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Long-term health and cognitive effects of indoor air quality in occupied public buildings

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Abstract

Indoor air quality (IAQ) in public buildings has traditionally been assessed through short-term measurements that capture immediate pollutant concentrations and ventilation performance. However, emerging evidence indicates that the long-term health and cognitive effects of chronic exposure to suboptimal IAQ are far more consequential, particularly in high-occupancy settings such as schools, hospitals, libraries, and administrative institutions. Poor IAQ characterized by elevated carbon dioxide, volatile organic compounds, particulate matter, and microbial contaminants has been linked to respiratory diseases, weakened immune response, and heightened vulnerability to infections. Yet beyond physical health, chronic exposure to polluted indoor environments affects cognitive function, concentration, memory formation, and emotional regulation. In classrooms, this manifests as learning loss, reduced test performance, and increased absenteeism. In healthcare environments, compromised IAQ can slow patient recovery rates, elevate stress among clinical staff, and increase cross-infection risks. This study situates IAQ as both a public health imperative and a determinant of human productivity and wellbeing, arguing that long-term exposure dynamics must be central to building management policy. It proposes a longitudinal monitoring and evaluation framework that integrates continuous air sensor data, occupant health records, and cognitive performance indicators. By examining multi-year trends, rather than isolated measurement snapshots, this approach captures the cumulative burden of air pollutants and identifies thresholds beyond which cognitive and physiological impairment becomes measurable. The study further emphasizes the need for international policy alignment to support proactive IAQ standards, especially in resource-limited regions where infrastructure upgrades may be incremental. Ultimately, improving IAQ is not only an environmental or engineering concern, but a foundational requirement for healthy learning, healing, and public service environments.

Keywords: Indoor Air Quality; Cognitive Performance; Chronic Exposure; Public Buildings; Learning and Recovery Outcomes; Environmental Health Policy

1. Introduction

1.1. Context and Importance of Indoor Air Quality

Indoor Air Quality (IAQ) has become a central concern in environments where large numbers of people gather, such as schools, hospitals, government facilities, and office buildings [1]. These spaces are characterized by prolonged occupancy, shared ventilation pathways, and recurrent exposure to airborne particulates, volatile organic compounds, carbon dioxide buildup, and microbial contaminants [2]. Historically, IAQ was evaluated mainly for comfort and short-term irritation effects such as headaches or mild respiratory discomfort [3]. However, emerging research highlights that chronic exposure to even moderate pollutant levels may influence long-term physiological and cognitive outcomes, particularly in vulnerable populations such as children, elderly patients, and clinical staff [4]. The implications extend

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beyond personal health to institutional effectiveness, affecting academic performance, patient recovery durations, employee productivity, and absenteeism rates [5]. As such, IAQ is now increasingly viewed as a public health priority with economic, behavioral, and developmental consequences that require sustained and systematic evaluation [6].

1.2. The Built Environment, Energy Efficiency, and Airtight Construction

Contemporary building design emphasizes energy efficiency through improved insulation, sealed envelopes, and reduced reliance on natural ventilation systems [7]. These strategies lower heating and cooling costs and contribute to climate mitigation objectives. However, unintended consequences arise when buildings become so airtight that internal pollutant concentrations accumulate faster than they can be diluted or expelled [8]. Common indoor sources including cleaning products, paints, human respiration, furniture off-gassing, and building material degradation may generate pollutants that persist and circulate through recirculating HVAC systems [9]. Without balanced ventilation strategies, the drive toward sustainable construction can conflict with occupant health by trapping contaminants rather than preventing their formation. The central challenge becomes achieving a design equilibrium that aligns energy efficiency goals with safe air exchange standards. This requires rethinking ventilation protocols, filtration technologies, building material selection, and occupancy behavior patterns to ensure that environmental sustainability does not compromise physiological well-being [10].

1.3. Research Gap and Study Purpose

Most IAQ assessments focus on short-term measurements that capture daily or episodic pollutant fluctuations rather than the cumulative exposure effects that occur over months or years [2]. Such "snapshot" approaches overlook how repeated low-level exposure contributes to gradual health and cognitive changes. This study addresses the need for sustained IAQ evaluation, specifically examining how chronic exposure influences respiratory health, immune response, attention regulation, memory performance, and overall cognitive functioning [4]. The purpose is to highlight long-term impacts in public buildings and demonstrate why IAQ must be interpreted as a developmental and behavioral determinant rather than merely an environmental comfort factor [6].

