-14.1	
			Chamber	PM2.5	> 0.99	13.3-21.5	
	Temtop LKC-1000S+ 2nd gen	2020	Ambient	PM2.5	0.91-0.92	3.1-3.6	
				PM10	0.31-0.35	11.7-17.9	
			Chamber	PM2.5	> 0.99	11.1-21.9	

Table 3.2.2 (cont'd). AQ-SPEC performance evaluations for **multi**-pollutant LCS.

Manufacturer	Model	Year of Evaluation	Setting	Pollutant(s)	R^2	MAE (µg/m³)	Intramodel Variability
IQAir	AirVisual Pro	2018	Ambient	PM2.5	0.63-0.81	3.5-5.5	Low
			Chamber		0.99	1.8-10.8	
	AirVisual Outdoor	2022	Ambient	PM1	0.52-0.65	4.5-5.6	
				PM2.5	0.53-0.65	4.4-6.0	
				PM10	0.38-0.61	105-14.4	
Qingping	Air Monitor Gen 2	2022-2023	Ambient	PM2.5	0.86-0.91	1.8-2.3	Low
	Air Monitor Lite	2022-2023		PM2.5	0.84-0.93	1.8-3.6	
				PM10	0.36-0.43	16.2-20.1	
TSI	AirAssure	2015-2016	Ambient	PM2.5	0.81-0.83		Low
			Chamber		> 0.99	32.4-55.0	Moderate to high
uHOO	Smart Air Monitor	2017	Ambient	PM2.5	< 0.01	9.5-17.8	High
				CO	0.0	3.6 ppm*	
				O_3	0.43-0.72	14.5-66.8 ppb*	

* Different units for gas pollutants MAE

Table 3.2.2 (cont'd). AQ-SPEC performance evaluations for **multi**-pollutant LCS.

Manufacturer	Model	Year of Evaluation	Setting	Pollutant(s)	R^2	MAE (µg/m³)	Intramodel Variability
uRADMonitor	Model A3	2018-2019	Ambient	PM1	0.81-0.85	4.0-5.2	Moderate
				PM2.5	0.70-0.84	5.2-8.9	
				PM10	0.15-0.41	20.3-29.1	
Wicked Device	Air Quality Egg Indoor	2016	Ambient	PM2.5	0.42-0.84		Low
				PM10	0.10-0.36		
	Air Quality Egg Indoor	2021-2022	Ambient	PM1	0.84-0.89	2.9-3.9	
				PM2.5	0.87-0.90	6.0-7.1	
				PM10	0.29-0.53	18.5-20.8	
				CO	0.60-0.79	0.15-0.21 ppm*	
				O_3	0.20-0.51	13.2-18.0 ppb*	
				NO_2	0.38-0.56	20.8-32.0 ppb*	
	Air Quality Egg Indoor	2021-2022	Chamber	PM2.5	> 0.99	5.0-8.0	
				O_3	> 0.98	4.7-21.0 ppb*	
				NO_2	0.99	5.5-61.8 ppb*	High

* Different units for gas pollutants MAE

4. References

4.1. Main Text

1. Klepeis, N. E.; Nelson, W. C.; Ott, W. R.; Robinson, J. P.; Tsang, A. M.; Switzer, P.; Behar, J. V.; Hern, S. C.; Engelmann, W. H. The National Human Activity Pattern Survey (NHAPS): A Resource for Assessing Exposure to Environmental Pollutants. Journal of Exposure Science & Environmental Epidemiology 2001, 11, 231–252. https://doi.org/10.1038/sj.jea.7500165.

2. Leech, J. A.; Nelson, W. C.; Burnett, R. T.; Aaron, S.; Raizenne, M. E. It's about Time: A Comparison of Canadian and American Time–Activity Patterns. *Journal of Exposure Science & Environmental Epidemiology* 2002, *12*, 427–432. https://doi.org/10.1038/sj.jea.7500244.

