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# Ten questions concerning low-cost indoor air quality sensors: Perspectives from research and practice

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ABSTRACT

Low-cost indoor air quality (IAQ) sensors are increasingly being used in homes and commercial and public buildings, driven by growing concerns about the impact of air on health, cognitive performance, and occupant wellbeing. These sensors offer a potentially transformative opportunity to increase spatial and temporal coverage of IAQ monitoring at a fraction of the cost of conventional reference instruments. However, their widespread use raises questions around accuracy, calibration, placement, data handling and interpretation, and integration into existing standards and workflows. This paper presents ten critical questions concerning the use of low-cost IAQ sensors in buildings, drawing on the latest empirical research, field deployments, and emerging practice. It discusses potential frameworks for deployment and evaluation, examines current sensor capabilities for measuring common pollutants, identifies methodological gaps in validation and uncertainty quantification, and outlines the extent to which existing IAQ standards can accommodate sensor-based evidence. The paper also explores how monitoring needs and deployment models vary by building type, the potential of real-time IAQ data to support building operations, and the ethical and legal implications of widespread sensor use. While significant challenges remain in ensuring data quality and building stakeholder trust, new applications are emerging through open data initiatives and advances in analytics and visualization. As the technology, science, and standards co-evolve, low-cost IAQ sensors are poised to become integral to routine building operation, building science, and environmental health research.

## 1. Introduction

Indoor air quality (IAQ) is a core determinant of health, cognitive performance, and occupant wellbeing in buildings. Yet a persistent gap remains between the IAQ performance implied by design intent and prescriptive requirements, and the conditions actually measured during building operation. Building codes and healthy building programs have driven important progress through requirements for ventilation, filtration, and source control. However, there is a need for decision-relevant evidence of real-world conditions to guide and refine efforts by stakeholders (e.g., facility managers, occupants, building owners) to improve IAQ.

Low-cost IAQ sensors offer a potentially transformative opportunity to close the gap between design intent and building operation [1]. These devices can generate near-real-time data at a fraction of the cost of conventional reference instruments. This shift is already changing

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expectations; monitoring is increasingly framed as a pathway from prescriptive compliance towards performance-based verification. Portfolio-scale monitoring providing rapid feedback at strategic locations also creates practical opportunities for more responsive ventilation and filtration strategies, supporting commissioning and fault detection, and clearer communication with occupants.

However, widespread availability of sensors does not automatically translate into meaningful impact. “Sensing” is often treated as equivalent to “improvement”, despite the intermediate steps required to turn data into decisions and outcomes. Deployments frequently fall short in practice because data are underutilized or disconnected from operational workflows. A further challenge is conceptual and definitional: “low-cost” is not a fixed technical category but is instead relative to user group and application. Measurement performance varies across indicators and environments, and laboratory performance can diverge from field performance due to environmental effects, ageing, and source variability. In sensitive settings, increasing visibility of IAQ data also raises ethical and legal questions, including reputational and contractual risk and the possibility that readings become de facto benchmarks in disputes. Together, these factors reinforce the need to implement low-cost IAQ sensing as a socio-technical system spanning hardware, data, interpretation, decision rights, and accountability.

This paper responds by presenting ten questions concerning the use of low-cost IAQ sensors in commercial buildings. The questions are intended to align scientific evidence with implementation realities to support integrated research–practice view. The questions address: frameworks linking sensing to decisions and workflows (Q1); current capabilities and limitations across pollutants, including the balance between accuracy and actionability in performance assessment (Q2); strategies for timing and placement (Q3); how standards and guidelines can accommodate sensor-based evidence (Q4); how monitoring needs vary by building type and use case (Q5); the most credible applications for IAQ sensor data (Q6); pathways to more comprehensive indoor environmental quality monitoring (Q7); methods for processing and communicating data to improve actionability and trust (Q8); strategies for scaling from sensing to systemic transformation, including indexing and benchmarking (Q9); and ethical, governance, and liability considerations as IAQ data become more visible and consequential (Q10).

By organizing the field around these questions, we aim to provide a coherent roadmap for researchers and practitioners. The objective is not a universal prescription, but a structured way to match sensor selection, deployment design, data handling, and interpretation to the decisions monitoring is meant to support. We clarify where evidence is strong, where it is conditional, and where key uncertainties remain.

## 2. Ten questions

### 2.1. Question 1: What is a robust framework for utilizing low-cost IAQ sensors in commercial buildings?

Continuous IAQ sensing in commercial buildings has been explored in research and early pilots for over a decade [2–4], and this experience has informed deployment frameworks for building monitoring and management [5–9]. A key starting point for such frameworks is conceptual clarity on what is being deployed and why. “Low-cost” is relative to user and application, and the literature distinguishes a sensor (measuring component) from a monitor (sensor(s) plus enclosure, power, and data storage/transmission), with “low-cost” often defined at different price thresholds depending on the user group [4]. As the market moves beyond initial exploration, IAQ sensors are likely to provide limited value if deployed only as isolated experiments or reactive solutions to external shocks (such as wildfire smoke or pandemics) without a plan for integration into ongoing building management.

A robust framework should therefore begin by defining the decision context. Monitoring programs should identify who will use the data, what decisions the data are expected to support, and what organizational capacity exists to respond. Experts now recommend integrating IAQ sensors into workflows and organizational strategic plans, acknowledging IAQ monitoring as one component of tracking and improving organizational and building performance [10,11]. A staged rollout targeting high-need or high-value spaces and indicators (e.g., carbon dioxide in classrooms, health care facilities, or high-density meeting areas) can generate early insights and build institutional trust when sensors are embedded in broader planning and response structures. For example, the CalSHAPE Ventilation Program links CO2 monitor installation in educational facilities with HVAC assessment, maintenance, filter replacement, repairs and upgrades, and prioritization of underserved communities [12]. Over time, such programs can be scaled to include additional indicators, cover portfolios more comprehensively, and support a wider suite of use cases and initiatives. Guidance on monitoring needs by building type is provided in Q5, and sensor performance considerations in Q2.

The second component is fit-for-purpose deployment design. Most current programs use the same monitor type, sampling interval and quality-check procedure across all rooms/buildings, even when they differ in sources, occupancy, ventilation, and intended use of the data. To optimize data utilization, indicator selection, spatial and temporal distribution, and quality assurance should match identified use cases (see Q2 for performance assessment, Q3 for placement guidance). Planning should also specify protocols for data collection, validation, storage, and interpretation, with contingencies for connectivity loss and security concerns. A large community field study suggests that higher data capture rates may be attained through the use of supplementary data backup provided by sensors, such as integrating Wi-Fi transmitted data with onboard microSD card data [13].