1.4. Structure of the Article

The article begins by outlining foundational IAQ science, followed by an examination of cognitive and health impacts of long-term exposure. It then analyzes sector-specific risks in schools and hospitals, evaluates monitoring challenges, and presents intervention frameworks. The discussion concludes with forward-looking recommendations for integrated building health strategies.

2. Foundations of indoor air quality science

2.1. Definition and Parameters of IAQ

Indoor Air Quality (IAQ) refers to the chemical, physical, and biological characteristics of air within enclosed built environments occupied for extended periods [7]. Several core parameters are used to assess IAQ. Carbon dioxide (CO_2) concentration is commonly used as a proxy for ventilation sufficiency, reflecting how effectively fresh outdoor air replaces exhaled indoor air [8]. Volatile organic compounds (VOCs), released from paints, cleaning agents, adhesives, office equipment, and furnishings, contribute to irritant and neurobehavioral effects when allowed to accumulate [9]. Particulate matter, particularly PM2.5 and PM10, presents respiratory hazards due to the ability of fine particles to bypass filtration defenses and deposit in the lungs [10]. Microbial contaminants, including mold spores and bacterial aerosols, become more prevalent in conditions of elevated humidity or poor ventilation, often creating chronic low-level inflammatory responses in occupants [11].

Humidity itself plays a regulatory role: high humidity encourages microbial growth, while excessively low humidity irritates mucosal surfaces, increasing susceptibility to infection [12]. Ventilation rate the balance between air supply, exhaust, and circulation determines the extent to which indoor pollutants are diluted or removed [13].

Indoor pollutants derive from both indoor and outdoor sources. Outdoor contaminants infiltrate through windows, cracks, and mechanical ventilation intakes, particularly in buildings located near traffic corridors or industrial zones [14]. Indoor sources, however, tend to be more persistent because emissions from furnishings, building materials, and metabolic processes occur continuously. The interaction between these sources and ventilation determines exposure intensity rather than the emission source alone [15]. Understanding IAQ therefore requires examining pollutant generation, accumulation, removal, and occupant behaviors collectively rather than as isolated variables [16].

2.2. IAQ Variation Across Building Types

IAQ patterns differ significantly across building types because each building category features distinct occupancy densities, ventilation strategies, material compositions, and functional uses [7]. Schools often experience high occupant density in enclosed classrooms, where CO_2 levels can build rapidly as students and teachers share limited air volumes [8]. Frequent activities such as floor cleaning and the use of art supplies increase VOC presence, and aging infrastructure can exacerbate mold formation due to inconsistent maintenance [9]. Long hours spent in the same room amplify steady exposure effects.

Hospitals, in contrast, are equipped with controlled air systems designed to limit infection transmission; however, their continuous operation, reliance on disinfection chemicals, and concentration of immunocompromised individuals create unique IAQ vulnerabilities [10]. The presence of specialized spaces such as isolation wards and operating theaters requires finely calibrated ventilation systems that, when poorly maintained, may recirculate particles rather than exhaust them effectively [11].

Libraries and administrative office buildings typically have lower occupancy density but extended exposure durations, meaning pollutants generated from furnishings, carpets, and office equipment accumulate over time [12]. Older public buildings may contain legacy materials, including formaldehyde-based adhesives or deteriorating insulation, which continuously off-gas VOCs into the occupied airspace [13]. Ventilation in these structures often depends on outdated systems not designed for modern occupancy levels.

Maintenance cycles further influence IAQ conditions. Buildings with proactive filter replacement, duct cleaning, and moisture control measures consistently report lower pollutant levels than those where HVAC upkeep is delayed or reactive [14].

The variability across building types demonstrates that IAQ cannot be generalized; health risk assessment must consider operational context, use intensity, and building lifecycle conditions [15]. Addressing IAQ effectively therefore requires targeted monitoring and intervention strategies tailored to each building category rather than a one-size-fits-all approach [16].

2.3. Physiological Pathways of Chronic Exposure

Chronic exposure to indoor pollutants influences the human body through interconnected respiratory, immunological, and neurological pathways [7]. Fine particulates (PM2.5), when inhaled repeatedly, penetrate deep into the bronchioles and alveoli, triggering persistent inflammatory responses that can contribute to asthma progression, reduced lung function, and heightened sensitivity to respiratory infections [8]. VOCs interact with mucosal and neural pathways, influencing autonomic regulation and producing symptoms such as headaches, concentration difficulty, and fatigue when exposure occurs over time [9].