3. Mannan, M.; Al-Ghamdi, S. G. Indoor Air Quality in Buildings: A Comprehensive Review on the Factors Influencing Air Pollution in Residential and Commercial Structure. *International Journal of Environmental Research and Public Health* 2021, *18*, 3276. https://doi.org/10.3390/ijerph18063276.

4. U.S. Environmental Protection Agency. Introduction to Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality (accessed 2024-07-08).

5. World Health Organization. Household air pollution. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health (accessed 2024-07-08).

6. Lee, K. K.; Bing, R.; Kiang, J.; Bashir, S.; Spath, N.; Stelzle, D.; Mortimer, K.; Bularga, A.; Doudesis, D.; Joshi, S. S.; et al. Adverse Health Effects Associated with Household Air Pollution: A Systematic Review, Meta-Analysis, and Burden Estimation Study. The Lancet Global Health 2020, 8, e1427–e1434. https://doi.org/10.1016/S2214-109X(20)30343-0.

7. Shupler, M.; Hystad, P.; Birch, A.; Miller-Lionberg, D.; Jeronimo, M.; Arku, R. E.; Chu, Y. L.; Mushtaha, M.; Heenan, L.; Rangarajan, S.; et al. Household and Personal Air Pollution Exposure Measurements from 120 Communities in Eight Countries: Results from the PURE-AIR Study. The Lancet Planetary Health 2020, 4, e451–e462. https://doi.org/10.1016/S2542-5196(20)30197-2.

8. Apte, K.; Salvi, S. Household Air Pollution and Its Effects on Health. F1000Research 2016, 5, F1000 Faculty Rev-2593. https://doi.org/10.12688/f1000research.7552.1.

9. Smith, K. R.; Bruce, N.; Balakrishnan, K.; Adair-Rohani, H.; Balmes, J.; Chafe, Z.; Dherani, M.; Hosgood, H. D.; Mehta, S.; Pope, D.; Rehfuess, E. Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. Annual Review of Public Health 2014, 35, 185–206. https://doi.org/10.1146/annurev-publhealth-032013-182356.

10. Cheng, E. S.; Egger, S.; Hughes, S.; Weber, M.; Steinberg, J.; Rahman, B.; Worth, H.; Ruano-Ravina, A.; Rawstorne, P.; Yu, X. Q. Systematic Review and Meta-Analysis of Residential Radon and Lung Cancer in Never-Smokers. European Respiratory Review 2021, 30. https://doi.org/10.1183/16000617.0230- 2020.

11. Allen, J. G.; Gale, S.; Zoeller, R. T.; Spengler, J. D.; Birnbaum, L.; McNeely, E. PBDE Flame Retardants, Thyroid Disease, and Menopausal Status in U.S. Women. Environmental Health 2016, 15, 60. https://doi.org/10.1186/s12940-016-0141-0.

12. Steinemann, A.; Wargocki, P.; Rismanchi, B. Ten Questions Concerning Green Buildings and Indoor Air Quality. Building and Environment 2017, 112, 351–358. https://doi.org/10.1016/j.buildenv.2016.11.010.

13. Samet Jonathan M.; Burke Thomas A.; Goldstein Bernard D. The Trump Administration and the Environment — Heed the Science. New England Journal of Medicine 2017, 376, 1182–1188. https://doi.org/10.1056/NEJMms1615242.

14. U.S. Environmental Protection Agency. Research on Health Effects from Air Pollution. https://www.epa.gov/air-research/research-health-effects-air-pollution (accessed 2024-07-08).

4. References

4.1. Main Text

15. Adamkiewicz, G.; Zota, A. R.; Fabian, M. P.; Chahine, T.; Julien, R.; Spengler, J. D.; Levy, J. I. Moving Environmental Justice Indoors: Understanding Structural Influences on Residential Exposure Patterns in Low-Income Communities. American Journal of Public Health 2011, 101, S238–S245. https://doi.org/10.2105/AJPH.2011.300119.