The third component is an explicit pathway from data to outcomes. More broadly, “utilization” spans a pathway from sensing hardware to outcomes: Morawska et al. [4] describe progressive phases from the sensor/monitor and deployment, through data transfer and visualization, to interpretation and end-use outcomes (e.g., compliance comparisons, exposure insights, maps, or operational actions). A robust framework therefore makes explicit which phases are in scope (and who is responsible for each), rather than treating sensing as equivalent to impact. Ethical and liability considerations are addressed in Q10.

The fourth component is governance and resourcing. Robust sensor initiatives require resources and authority to address identified issues, with guidance for balancing competing priorities [14]. Successful programs assign time, budget, authority, and training to make actions feasible. While data interpretation currently depends on human expertise, emerging analytics and visualization tools are translating high-volume data into insights for a range of users (see Q8 for data processing and communication).

Finally, sustained value depends on institutional integration and impact evaluation. Given the intermediate stage of market maturity for IAQ sensors, voluntary programs risk being deprioritized or decommissioned unless they include a component related to financial and health impact verification and storytelling. Verifying impact in terms or KPIs that are meaningful for an organization, and integrating sensing into routine operational workflows can help ensure that outcomes are repeatable and not dependent on exceptional individual effort [15].

### 2.2. Question 2: How reliable are low-cost IAQ sensors, and how should their performance be assessed?

The promise of affordable, scalable measurements has spurred strong interest in low-cost IAQ sensors, but trust in the data depends on how reliably these sensors perform and how rigorously that performance is assessed. “Performance” in this context encompasses accuracy, precision, stability, and usability, each of which determines whether data are fit for purpose and credible for decision-making.

Low-cost IAQ sensing most commonly focuses on three indicators embedded in green-building programs: particulate matter (PM), carbon dioxide ($CO_2$), and total volatile organic compounds (TVOC). Reliability differs substantially across these indicators and depends on the intended use. $CO_2$ and $PM_{2.5}$ are currently the most mature for trend detection, event identification and operational diagnostics, although this does not imply equal suitability for all applications. Low-cost $CO_2$ monitors, typically based on non-dispersive infrared sensing, are considered accurate and useful for tracking ventilation-related patterns when they are properly placed, periodically checked, and interpreted with awareness of calibration. This is reflected in their widespread use in demand-controlled ventilation over the past two decades. Better performing optical PM sensors show moderate to strong correlations against research-grade instrumentation ($r^2 > 0.5$ in the field, $r^2 > 0.8$ in laboratories), though performance varies substantially across products and absolute mass accuracy depends on particle characteristics, environmental conditions, and device-specific design and data-processing choices [16–19].

TVOC sensing is less reliable for direct interpretation because the signal is broad, compound-dependent, and strongly influenced by calibration assumptions and sensor response factors [20–22]. TVOC sensors can indicate changes in chemical conditions, but they generally cannot identify specific compounds, sources, or health relevance without additional context. Additional contaminants, including $O_3$, $NO_2$, formaldehyde, radon, should be prioritized based on source profiles and building context [23,24]. Low-cost $O_3$ and $NO_2$ sensors may be useful for selected screening or trend applications, but their interpretation often requires expertise because readings can be affected by cross-sensitivities, temperature, humidity and calibration drift.

A recurring lesson is the divergence between laboratory and field performance [24]. Laboratory tests frequently report tight correlations using aerosols that may not represent real-world composition or concentration ranges [4,25]. Field studies capture humidity swings, aging/fouling, and source variability, occupant behavior and maintenance conditions that alter response factors [23,26].

Specific error mechanisms also vary by technology. For optical PM sensors, humidity above ~85% biases measurements [17,19], and correlations degrade below ~10–20 $\mu g\ m^{-3}$ for $PM_{2.5}$ [17,27]. For $CO_2$ monitors, automatic baseline correction can introduce bias where concentrations do not regularly return to outdoor-background levels [28]. Long-term stability remains an open question, with small but meaningful drifts documented over months to a year [29,30].

Current assessment practices for low-cost IAQ sensors are varied and difficult to compare across studies. A review of 112 studies found that correlation (r or $r^2$) is the dominant metric, with fewer evaluations reporting recommended error and precision measures such as RMSE, mean normalized bias, and coefficient of variation [23]. Consequently, the same commercial device can be labeled "excellent" in one study and "poor" in another, largely due to differing methodologies and sources. For example, calibration factors for common devices can differ by nearly a factor of three depending on aerosol source and protocol [31,32]. This reflects sensor variability as well as methodological inconsistency [33,34], where reference choices, test duration, and regression model all shape perceived "performance." Greater transparency on sensor modules and embedded algorithms would improve comparability [35,36]. Taken together, current evidence suggests observed performance variability stems from methodological diversity as well as sensor and monitor design, including the sensing principle, inlet and housing configuration, firmware, calibration algorithms, and assumptions used to convert raw signals into reported concentrations.

Beyond correlation to reference, key performance metrics include: (i) repeatability and reproducibility [26,37]; (ii) limit of detection and low-concentration performance [27,38]; (iii) dependence on particle size/composition and on indoor climate [19,39]; and (iv) long-term drift and robustness [29,30]. For gases, cross-sensitivities, temperature/RH compensation, and field calibration procedures are decisive for sensor performance [21,40].

In variable real-world environments (see Q3), fitness for purpose must balance accuracy and actionability (Fig. 1). In this framework, reference-grade or regulatory instruments define the high-accuracy/high-actionability corner as the "gold standard" used for compliance monitoring. Low-cost sensors are not designed for that precision but can be highly valuable when accuracy is sufficient for meaningful action. We therefore define three use tiers as a practical framework. Tier 1 applications use sensors for screening, trend detection, and source/event identification. Tier 2 applications use sensors to support behavior change, facility diagnostics, or automated control. For example, when calibrated and validated, $CO_2$ and $PM_{2.5}$ sensors can occupy a medium-accuracy/high-actionability zone that is adequate for Tier 1 (trend detection) and Tier 2 applications (behavior- and automation-support) [41]. Finally, Tier 3 applications use sensors for performance verification or compliance support, requiring stronger QA/QC, calibration, uncertainty reporting, and defensible placement protocols. For Tier-3 applications, low-cost sensors may not be suitable [4] except in certain applications [42,43]. In short, data can be considered "good enough" when they consistently capture the direction and magnitude of change, even if they miss exact absolute concentrations, provided that uncertainty is quantified and communicated transparently.