CO_2 accumulation, while not directly toxic at moderate levels, affects oxygen exchange efficiency in the bloodstream and has been associated with reduced cognitive performance, including impaired decision-making and slowed response time in controlled studies [10]. Elevated indoor humidity promotes mold spore proliferation, which in turn activates immune sensitivity responses, contributing to long-term allergic inflammation, sinus irritation, and increased risk of chronic respiratory disease in susceptible individuals [11].

Neurological stress arises when repeated exposure to irritants and CO_2 disrupts normal neurotransmitter regulation, influencing attention, memory retention, and emotional regulation [12]. This is particularly critical in children, whose neural development is ongoing, and in hospital patients recovering from systemic illness [13].

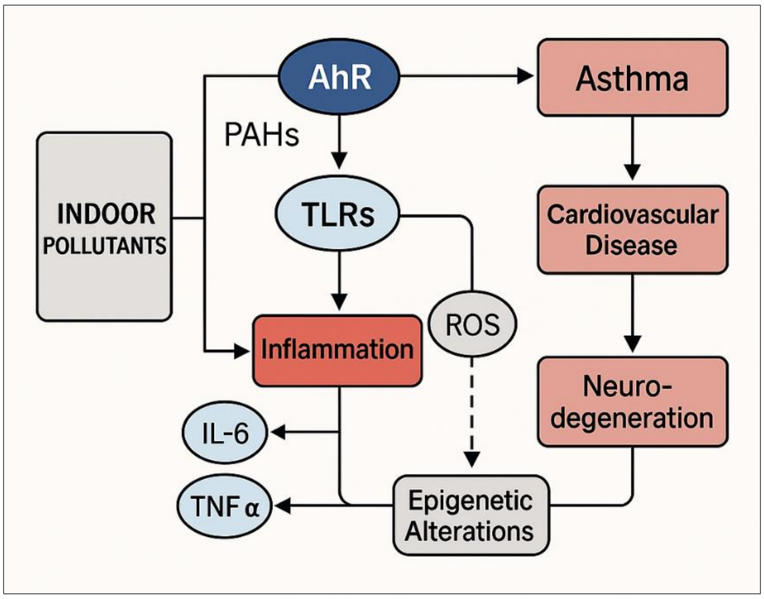

Figure 1 Key Biological Pathways Linking Indoor Pollutants to Long-Term Health Outcomes

This figure should illustrate pollutant entry routes, respiratory inflammation cascades, immune modulation pathways, and neural cognitive effects, emphasizing cumulative exposure rather than acute reaction [14].

Over months and years, these physiological stress processes interact, gradually affecting wellbeing even when pollutant levels remain below acute regulatory thresholds [15]. Thus, IAQ must be understood not only in terms of immediate symptom onset but also long-term cumulative health implications across diverse population groups [16].

3. Cognitive and behavioral consequences of long-term exposure

3.1. Effects on Cognitive Performance and Attention

Long-term exposure to suboptimal Indoor Air Quality (IAQ) has been consistently associated with declines in cognitive functioning, particularly in environments requiring sustained mental engagement such as classrooms and office workspaces [13]. Elevated carbon dioxide (CO_2) levels can reduce oxygen exchange efficiency and impair cerebral blood flow, leading to slower processing speed, decreased attention span, and difficulty maintaining task focus over time [14]. Concurrently, volatile organic compounds (VOCs) and fine particulate matter (PM2.5) exert subtle but cumulative neurophysiological effects, influencing neurotransmitter regulation and cortical activation patterns associated with working memory and executive decision-making [15]. These effects may not manifest as immediate symptoms but instead emerge gradually as chronic cognitive fatigue, increased distractibility, and lowered mental endurance during complex or repetitive tasks [16].

In office environments, this reduced cognitive function translates to diminished ability to sustain analytical reasoning, lowered concentration during meetings, and increased likelihood of errors in routine decision-making tasks [17]. In classrooms, where attention and memory are foundational for learning continuity, the consequences may be even more pronounced, resulting in reduced capacity for concept retention, weaker reading comprehension, and slower problem-solving performance [18]. The subtlety of these cognitive shifts often leads them to be attributed to stress or workload rather than environmental exposure, further delaying recognition and intervention [19]. As such, understanding IAQ as a determinant of cognitive performance challenges traditional assumptions that associate indoor air considerations solely with physical comfort rather than intellectual capacity and productivity [20].