16. Swope, C. B.; Hernández, D. Housing as a Determinant of Health Equity: A Conceptual Model. Social Science & Medicine 2019, 243, 112571. https://doi.org/10.1016/j.socscimed.2019.112571.

17. Jacobs, D. E. Environmental Health Disparities in Housing. American Journal of Public Health 2011, 101, S115–S122. https://doi.org/10.2105/AJPH.2010.300058.

18. Office of the Surgeon General (US). The Surgeon General's Call to Action to Promote Healthy Homes; Publications and Reports of the Surgeon General; Office of the Surgeon General (US): Rockville (MD), 2009. https://www.ncbi.nlm.nih.gov/books/NBK44192/.

19. Tessum, C. W.; Paolella, D. A.; Chambliss, S. E.; Apte, J. S.; Hill, J. D.; Marshall, J. D. PM2.5 Polluters Disproportionately and Systemically Affect People of Color in the United States. Science Advances 2021, 7, eabf4491. https://doi.org/10.1126/sciadv.abf4491.

20. Mohai, P.; Lantz, P. M.; Morenoff, J.; House, J. S.; Mero, R. P. Racial and Socioeconomic Disparities in Residential Proximity to Polluting Industrial Facilities: Evidence From the Americans' Changing Lives Study. American Journal of Public Health 2009, 99, S649–S656. https://doi.org/10.2105/AJPH.2007.131383.

21. U.S. Environmental Protection Agency. Indoor Particulate Matter. https://www.epa.gov/indoor-air- quality-iaq/indoor-particulate-matter (accessed 2024-07-18).

22. U.S. Environmental Protection Agency. Hazardous Air Pollutants. https://www.epa.gov/haps (accessed 2024-07-18).

23. U.S. Environmental Protection Agency. Introduction to Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality (accessed 2024-07-18).

24. National Academies of Sciences, Engineering, and Medicine. Why Indoor Chemistry Matters; National Academies Press: Washington, D.C., 2022; p 26228. https://doi.org/10.17226/26228.

25. U.S. Environmental Protection Agency. Indoor Pollutants and Sources. https://www.epa.gov/indoor- air-quality-iaq/indoor-pollutants-and-sources (accessed 2024-08-02).

26. California Air Resources Board. Indoor Air Pollution in California. https://ww2.arb.ca.gov/resources/documents/comprehensive-indoor-air-quality-report-2005 (accessed 2024-08-02).

27. California Air Resources Board. Combustion Pollutants & Indoor Air Quality. https://ww2.arb.ca.gov/resources/documents/combustion-pollutants-indoor-air-quality (accessed 2024-08-02).

28. South Coast Air Quality Management District. Wildfire Health Information & Smoke Tips. https://www.aqmd.gov/home/air-quality/wildfire-health-info-smoke-tips (accessed 2024-08-02).

29. U.S. Environmental Protection Agency. Wildfires and Indoor Air Quality (IAQ). https://www.epa.gov/indoor-air-quality-iaq/wildfires-and-indoor-air-quality-iaq (accessed 2024-08-02).

30. U.S. Environmental Protection Agency. Improving Your Indoor Environment. https://www.epa.gov/indoor-air-quality-iaq/improving-your-indoor-environment (accessed 2024-08-02).

31. California Air Resources Board. Indoor Air Pollution from Cooking. https://ww2.arb.ca.gov/resources/documents/indoor-air-pollution-cooking (accessed 2024-08-02).

4. References

4.1. Main Text

32. California Air Resources Board. Reducing Your Exposure to Indoor Air Pollution. https://ww2.arb.ca.gov/resources/fact-sheets/reducing-your-exposure-indoor-air-pollution (accessed 2024-08-02).