Looking forward, three priorities can broaden the applicability and strengthen the performance reliability of low-cost IAQ sensors for primary indicators. First, converge on standardized evaluation protocols covering both chamber and field testing with harmonized reporting [4,23,25]. Second, institutionalize calibration/maintenance pathways supported by transparent data schemas and metadata [32,44]. Third, leverage advanced analytical techniques to correct non-linearities and environmental interferences in real time [20,23]. Many low-cost sensors are already "good enough" for Tier-1/Tier-2 insight and control support, while ongoing advances in both sensor technologies and data interpretability (see Q8) are needed before they can shoulder Tier-3 compliance responsibilities. Transparent and standardized performance assessment is a prerequisite for public trust and the integration of low-cost IAQ sensing into the broader ecosystem of building management and policy frameworks [43].

### 2.3. *Question 3: How should IAQ monitoring be timed and located to support meaningful decisions?*

IAQ monitoring provides data to understand, manage, and improve

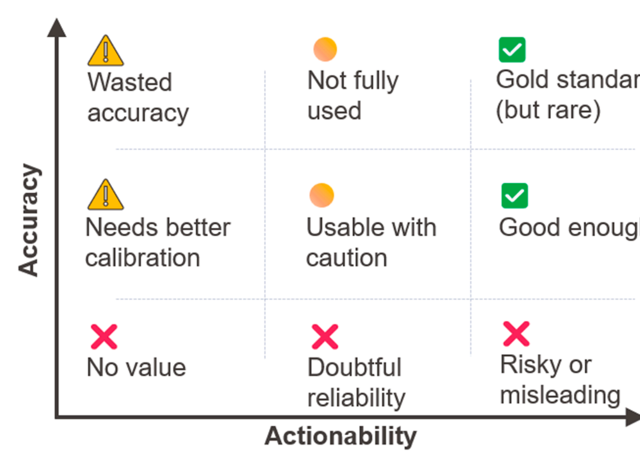


**Fig. 1.** Accuracy versus actionability framework for evaluating low-cost IAQ sensor performance. Here the term actionability refers to the usefulness of sensor data to inform the behaviours and practice of building stakeholders. For example, a high-quality TVOC sensor might be accurate but not be highly actionable due to the unclear source of chemical makeup. Low-cost sensors can be "good enough" when they fall in the medium-accuracy/high-actionability zone; suitable for Tier 1 (trend detection) and Tier 2 (behavior adjustment & automation) applications, but typically not for Tier 3 regulatory compliance.

building conditions. Yet despite widespread claims of good IAQ, a review of 100 case study buildings found that only 2% presented measurements in support of claimed building performance [45]. Following the sensor performance considerations in Q2, there are open questions about when and where to deploy sensors to generate meaningful information.

IAQ varies across multiple dimensions: sharp temporal dynamics (orders-of-magnitude shifts over minutes), pronounced spatial heterogeneity (room-to-room and within-room gradients), a thousand-fold span in particle sizes (from ultrafine to coarse particles), and strong chemical/biological specificity needs [20,46]. Because building functions and systems also vary widely, many experts recommend tailoring monitor placement, timing, and sampling frequency to program objectives, with a preference for a smaller network of high-quality, well-maintained sensors over a larger network that cannot be serviced reliably [47].

Practitioners should first define their monitoring objectives and maintenance capacity rather than seeking a universal approach. Short-term monitoring is common in commissioning, code compliance, and periodic audits. PNNL's H-BEST guide recommends one to two typical work weeks in both heating and cooling seasons [48]. Such campaigns can diagnose specific sources or support seasonal comparisons but may miss short-duration peaks unless timing is carefully selected [24,49]. Continuous monitoring, by contrast, provides insight into daily, weekly, and seasonal patterns and can support automated ventilation responses when integrated with building automation systems. High-frequency measurements (1 to 5 min intervals) capture transient events and occupant-driven variability that lower frequencies may miss [50,51].

Good practice calls for locating sensors in the breathing zone (0.9 to 1.8 m above floor level) and away from immediate pollution sources, operable windows and doors, and supply/exhaust jets [8]. Sensor placement should reflect the monitoring purpose. For room-level ventilation assessment, $CO_2$ sensors should be placed in the occupied zone but away from direct exhalation plumes, doors, windows, and supply or exhaust jets; near-occupant or wearable measurements are more appropriate for personal exposure studies [52,53]. This reflects the "personal cloud" phenomenon, where exhaled air and human emissions create localized elevations of particles and $CO_2$ around individuals [50,52]. Personal exposure zones can exhibit 200–800 ppm above room-average concentrations [50,51].

Practitioners should account for spatial variability in IAQ measurement, key drivers of which include pollutant sources, room volume, HVAC zoning, and operation. Dense human occupancy, chemical storage, combustion, and perimeter infiltration create spatial gradients. For example, smaller rooms with intermittent occupancy (meeting rooms, focus rooms) are more susceptible to temporal $CO_2$ variation than larger, steadily occupied spaces. Air handling units and associated components (filters, dampers, fans, economizers) introduce additional variability across zones. Zone-level sensors are needed for detailed understanding of occupancy, exposure, and source-driven peak dynamics. Return-air $CO_2$ sensors provide system-level information but typically measure 100–200 ppm lower than in-zone sensors due to mixing effects [49]. Wearable sensors offer value for personal exposure or cognitive performance studies, though room-level sensors are generally sufficient for ventilation control and diagnostics.

Stationary sensors can capture personal inhalation exposure in office environments, but reliability depends on occupancy patterns and environmental conditions. Specific placements (e.g., walls within 1 m of occupants) perform better under certain ventilation modes [49]. Multi-sensor layouts can sometimes approximate personal exposure as effectively as wearables [54,55], though evidence on minimum sensor counts and ideal placement strategies remains limited. Ultimately, the timing and spatial design of IAQ monitoring should align with the purpose of the monitoring, the pollutant of interest, the magnitude and variability of emission sources, and the decisions that the data are intended to support.

### *2.4. Question 4: Should existing standards and guidelines evolve to incorporate low-cost sensors?*

IAQ occupies a unique position in the regulatory landscape. Unlike outdoor air quality, which is backed by enforceable standards, most countries currently have no binding standards for indoor pollutant concentrations. However, many IAQ guidelines exist worldwide, covering various indoor pollutants with a wide range of recommended limit values [56–59]. These normally use health-based reference levels, such as the World Health Organization's Air Quality Guidelines [60] and California Air Resources Board IAQ guidelines [61], including its ongoing update for nitrogen dioxide ($NO_2$) [62], and are advisory in nature.