3.2. Behavioral and Productivity Outcomes

Beyond cognitive functioning, chronic exposure to poor IAQ influences emotional regulation, task motivation, and occupational or academic productivity [21]. Irritants such as VOCs and airborne microbial fragments have been linked to heightened inflammatory responses that, over time, may contribute to mood instability, irritability, and decreased frustration tolerance [13]. These subtle behavioral changes can compound workplace or classroom stress, reducing social cohesion and collaborative effectiveness.

Decision fatigue is also a documented outcome in environments with elevated CO_2 concentrations, where individuals may experience diminished confidence in judgment and increased reliance on routine or simplified decision pathways, potentially influencing organizational efficiency and learning outcomes [14]. In professional settings, this fatigue often correlates with decreased workflow efficiency, slower task completion rates, and increased need for breaks to maintain performance [15].

Absenteeism is another long-term behavioral indicator of IAQ influence. Repeated exposure to airborne irritants can increase susceptibility to respiratory infection, sinus irritation, and fatigue-related illness, prompting longer or more frequent absences from work or school [16]. Over time, this pattern generates measurable productivity losses at organizational and system levels [17]. Burnout risk is similarly elevated when cognitive load is persistently intensified by environmentally induced fatigue, especially in high-demand settings such as healthcare and education [18].

These behavioral effects illustrate that IAQ is not solely an environmental parameter but a factor embedded in the broader psychosocial and operational dynamics that shape well-being, workforce sustainability, and institutional performance [19]. Addressing IAQ can therefore produce measurable gains in both emotional wellness and productivity outcomes [20].

3.3. IAQ and Cognitive Development in Children

Children are particularly vulnerable to chronic IAQ exposure due to ongoing neurological development and higher respiration rates relative to body mass [21]. Their developing brains rely on stable oxygenation and balanced neurotransmitter systems; long-term exposure to elevated CO_2 and particulate matter can alter synaptic development and neural connectivity patterns essential for memory formation, emotional regulation, and language acquisition [22].

In educational settings, these environmental burdens intersect with formative learning processes, amplifying consequences. Children spending multiple hours in poorly ventilated classrooms may experience slower reading fluency progression, reduced numeracy retention, and decreased capacity to sustain attention during instructional activities [15]. These changes may persist subtly over time, contributing to learning delays, uneven achievement patterns, and differential educational outcomes across school environments [17].

Table 1 Documented Cognitive Effects of Chronic Indoor Air Quality (IAQ) Exposure Across Age Groups

Age Group	Primary IAQ Sensitivities	Documented Cognitive Effects	Typical Exposure Settings	Notes on Vulnerability
Young Children (0–10 yrs)	Elevated CO_2, PM2.5/PM10, mold spores, VOCs	Reduced attention span, slowed information processing, impaired working memory, difficulty sustaining classroom engagement	Daycare centers, primary schools, shared residential living spaces	Rapid neurological development periods make this group highly sensitive to even moderate chronic exposure. Effects may manifest as learning delays over time.
Adolescents (11–18 yrs)	CO_2 buildup in enclosed classrooms, chemical residues from cleaning products, poor ventilation cycles	Increased mental fatigue, reduced problem-solving accuracy, decreased test performance, task disengagement	Secondary schools, boarding schools, exam halls	Cognitive load during academic development amplifies the impact of air quality on performance outcomes and long-term academic achievement trajectories.
Adults (19–64 yrs)	VOCs from furnishings, chronic CO_2 elevation in offices, particulate matter in poorly filtered HVAC environments	Lowered decision-making speed, decreased productivity, increased irritability and cognitive fatigue, reduced sustained focus	Office buildings, government facilities, industrial workspaces, libraries	Effects often appear subtly and accumulate, influencing workplace efficiency and burnout patterns rather than immediate clinical symptoms.

Older Adults (65+ yrs)	PM2.5, microbiological contaminants, fluctuating humidity promoting mold growth	Compromised short-term memory stability, worsened executive function, increased confusion or disorientation in unfamiliar spaces	Hospitals, long-term care facilities, community centers	Pre-existing respiratory and neurological conditions heighten the magnitude of IAQ-related cognitive decline, with slower recovery from exposure.

This table should categorize cognitive impacts according to children, adults, and older adults, noting effects such as attention disruption, slowed processing speed, emotional dysregulation, and memory decline [19].