33. Tsoulou, I.; Senick, J.; Mainelis, G.; Kim, S. Residential Indoor Air Quality Interventions through a Social-Ecological Systems Lens: A Systematic Review. Indoor Air 2021, 31, 958–976. https://doi.org/10.1111/ina.12835.

34. Rudel, R. A.; Dodson, R. E.; Perovich, L. J.; Morello-Frosch, R.; Camann, D. E.; Zuniga, M. M.; Yau, A. Y.; Just, A. C.; Brody, J. G. Semivolatile Endocrine-Disrupting Compounds in Paired Indoor and Outdoor Air in Two Northern California Communities. Environmental Science & Technology 2010, 44, 6583– 6590. https://doi.org/10.1021/es100159c.

35. Kumar, P.; Skouloudis, A. N.; Bell, M.; Viana, M.; Carotta, M. C.; Biskos, G.; Morawska, L. Real-Time Sensors for Indoor Air Monitoring and Challenges Ahead in Deploying Them to Urban Buildings. Science of The Total Environment 2016, 560–561, 150–159. https://doi.org/10.1016/j.scitotenv.2016.04.032.

36. Chojer, H.; Branco, P. T. B. S.; Martins, F. G.; Alvim-Ferraz, M. C. M.; Sousa, S. I. V. Development of Low-Cost Indoor Air Quality Monitoring Devices: Recent Advancements. Science of The Total Environment 2020, 727, 138385. https://doi.org/10.1016/j.scitotenv.2020.138385.

37. Sá, J. P.; Alvim-Ferraz, M. C. M.; Martins, F. G.; Sousa, S. I. V. Application of the Low-Cost Sensing Technology for Indoor Air Quality Monitoring: A Review. Environmental Technology & Innovation 2022, 28, 102551. https://doi.org/10.1016/j.eti.2022.102551.

38. Clements, A.; Duvall, R.; Greene, D.; Dye, T. The Enhanced Air Sensor Guidebook; Overviews and Factsheets EPA/600/R-22/213; U.S. Environmental Protection Agency, Washington, DC: U.S. Environmental Protection Agency, Washington, DC, 2022. https://www.epa.gov/air-sensor- toolbox/how-use-air-sensors-air-sensor-guidebook (accessed 2024-05-26).

39. Ródenas García, M.; Spinazzé, A.; Branco, P. T. B. S.; Borghi, F.; Villena, G.; Cattaneo, A.; Di Gilio, A.; Mihucz, V. G.; Gómez Álvarez, E.; Lopes, S. I.; Bergmans, B.; Orłowski, C.; Karatzas, K.; Marques, G.; Saffell, J.; Sousa, S. I. V. Review of Low-Cost Sensors for Indoor Air Quality: Features and Applications. Applied Spectroscopy Reviews 2022, 57, 747–779. https://doi.org/10.1080/05704928.2022.2085734.

40. U.S. Environmental Protection Agency. U.S. Air Quality Index (AQI). https://www.airnow.gov/aqi/ (accessed 2024-07-20).

41. Li, J.; Mattewal, S. K.; Patel, S.; Biswas, P. Evaluation of Nine Low-Cost-Sensor-Based Particulate Matter Monitors. Aerosol and Air Quality Research 2020, 20, 254–270. https://doi.org/10.4209/aaqr.2018.12.0485.

42. Polidori, A.; Papapostolou, V.; Collier-Oxandale, A.; Hafner, H.; Blakey, T. Community in Action: A Comprehensive Guidebook on Air Quality Sensors; South Coast Air Quality Management District: South Coast Air Quality Management District, 2021. https://www.aqmd.gov/aq-spec/special- projects/star-grant (accessed 2024-05-29).