Building codes, such as California's 2025 Building Energy Efficiency Standards [63], influence IAQ indirectly by requiring ventilation, filtration, and envelope measures for meeting energy, affordability, and air quality goals. These requirements are informed by models and assumptions related to occupant behavior (e.g., cooking patterns, use of ventilation) [63]. While ventilation and filtration requirements have advanced building design, they do not guarantee good indoor air quality during the operational phase [64,65]. Occupant behavior is also a key factor influencing whether the intended performance is achieved; for example, many people choose not to use kitchen range hoods because of noise or perceived inconvenience, which reduces the effectiveness of even well-designed systems [66]. The recent shift toward capture efficiency metrics in California's 2022 Energy Code [67] represents a move toward more representative performance-based design metrics for pollutant removal, informed in part by occupant behavior, though it does not constitute verification of real-world IAQ and its impact remains uncertain. The persistent gap between expected and delivered IAQ underscores the opportunity for low-cost sensors to provide real-world evidence of indoor conditions.

Low-cost IAQ sensors for $PM_{2.5}$, $CO_2$, and, to a lesser extent, $NO_2$ and total volatile organic compounds (TVOCs), now make it possible to generate real-time, localized data at a fraction of the cost of reference instruments. Lower-cost volatile organic compounds (VOCs) sensors that are tuned to specific chemicals with low cross-sensitivity are also starting to emerge. A recent USGBC report argues that the monitoring can shift the sector from prescriptive compliance toward performance-based verification [10]. Similarly, a recent review in California emphasizes that broader deployment of low-cost sensors could empower low-income and disadvantaged communities by increasing visibility into indoor exposures that would otherwise go unnoticed [68].

Evolution of standards could yield meaningful health and equity benefits. First, chronic $NO_2$ and $PM_{2.5}$ exposure is associated with asthma, cardiovascular disease, and premature mortality [69,70]. Low-cost sensors can identify elevated exposures in priority settings, supporting targeted interventions for vulnerable populations. Second, continuous monitoring can reveal when ventilation or filtration systems are underperforming, particularly during outdoor events such as wildfires or when occupant activities elevate pollutant levels. Sensor-informed feedback could allow building operators to optimize ventilation and filtration in real time, balancing energy (cost) and health goals [71]. Market and policy momentum has been generated by green building frameworks that have been incentivizing the voluntary adoption of IAQ testing and monitoring. Authoritative action thresholds, peer benchmarking datasets, and financial incentives are needed to accelerate adoption [10].

At the same time, several barriers limit the applications of low-cost sensors in advancing building performance goals. Measurement performance across key IAQ parameters varies markedly (see Q2) and data interpretation needs to improve how measurements are processed into actionable insights (see Q3 and Q8). There is a need for standardized reporting protocols, opportunities for community-level databases tied to research or pilot programs, and exploration of alternative data governance models. A hybrid model could be explored in which public agencies serve as custodians or coordinators of aggregated, anonymized IAQ data, supported by experts, nonprofits, and local agencies that manage pilot and community-scale deployments. At present, most building codes and standards regulate ventilation and filtration system design rather than measured pollutant concentrations. Possible regulatory pathways to close that gap include health and safety codes/regulations (if public health risks and related economic impacts from not monitoring IAQ performance can be accurately quantified) and building energy codes.

Introducing new compliance requirements risks exacerbating concerns about rising implementation and operation costs. A pragmatic way forward is for guidelines and standards to incrementally incorporate low-cost sensors through voluntary measures, standardized reporting protocols, pilot programs that link IAQ improvements to measurable health and economic benefits, and optional or parallel performance-based pathways alongside prescriptive requirements, such as the Indoor Air Quality Procedure in ASHRAE 62.1 [6]. These pathways could allow sensor-based evidence to support operational verification and targeted interventions without immediately making low-cost sensors universal compliance tools. As research continues to demonstrate improved sensor performance and the economic and societal benefits from continuous monitoring, the argument for integrating sensors into enforceable standards will grow. An important question to address is how to ensure that the evolving guidelines and standards are credible, equitable, and aligned with regulatory readiness. At this stage, low-cost sensors should not yet be treated as universal stand-alone compliance tools across all pollutants and building contexts, although selected sensors and applications may already support performance verification when appropriate QA/QC, calibration, placement and uncertainty protocols are in place.

### 2.5. Question 5: How do IAQ monitoring needs vary across building types?

Beyond baseline code compliance, IAQ monitoring needs vary significantly by building type due to differences in occupant activities, pollutant sources, and vulnerability [10]. To design a fit for purpose monitoring strategy, these variations must be addressed across two primary aspects: the specific pollutants that need to be monitored and the appropriate temporal and spatial resolution for data collection.

While a core set of parameters, such as $CO_2$ as a ventilation indicator [72] and $PM_{2.5}$ given its health significance [73], is relevant across many building types, their usefulness is context-dependent. $CO_2$ is often less informative in residences than in classrooms or offices because occupancy is intermittent, spaces may not reach steady state and there is usually no single $CO_2$ peak of concern, unless the objective is to assess ventilation behavior under specific conditions (e.g. [74]). Instead, everyday residential activities like cooking and heating produce episodic spikes in combustion byproducts, causing carbon monoxide (CO), nitrogen dioxide ($NO_2$), and $PM_{2.5}$ to exceed critical monitoring targets [66,75]. In new constructions, continuous monitoring often prioritizes formaldehyde and total volatile organic compounds (TVOCs) stemming from off-gassing building materials and furnishings (Justo [76–78]). Schools frequently focus on $CO_2$ to monitor high occupant density and to signal when actions should be taken to ensure adequate ventilation and reduce airborne transmission risks in classrooms [79, 80].

The infiltration of outdoor pollutants, such as $PM_{2.5}$ from wildfires [81] or traffic, significantly impacts indoor air quality. Paired indoor and outdoor low-cost sensors may be used to calculate building-specific infiltration and filtration efficacy when data quality is carefully considered [82,83]. In commercial buildings, these sensors can verify how well high-efficiency HVAC filters limit $PM_{2.5}$ intrusion during pollution spikes [84]. Conversely, in naturally ventilated homes and older schools, they are critical for detecting rapid indoor PM accumulation, prompting immediate interventions like closing windows or activating portable air cleaners [85].

The sensor deployment design, specifically how often and where to measure, needs to take into account the physical layout and activity dynamics of the building (see Q3). Residential environments often see rapid, order-of-magnitude shifts over minutes due to events like cooking, requiring high-resolution sampling (e.g., 1-minute intervals) to accurately capture peak exposures [75]. Capturing these transient events would ideally automatically trigger source control through systems like exhaust hoods when cooking [86]. Conversely, office buildings typically experience gradual, occupancy-driven changes. In this scenario, 5- to 15-minute averages are generally sufficient for tracking trends and supporting HVAC control [87] and 1 hour average is sufficient to capture the diurnal variations to estimate exposure [88]. In schools, a logging interval between homes and offices (e.g., 5-minute intervals) is necessary to capture transient events and dynamic concentration changes during class periods [13,89]. Table 1 below summarises these general considerations for several common building types.

Spatial heterogeneity is driven by room volume, HVAC zoning, and localized sources. In open-plan commercial offices, required sensor densities can range from one sensor per 150 $m^2$ [87] to 325 $m^2$ (Fitwel v3), 325 -1000 $m^2$ (WELL v2), 500 $m^2$ (RESET AIR), 2500 $m^2$ (LEED v5). ASHRAE G45P [[90]; draft under development] introduces a tiered approach, ranging from 2500 $m^2$ (basic), 500 $m^2$ (diagnostic) to up to every occupied zone (advanced), allowing operators to scale their networks based on their specific 'fit-for-purpose' goals. Schools may require denser spatial networks because individual classrooms operate as distinct microenvironments influenced by varying occupancy and - how teachers manage the opening and closing of windows and doors. For example, the use of one sensor per selected typical classroom has been documented in numerous studies [79,85,89,91].

As discussed in Q3, the indoor pollutant dynamics are influenced by many factors beyond building type, and the timing and spatial design of IAQ monitoring should coordinate with the data analysis plan to support the decision-making for which the data are intended. Therefore, the optimal monitoring strategy may vary even within the same building type. Reflecting these nuances, leading building rating systems emphasize context-specific IAQ metrics and provide guidance tailored to different use cases and occupancy [5,7–9]. Building owners and facility managers should therefore work with qualified experts, commissioning teams, or service providers to develop practical monitoring plans aligned with building characteristics, monitoring objectives, maintenance capacity, and response procedures.

### 2.6. Question 6: What are the most promising applications of IAQ sensor data?

Common applications of IAQ data include raising public awareness, identifying pollutant sources, and informing building operations [77]. These play to low-cost sensor strengths: small form-factor, real-time data, and connectivity. However, accuracy and calibration limitations (see Q2) make low-cost sensors less suitable for toxicological studies or legal compliance except for specific air pollutants that come with application-specific calibration, uncertainty characterization, and often confirmatory reference measurements - the Tier 3 applications in Fig. 1. Wildfire smoke and the COVID-19 pandemic accelerated public interest, particularly for PM monitoring during smoke events [81] and $CO_2$ as a ventilation indicator in schools. The SAMHE project installed sensors in over 300 U.K. schools [92], demonstrating $CO_2$ monitoring as a practical strategy to signal whether actions should be taken to reduce airborne transmission risk in naturally ventilated classrooms [93].

There is potential for low-cost IAQ sensors to empower communities to take a more active role in managing their exposure to air pollutants [94,95]. This requires overcoming barriers, such as the absence of simple metrics that can be easily understood while avoiding the pitfall of oversimplification that an IAQ index or colored scale may present. Educational resources, such as the air quality sensor toolkit funded by

**Table 1**
Example IAQ monitoring considerations for several common building types.

| Building Type | Temporal Resolution | Spatial Resolution |
|---|---|---|
| **Homes** | Higher sampling frequency during events (e.g., at 1-minute intervals during cooking) | At least one sensor for each key living area with potentially significant pollutant concentration difference (e.g., kitchen for $PM_{2.5}$ and main bedroom for $CO_2$). |
| **School Classrooms** | To capture pollutant dynamics during school hours (e.g., at intervals of 5 minutes) | At least one sensor for a group of classrooms with similar occupancy and ventilation configurations. |
| **Office Buildings** | 5 minutes – 1 hour intervals [a] | One sensor per 150 – 2500 $m^2$ or per HVAC zone [b] |

[a] : Fitwel v3: 5-minute interval during occupied hours; LEED v5: 15-minute intervals for $CO_2$ and 1-hour intervals for $PM_{2.5}$ & TVOC; WELL v2: ≤ 15-minute intervals; RESET Air and ASHRAE G45P: 30 minutes reporting

[b] : LEED v5: 1 sensor per 2,500 $m^2$; Fitwel v3: 1 monitor per 325 $m^2$; WELL v2: 1 monitor per 325 - 1000 $m^2$ depending on the project area; RESET AIR: 1 sensor per 500 $m^2$

the U.S. EPA [96], are also needed. Efforts to integrate IAQ sensing data with other sources of information can also promote the usefulness of the data. For example, through the development of U.S. nationwide correction factors [97], $PM_{2.5}$ measured using PurpleAir can now be compared directly with outdoor $PM_{2.5}$ measured using regulatory instruments. Being able to compare indoor and outdoor measurements on a unified data platform is another important feature that makes IAQ sensing data more actionable.

Integration with building management systems and fault detection capabilities are emerging but remain focused on visualisation rather than advanced control (see Q8). More advanced multi-objective optimizations to dynamically control building operations and improve IAQ, thermal comfort, and energy efficiency remain an active research area. Even though early work by Rackes and Waring [98] did not include IAQ sensing, their modeling framework planted the seed for improving IAQ while saving energy through multi-objective optimization to determine HVAC outdoor airflow and zone temperature setpoints. Recent exploratory studies [99,100] have proposed using approaches such as digital twin model and machine learning to generate insights from IAQ sensing data that can be used to control building operations. The untapped potential of integrating IAQ sensing in dynamic control of building system operation, such as in response to sudden changes like wildfire smoke or elevated risk of airborne infection, will require further exploration to be realized.

Low-cost IAQ sensors are useful tools for researchers to study a larger number of occupants and their exposure to indoor air pollutants than before. Because researchers have better access to research grade instruments for calibration, some of their limitations can be more easily overcome than if used by the public. However, researchers are still limited by fundamental shortcomings of low-cost IAQ sensors [73,101]. There is a need to continue to improve capabilities of low-cost IAQ sensors to measure household air pollutants in low- and middle-income countries to support future exposure and health studies.