4. References

4.2. LCS Devices (see Tables 2.3.1 and 2.3.2)

1. Aethair. Aethair IAQ | Real-time indoor air quality monitoring. https://aethair.io/products/iaq/ (accessed 2024-07-04).
2. AirGradient Co. Indoor Air Quality Monitor. https://www.airgradient.com/indoor/ (accessed 2024-07- 04).
3. air-Q. Sensor Products. https://en.air-q.com/produktvarianten (accessed 2024-07-04).
4. AirThings. Comprehensive Air Quality Monitors. https://www.airthings.com/products/comprehensive (accessed 2024-07-04).
5. AIRVALENT. Premium Indoor Air Quality Monitor. https://airvalent.com/ (accessed 2024-07-04).
6. Amazon. Smart Air Quality Monitor. https://www.amazon.com/Introducing-Amazon-Smart-Quality-Monitor/dp/B08W8KS8D3/ (accessed 2024-07-04).
7. Applied Particle Technology. Real-Time APT Sensor Technology. https://www.appliedparticletechnology.com/technology (accessed 2024-07-04).
8. ATMOTECH INC. Air Quality Monitors for Consumers and Businesses. https://atmotube.com/ (accessed 2024-07-04).
9. Awair Inc. Become Awair | Start monitoring your indoor air quality. https://www.getawair.com/ (accessed 2024-07-04).
10. Davis Instruments. AirLink Air Quality Monitor. https://www.davisinstruments.com/pages/airlink (accessed 2024-07-04).
11. DylosCorporation. AIR QUALITY MONITORS. http://www.dylosproducts.com/index.html (accessed 2024-07-04).
12. Ecowitt. Air Quality Monitor Series. https://shop.ecowitt.com/collections/air-quality-sensor (accessed 2024-07-04).
13. EDIMAX. Air Quality Detection. https://www.edimax.com/edimax/merchandise/merchandise_list/data/edimax/us/air_quality_detecti on/ (accessed 2024-07-04).
14. Elitech Technology, Inc. Temtop Air Quality Monitors. https://www.elitechus.com/collections/air-quality-detector (accessed 2024-07-04).
15. Eve Home. Eve Room. https://www.evehome.com/en-us/eve-room (accessed 2024-07-04).
16. HabitatMap. AirBeam. HabitatMap is an environmental tech org and maker of AirBeam. https://www.habitatmap.org/ (accessed 2024-07-04).
17. IKEA. VINDSTYRKA air quality sensor. https://www.ikea.com/us/en/p/vindstyrka-air-quality-sensor-smart-30498239/ (accessed 2024-07-04).
18. INKBIRD. IAM-T1. https://inkbird.com/pages/iam-t1 (accessed 2024-07-04).
19. IQAir. AirVisual Series Air Quality Monitors | IQAir. https://www.iqair.com/us/air-quality-monitors (accessed 2024-07-04).
20. Kaiterra. Smart Air Quality Monitors. https://www.kaiterra.com (accessed 2024-07-04).
21. Netatmo. Indoor air quality measuring instruments. https://shop.netatmo.com/en-us/aircare (accessed 2024-07-04).
22. NuWave Sensors. AirSentric - Indoor Air Quality Monitor. https://airsentric.com/ (accessed 2024-07- 04).
23. Piera Systems. Canāree Air Quality Monitors. https://pierasystems.com/canaree/ (accessed 2024-07- 04).

4. References

4.2. LCS Devices (see Tables 2.3.1 and 2.3.2)

24. PurpleAir. Air Quality Monitors. https://www2.purpleair.com/products/list (accessed 2024-07-04).
25. Qingping. Air Monitors. https://www.qingping.co/air-monitor/overview (accessed 2024-07-04).
26. SAF Tehnika. Aranet4 HOME. https://aranet.com/en/home/products/aranet4-home (accessed 2024- 07-04).
27. Smart Air. CO_2 Monitor. https://smartairfilters.com/en/product/co₂-monitor/ (accessed 2024-07-04).
28. TSI Incorporated. Environmental Air Monitors - BlueSky. https://tsi.com/products/environmental-air-monitors/ (accessed 2024-07-04).
29. uHoo. Smart Air Quality Monitor. https://getuhoo.com/smart-air-monitor/ (accessed 2024-07-04).
30. uRADMonitor. Real-time Environmental Monitoring. https://www.uradmonitor.com/products/ (accessed 2024-07-04).
31. Wicked Device. Air Quality Egg. https://airqualityegg.com/egg (accessed 2024-07-04).