### 2.7. *Question 7: What is needed to expand from Indoor Air Quality to comprehensive Indoor Environmental Quality monitoring?*

Indoor environmental quality (IEQ) extends the concept of IAQ by integrating additional sensory domains that shape occupants' comfort, health, and performance. The conventional articulation consists of four domains: thermal, visual, acoustics, and IAQ. Each of these domains affect people through distinct physiological and psychological pathways [102]. A growing body of research on integrated environmental comfort highlights the value of multi-domain assessments for both occupant wellbeing and building performance [103]. Despite this, three key challenges currently constrain the practical implementation of comprehensive IEQ monitoring: how human perception shapes trust in sensor data, the technical and operational integration of multiple sensors into a holistic monitoring system, and the weighting of different IEQ domains when providing a summative building performance evaluation.

The first challenge focuses on a key distinction between IAQ and other IEQ domains, which is the way humans perceive many air pollutants. We have acute sensory awareness of temperature, light, and sound, but are relatively less sensitive to factors like fine particulate matter or certain gaseous pollutants that are not odorous such as CO, $CO_2$ and NOx [104,105]. This perceptual asymmetry shapes how occupants relate to IEQ sensor data. Lower sensory acuity to IAQ parameters, combined with their established link to health outcomes, may help occupants trust IAQ sensors to reveal invisible risks. Establishing this same trust in thermal, visual, or acoustic sensors is challenging when measurements contradict personal experience. In addition, subjective perception of comfort or air freshness varies widely between individuals and contexts [32,106]. For this reason, IEQ monitoring often relies on coupling objective measurements with subjective feedback through occupant surveys [107,108] or wearable devices [109]. One way to address this challenge is to enhance literacy around the purpose of IEQ monitoring and how the data are used to characterize the "average" experience. Such transparency may strengthen trust and enable more meaningful occupant engagement. Understanding these perceptual dynamics and risk perception [110,111] is essential if multi-domain IEQ monitoring is to effectively inform occupant behaviour and building operation.

The second challenge requires addressing how different sensors are technically and operationally integrated within buildings. On the technical side, aligning data from heterogeneous sensors with different sampling frequencies (see Q5), accuracy (see Q2), and long-term calibration stability is challenging. These differences stem from the physical properties of the quantities being measured. IEQ parameters vary across space and time; pollutant hotspots, glare, or acoustic reflections are examples of pronounced variability within a single room. Low-cost sensors facilitate denser deployments that can reveal some of these variations, but integrating a range of sensor requirements into one package requires careful product engineering and inevitable performance tradeoffs. On the operational side, air quality sensors can typically provide a linear feedback loop: detecting increasing indoor pollutant concentrations triggers higher ventilation rates if the outside air is clean. In contrast, temperature, lighting, and acoustics are subject to diverse individual preferences and often have personal control options that establish a human-in-the-loop dynamic [112]. Integrating sensor data across domains requires control systems that can interpret and adapt to both environmental conditions and occupant preferences simultaneously, which remains too complex for practical deployment in many contexts.

The third challenge is the inevitable question of how to meaningfully integrate IEQ domains within a broader performance framework. Many environmental monitoring systems were historically deployed for safety (e.g., smoke detection), which was subsequently followed by efforts toward energy efficiency. The current emphasis is linking the multi-domain effects to wellbeing and cognitive performance [113,114]. However, determining the relative importance of multiple IEQ domains in every instance is not straightforward [115]. IEQ priorities vary by context: acoustic and visual comfort in workplaces, $CO_2$ and temperature in schools (see Q5), or infection control and circadian lighting in hospitals [116]. Some approaches to universal weighting exist [117, 118], but none that have adaptive and context-sensitive prioritization. Emerging AI-enabled systems may eventually adjust these weightings dynamically [119], guided by occupancy data, environmental context, or even public health alerts. Personalized or learning-based systems that infer which parameters matter most to individual occupants [120] or entire cohorts [121] could represent the next step toward genuinely human-centred environmental control, comfort and wellbeing.

### 2.8. Question 8: How should IAQ sensor data be processed and communicated for decision-making?

Current IAQ data communication commonly takes three forms. The first is the dashboard, often showing time-series, temporal averages, or room-by-room comparisons [122]. The second is threshold-based altering, where users and facility managers are notified when pollutant levels exceed certain safety or comfort-related boundary values [123]. The third, especially common in commercial and consumer monitors, is an integrated IAQ score or red-yellow-green display. While these three methods have helped establish the foundation of IAQ monitoring in the built environment, they have likely reached their limit in terms of adoption amongst the building stock. Monitoring indoor environments using sensors and alarms falls into the general category of building optimization through anomaly detection, which has several significant adoption barriers related to perceived value versus initial implementation cost [124]. There is also the well-studied phenomenon of alert fatigue which has been studied extensively in other fields and impacts the adoption and use of sensor data in buildings [125].

A discussion of who would potentially want to use the data would help identify how they can be better utilized to increase the likelihood of adoption. There are two general types of users of the data: facility managers wanting to improve the operations of the building or the design of future buildings, and the occupants who want to better understand their exposures and environmental conditions. In the first category, facility managers need automated processing, exception-based alerts, and diagnostic summaries rather than routine manual inspection of raw data [126]. For the second category, the average occupant is a layperson who would need aggregation and consolidation of raw data into high-level insights understandable by a non-specialist. The occupant, as a user, might never be exposed to data at all, and instead given messages triggered based on models trained using the data to detect specific behavioral changes or actionable insights [127].

Potential innovations within the category of professionals who use the data to make policy, system, and facility decisions focus on better navigation of data from processing and consolidation. The field of modern visual analytics would facilitate innovation with interfaces that leverage established techniques such as the Overview First, Zoom and Filter, Details-on-Demand mantra [128]. This approach within the visual analytics community is a departure from typical IAQ dashboard design in that it focuses on the process of investigation rather than general information digestion. The user can detect potential problems at a high level before using fast tools for investigating reasonable alerts. Interviews with building operators showcase their need to trust the information through these types of systems, and the ability to inspect alerts faster and easier could better facilitate utilization [129]. Deeper interaction between operators and the building through human language queries of data could be enhanced by the innovations in large language models and automated agentic analysis workflows [130]. Another emerging data fusion technique is with digital twin platforms that seek to couple a virtual model with reality towards various benefits [131]. The integration of these data streams in more occupant-centric ways would enhance controls and automation systems [132].

From the perspective of the building occupants, there are several innovations that would enhance usability of IAQ data in the indoor context. These users require the distillation of raw data into practical actionable insights related to a layperson's behavior. There are several methods for converging multi-scale data to influence indoor occupants. These range from the urban, building, and human-scale levels, including data sources such as imaging, wearables, and even geospatial sources that could enhance the data models towards predictive methods [133]. The field of behavior nudging, recommendation engines, and context-aware personal decision support has begun to be adapted to the built environment context [134]. Just-in-Time Adaptive Interventions may be useful when occupants control relevant behaviors, such as window opening, cooking ventilation, or portable air-cleaner use [135], but they should complement rather than replace source control, ventilation, filtration, maintenance, and institutional responsibility for healthy indoor environments. The predictive models behind these types of methods are nontrivial, and innovation in open data and machine learning crowdsourcing could prompt innovation there as well [136].