4. References

4.3. AQ-SPEC Evaluations (see Tables 3.2.1 and 3.2.2)

1. Applied Particle Technology (APT) - MINIMA. https://www.aqmd.gov/aq-spec/sensordetail/applied-particle-technology-(apt)---minima (accessed 2024-07-14).
2. Davis Instruments - Airlink. https://www.aqmd.gov/aq-spec/sensordetail/davis-instruments---airlink (accessed 2024-07-14).
3. Dylos - DC1100 PRO. https://www.aqmd.gov/aq-spec/sensordetail/dc1100-pro (accessed 2024-07-14).
4. Dylos - DC1700-PM. https://www.aqmd.gov/aq-spec/sensordetail/dc1700pm (accessed 2024-07-14).
5. Ecowitt WH41B. https://www.aqmd.gov/aq-spec/sensordetail/ecowitt-wh41b (accessed 2024-07-14).
6. HabitatMap - AirBeam3. https://www.aqmd.gov/aq-spec/sensordetail/habitatmap---airbeam3 (accessed 2024-07-14).
7. PurpleAir PA-II. https://www.aqmd.gov/aq-spec/sensordetail/purpleair-pa-ii (accessed 2024-07-14).
8. PurpleAir PA-II-FLEX. https://www.aqmd.gov/aq-spec/sensordetail/purpleair-pa-ii-flex (accessed 2024- 07-14).
9. PurpleAir PA-I-Indoor. https://www.aqmd.gov/aq-spec/sensordetail/purpleair-pa-i-indoor (accessed 2024-07-14).
10. TSI - BlueSky. https://www.aqmd.gov/aq-spec/sensordetail/tsi---bluesky (accessed 2024-07-14).
11. Magnasci SRL - SMOGGIE-PM. https://www.aqmd.gov/aq-spec/sensordetail/magnasci-srl---smoggie- pm (accessed 2024-07-14).
12. AirThinx IAQ. https://www.aqmd.gov/aq-spec/sensordetail/airthix-iaq (accessed 2024-07-14).
13. Atmotube - Pro. https://www.aqmd.gov/aq-spec/sensordetail/atmotube---pro (accessed 2024-07-14).
14. Edimax - EdiGreen Home. https://www.aqmd.gov/aq-spec/sensordetail/edimax---edigreen-home (accessed 2024-07-14).
15. Elitech - Temtop M2000 2nd Generation. https://www.aqmd.gov/aq-spec/sensordetail/elitech---temtop-m2000 (accessed 2024-07-14).
16. Elitech - Temtop LKC-1000S+. https://www.aqmd.gov/aq-spec/sensordetail/elitech---temtop-lkc-1000s (accessed 2024-07-14).
17. IQAir - AirVisual Pro. https://www.aqmd.gov/aq-spec/sensordetail/iqair---airvisual-pro (accessed 2024- 07-14).
18. IQAir - AirVisual Outdoor. https://www.aqmd.gov/aq-spec/sensordetail/iqair---airvisual-outdoor (accessed 2024-07-14).
19. Qingping - Air Monitor. https://www.aqmd.gov/aq-spec/sensordetail/qingping---air-monitor (accessed 2024-07-14).
20. Qingping - Air Monitor Lite. https://www.aqmd.gov/aq-spec/sensordetail/qingping---air-monitor-lite (accessed 2024-07-14).
21. TSI - AirAssure. https://www.aqmd.gov/aq-spec/sensordetail/tsi---airassure (accessed 2024-07-14).
22. uHoo. https://www.aqmd.gov/aq-spec/sensordetail/uhoo (accessed 2024-07-14).
23. Magnasci SRL - uRADMonitor A3. https://www.aqmd.gov/aq-spec/sensordetail/magnasci-srl---uradmonitor-a3-(hw105) (accessed 2024-07-14).
24. Air Quality Egg (v.2) - PM. https://www.aqmd.gov/aq-spec/sensordetail/air-quality-egg-(v.2)---pm (accessed 2024-07-14).
25. Air Quality Egg 2022 Model. https://www.aqmd.gov/aq-spec/sensordetail/air-quality-egg-2022-model---co-and-pm (accessed 2024-07-14).