### 2.9. Question 9: How can IAQ monitoring be scaled from sensing to systemic transformation?

Scaling IAQ monitoring means moving beyond isolated pilots toward interoperable, enduring systems that support benchmarking, policy, and public health. Even when single-building deployments meet all requirements (validated sensors, thoughtful placement, transparent data handling), that is only a foundation. To translate into systemic impact, a broader architecture that integrates technology, data, and governance is needed. A helpful lens to understand this challenge is a three-tier pyramid (see Fig. 2): sensing, indexing, and benchmarking. Sensing provides visibility; indexing converts complexity into decision-ready indicators; benchmarking enables cross-building learning and accountability. This structure and flow helps turn raw signals into comparable knowledge, but each tier introduces distinct challenges and opportunities.

Scaling requires measurements reliable enough to support decisions, not perfect accuracy [4]. The performance challenges discussed in Q2 (standardization gaps, laboratory-field divergence, environmental effects) become acute at scale. Programs typically address these through periodic field collocation, humidity adjustment for PM sensors, and automated drift checks. Integration with building systems introduces additional constraints: communication protocols, data formats, and platform APIs must be consistent enough to link IAQ time series to HVAC operation, occupancy estimates, and outdoor conditions. Finally, large deployments require predictable maintenance processes that cover installation, firmware, cleaning/replacement, and periodic recalibration. These must be simple and predictable, otherwise small failure rates become large operational burdens [44].

For IAQ monitoring to scale, measurements must be interpretable for the people making decisions (see Q8). Indexing provides this bridge by combining multiple parameters into indicators that relate directly to health, comfort, or operational performance. Building on this concept (see Q7), the recent ATLAS index is a fully performance-based and

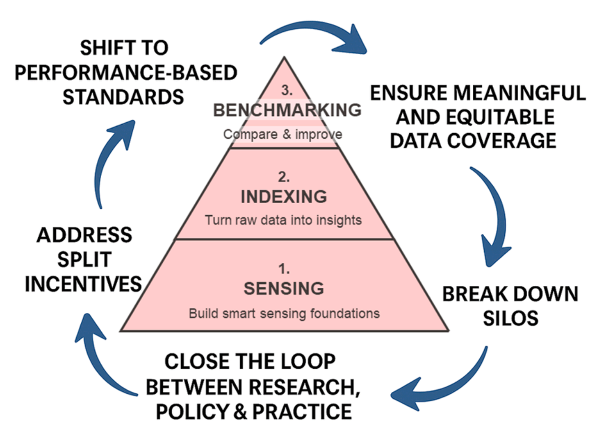


**Fig. 2.** Conceptual framework for scaling IAQ monitoring.

sensor-compatible framework for residential environments designed to translate continuous IEQ data into actionable insights [119]. Indexing also benefits from combining IAQ metrics with contextual information such as occupancy, HVAC operation, and outdoor air quality, which helps distinguish changes driven by human activity from those driven by system faults or outdoor conditions.

Benchmarking extends indexing from individual buildings to broader comparisons across building stock. It does not replace compliance with enforceable IAQ standards, but can complement it by stimulating positive competition, supporting green building and portfolio-level performance programs, identifying leaders and laggards, prioritizing interventions, and tracking improvement over time. Such comparisons require privacy-preserving data infrastructures and normalization for building type, climate, occupancy, outdoor air quality, and operational context. The ASHRAE Global Thermal Comfort Database provides a useful model: by aggregating standardized field data from thousands of buildings, it has supported improved comfort models and adaptive standards [137]. A parallel initiative for IAQ, referred to as the Global IAQ Database, is now being developed to facilitate cross-building and cross-regional analyses (https://iaqdb-dev.epfl.ch). Benchmarking methods need to account for differences in climate, building type, occupancy, and location-specific outdoor air quality using metrics such as time-in-target ranges or exceedance hours to allow fair comparisons [4,23]. As datasets expand, data governance becomes critical [44]. Equity considerations, such as ensuring representation of low-income housing, smaller clinics, and rural schools, are discussed in Q10.

When sensing, indexing, and benchmarking are aligned, low-cost IAQ monitoring can influence practice at a broader institutional level. The three-tier pyramid (Fig. 2) illustrates how sensing provides visibility, indexing translates data into insight, and benchmarking drives accountability and improvement. Around this structure, several systemic factors determine whether monitoring efforts lead to meaningful change. One is the development of performance-based standards (Q4) that specify pollutant targets, averaging times, measurement methods, uncertainty requirements, and compliance procedures, so that actual indoor conditions can be assessed rather than inferred solely from prescriptive design requirements. Another is ensuring that continuous IAQ monitoring is deployed in places where risks are highest, not only where budgets are largest. Persistent split incentives also complicate adoption: the costs of sensors and maintenance are often borne by different parties than those who benefit from healthier air. Addressing this requires coordinated policies and incentive structures that distribute responsibilities and benefits more evenly across stakeholders.

Scaling IAQ monitoring is a systems challenge, requiring collaboration across multiple levels of decision-making. Progress also depends on contributions from several fields, including building science, public health, policy, and data analytics. In a mature system, continuous sensing would support an iterative process in which building-level observations inform scientific analysis, scientific evidence shapes policy and standards, and those policies guide operational practice. Establishing this feedback structure offers a path toward a more coherent evidence base, where IAQ conditions become measurable, comparable, and easier to act on across many buildings.

### 2.10. Question 10: What ethical and liability issues arise as IAQ data becomes more visible and widespread?

There is currently minimal direct legal liability associated with the collection of IAQ monitoring data from buildings, but lawsuits could conceivably leverage IAQ data collected by low-cost sensors. Indirect liability may also arise through evolving standards-of-care principles that increasingly frame clean indoor air as a fundamental human right. In this context, occupants of residential or commercial properties may pursue legal recourse against landlords, property managers, or building owners for failing to maintain safe and healthy indoor environments [138]. As IAQ data become more widely recorded, displayed to occupants, shared with third parties, and incorporated into databases, sensor readings may also introduce reputational and contractual risk, or be treated as de facto performance benchmarks in disputes. This risk is amplified in sensitive settings, where adverse readings can trigger media scrutiny and public censure, with owners and operators facing accusations of negligence or poor stewardship (School District Liability for Indoor Air Quality Conditions, [139,140]). Another risk is simple misunderstanding: low-cost sensor packages often measure only some pollutants, so people may treat "normal" readings as proof that the air is safe. This can lead to false reassurance, disputes, and loss of trust if other hazards were never measured. These vulnerabilities may be mitigated by adapting outdoor-air precedents for QA/QC and reporting, through transparent decision-making protocols that clearly articulate how IAQ data are interpreted, governed, and translated into action for stakeholders [79].

The regulatory space is maturing and trending towards increased scrutiny for building owners to demonstrate acceptable IAQ. Efforts are underway to close the lack of accountability for indoor air conditions during operations using real-time IAQ sensors. This accountability may be achieved via a trajectory in which voluntary metrics are gradually converted to mandatory requirements [141]. A similar trajectory succeeded for energy metrics in cities like New York, where voluntary reporting evolved into mandatory standards [142,143] over a decade.

Current IAQ performance regulations are largely organized around building product emissions with limited protocols for regular inspection of IAQ [144,145]. However, several jurisdictions have established precedents: Japan's Law for Maintenance of Sanitation requires bimonthly IAQ measurements in large buildings [146,147]; Belgium's 2022 law mandates $CO_2$ monitoring in public spaces (Belgium Federal Public Service [[148] Public Health, 2022]; and Singapore code SS 554 [149] provides IAQ benchmarks for air-conditioned buildings.

While widespread sensor deployment can drive accountability and build a shared evidence base to guide standards and design, programs without allocated resources to address data governance and performance inconsistencies have the potential to backfire. Exemplar initiatives incorporate public deliberation, co-design, and community engagement into decision-making processes [150–152]. Clear data ownership agreements reduce disputes over disclosure and reuse. Residential deployments require particular care because IAQ data can reveal private behaviors and cultural practices, including cooking, smoking, incense burning, candle use, cleaning, air-freshener use, product purchases, and window-opening behavior. Such programs should therefore prioritize informed consent, data minimization, household control over data access and sharing, and non-punitive communication. Data efforts can acknowledge power differentials and historical contexts with resources such as the CARE Principles for Indigenous Data Governance [153]. This can ensure open data decision-making and mechanisms to protect access to data to minimize harms and maximize benefits [96].

Low-cost sensor data quality is currently sufficient for some applications, but not for others (see Q2 and Q5). However, awareness of this nuance is low across the building industry and the public, resulting in a risk of intentional or inadvertent data misuse [154]. There are promising trends in the development of third-party sensor performance standards [8,90,155,156] that provide some assurance of performance for brands that certify. As sensor technology matures, there is also an expectation that out-of-the-box data quality will improve and be less of a differentiator across devices and brands.

In the interim, the onus is on users to maintain data quality and access over time (through sensor replacements and software upgrades from manufacturers), and to interpret and use sensor data appropriately. The resulting inconsistency is a barrier to effective benchmarking across deployments and brands. In extreme cases, where the interpreting body stands to gain by demonstrating levels of indicators are low, there is a risk they will be incentivized to adopt algorithmic calibrations that bias readings downward, or to place sensors in less sensitive locations (e.g., away from pollutant sources). This gap needs to be accounted for while the standards and technology mature.

## 3. Conclusion

Low-cost IAQ sensing is moving from opportunistic deployments towards routine use in buildings, but the central message of this paper is that sensing does not always equate to impact. A theme running through the ten questions is that value emerges only when measurement choices, performance evidence, and data workflows are explicitly coupled to decisions, responsibilities and outcomes. In Q1, we argue that a robust utilization framework begins with conceptual clarity regarding purpose, and extends along the full pathway from hardware to interpretation and action. This framing is essential because unsuccessful deployments are often failures of integration (e.g., underused data, unclear decision rights, lack of operational follow-through) rather than technology. Programs should therefore be designed as governance-and-workflow systems as much as technical systems.

Questions 2 and 3 focus on the technical requirements for reliable data. Q2 shows that low-cost sensing can be “good enough” for many Tiers 1–2 use cases (e.g. trend detection and behavior/control support), yet performance remains parameter- and context-dependent. This motivates Q3’s emphasis that when and where sensors are deployed is not a procedural detail but a scientific determinant of interpretability. Together, these questions converge on a common requirement: transparent uncertainty, standardized evaluation/reporting, and field-aware validation approaches that reflect the environments where sensors actually operate.

Questions 4–7 broaden the lens from measurement to adoption and meaning. Q4 highlights that indoor air is still governed largely through prescriptive design requirements rather than verified operational performance. The opportunity is substantial, but regulatory readiness depends on credible protocols, defensible action thresholds, and clear differentiation between informational monitoring and compliance-grade determinations. Q5 emphasizes that monitoring needs vary by building type, because occupancy, sources, vulnerability, and operational goals differ across homes, offices, schools, and healthcare settings. Q6 then clarifies where low-cost sensing is currently most promising: education and awareness, operational diagnostics, targeted interventions during episodic events, and research studies that benefit from broad coverage. Q7 extends the conversation beyond IAQ to comprehensive IEQ, arguing that multi-domain monitoring is valuable but complex.

Finally, Questions 8–10 focus on the socio-technical conditions required for sustained scale. Q8 argues that data pipelines and visualization must serve distinct user groups while avoiding alert fatigue and opaque “black-box” outputs. Q9 synthesizes scaling as a progression from sensing to indexing to benchmarking, supported by interoperability, privacy-preserving data infrastructures, normalized metrics, and sustainable maintenance practices. Q10 closes by showing that as IAQ data become more widely recorded, displayed to occupants, shared with third parties, and incorporated into databases, ethical and liability issues will shift from hypothetical to practical, and they must be addressed alongside technical performance.

Looking ahead, the outlook is cautiously optimistic. Low-cost IAQ sensing is already enabling meaningful improvements when deployed with fit-for-purpose expectations and credible performance evidence, but the next phase will require three advances to unlock broader and higher-stakes applications: (i) international convergence on evaluation protocols and reporting conventions; (ii) operationally realistic pathways for calibration, drift management, and QA/QC that preserve data integrity over months to years; and (iii) integration of sensor data into decision systems that can translate measurements into repeatable improvements instead of isolated successes. If these conditions are met, low-cost sensors can evolve from simple measurement instruments into systems that meaningfully improve building operations, making indoor air quality more visible, comparable, and actionable across buildings, portfolios, and communities.

## Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the views or opinions of the California Department of Public Health or the California Health and Human Services Agency.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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