4. References

4.4. Additional Resources

The Inside Story: A Guide to Indoor Air Quality, United States Environmental Protection Agency (EPA), last updated on June 16, 2024.

- Comprehensive article on indoor air quality concerns, major indoor air pollutants, and source-specific controls

https://www.epa.gov/indoor-air-quality-iaq/inside-story-guide-indoor-air-quality

Indoor Air Pollution in California, California Air Resources Board (CARB), July 2005.

- Comprehensive report on indoor air pollution, sources and health effects of indoor air pollutants, and mitigation strategies.

https://ww2.arb.ca.gov/resources/documents/comprehensive-indoor-air-quality-report- 2005

Low-Cost Air Pollution Monitors and Indoor Air Quality, United States Environmental Protection Agency (EPA), last updated January 3, 2024.

- Guidance article that aims to increase consumer understanding of the use, benefits, and limitations of low-cost indoor air monitors.

https://www.epa.gov/indoor-air-quality-iaq/low-cost-air-pollution-monitors-and-indoor- air-quality

Community in Action: A Comprehensive Guidebook on Air Quality Sensors, Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District (SCAQMD), September 2021.

- Guidebook for community planning that educates on the appropriate selection, use, and maintenance of air quality sensors; performance evaluations of commercially-available low-cost sensors; and data collection, interpretation, and communication.

https://www.aqmd.gov/aq-spec/special-projects/star-grant

The Enhanced Air Sensor Guidebook, Office of Research and Development, Center for Environmental Measurement and Modeling, United States Environmental Protection Agency (EPA), September 2022.

- Guidebook provides information on air quality and pollution monitoring, sensor selection for various applications; data analysis, interpretation, communication, and sensor performance.

https://www.epa.gov/air-sensor-toolbox/how-use-air-sensors-air-sensor-guidebook

4. References

4.4. Additional Resources

Air Quality Sensors: Policy Options to Help Address Implementation Challenges, United States Government Accountability Office (GAO), March 2024.

- Report describing air quality monitor technologies, the benefits and uses of monitors; performance evaluations of monitors; limitations; and options for policymakers to address challenges.

https://www.gao.gov/products/gao-24-106393

Guidebook for Developing a Community Air Monitoring Network, Tracking California, October 2018.

- A guidebook educating on community engagement, sensor selection, quality control and assurance, site selection for monitor installation, data analysis and interpretation, and community monitoring network sustainability.

https://trackingcalifornia.org/images/uploads/imperial-air-guidebook.pdf

Integrating Low-cost Sensor Systems and Networks to Enhance Air Quality Applications, World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), International Global Atmospheric Chemistry project (IGAC), June 2024.

- This document is a resource for utilizing LCS data for air quality applications.

https://library.wmo.int/records/item/68924-integrating-low-cost-sensor-systems-and-networks-to-enhance-air-quality-applications

Air Sensor Technology and IAQ, United States Environmental Protection Agency (EPA)
https://www.epa.gov/indoor-air-quality-iaq/air-sensor-technology-and-indoor-air-quality

Air Quality Sensor Performance Evaluation Center (AQ-SPEC), South Coast Air Quality Management District
http://www.aqmd.gov/aq-spec

Guidance: Low-Cost Sensors for Healthier Indoor Air

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