Recognizing IAQ as a developmental determinant supports the need for long-term monitoring and intervention strategies in child-occupied public spaces, particularly those with aging infrastructure or high population density [20].

4. IAQ in schools and hospitals: sector-specific risks

4.1. Schools as High-Impact Exposure Environments

Schools represent some of the highest-risk public buildings for long-term Indoor Air Quality (IAQ) exposure because students and teachers occupy classrooms for extended hours within relatively enclosed spaces [20]. Classroom layouts often involve many individuals sharing a single air volume, and ventilation systems are frequently outdated, insufficiently maintained, or reliant on manual window opening rather than mechanical air exchange [21]. In many regions, schools originally designed for natural ventilation have since undergone window sealing for security or energy efficiency purposes, reducing fresh air flow while failing to integrate compensatory ventilation upgrades [22].

Children contribute additional respiratory load through organic bioeffluents, while classroom materials such as markers, cleaning sprays, glues, and aging flooring introduce volatile organic compounds (VOCs) that accumulate over time when airflow is limited [23]. Moreover, older school buildings are more susceptible to mold infiltration due to roof leaks, plumbing failures, and poor humidity regulation. These microbial contaminants can remain aerosolized and continuously recirculated, particularly in schools with forced-air systems that lack adequate filtration [24].

The consequences of inadequate IAQ in schools extend beyond respiratory discomfort. Research shows that elevated carbon dioxide (CO_2) levels and fine particulate concentrations correlate with decreased attention, slower learning progression, disrupted memory recall, and lower standardized test performance in children [25]. These cognitive effects are gradual and cumulative, making them easily misattributed to behavioral or socioeconomic factors rather than environmental exposure [26]. Teachers are similarly affected: chronic exposure contributes to increased fatigue, voice strain, headaches, and absenteeism, conditions that may reduce instructional quality and continuity [27].

Addressing IAQ in schools therefore requires systematic and sustained environmental intervention rather than isolated remediation efforts, recognizing that healthy learning environments are foundational for cognitive development and educational equity across communities [28].

4.2. Hospitals and Clinical Spaces

Hospitals present a different but equally critical IAQ context, where indoor air influences not only comfort but clinical outcomes, infection control, and staff performance [20]. Unlike schools, hospitals operate continuously, meaning ventilation, cleaning, and occupancy pressures occur around the clock. Medical facilities house individuals with compromised immune systems, making them more sensitive to airborne pathogens, particulate matter, and chemical disinfectant fumes [21]. Even mild reductions in IAQ can slow patient healing, exacerbate existing respiratory conditions, and increase susceptibility to hospital-acquired infections [22].

Ventilation systems in hospitals are typically more complex, integrating isolation wards, filtered intake systems, and positive or negative pressure differentials designed to prevent microbial spread. However, when these systems are improperly calibrated or filters are not regularly replaced, pollutants and pathogens may recirculate rather than be removed [23]. Additionally, the heavy use of sterilizing chemicals, anesthetic gases, and pharmaceutical aerosols introduces airborne compounds that can accumulate in poorly ventilated zones, contributing to irritation and long-term inflammatory effects [24].

Clinical staff also face continuous IAQ exposure. Long working hours in air-controlled environments increase vulnerability to CO_2 buildup and VOC concentration shifts. These exposures have been associated with fatigue, decreased attention, slowed response times, and burnout risk among healthcare workers, particularly in emergency and surgical units requiring high alertness and rapid decision-making [25].

Patients recovering from surgery or respiratory illness are particularly at risk; even minor shifts in humidity or particulate concentration can influence recovery progression, lung function, and infection probability [26]. Thus, IAQ is not merely a facilities-management concern but an integral component of medical treatment and operational efficiency within healthcare systems [27]. Ensuring adequate ventilation, filtration, and material safety standards is therefore essential for both patient outcomes and staff resilience [28].

4.3. Economic and Social Consequences of IAQ in Public Institutions

The long-term implications of inadequate IAQ extend beyond immediate health effects and influence broader economic and social outcomes across communities [21]. In schools, reduced cognitive performance and attention capacity contribute to measurable learning loss, which can accumulate over academic years and translate into lower educational attainment, decreased workforce readiness, and diminished lifetime earning capacity [22]. These effects have cascading impacts on national productivity, as educational systems are foundational to economic development and social mobility [23].

In hospitals, delays in patient recovery due to respiratory irritation, immune stress, or microbial exposure increase treatment duration and resource consumption [24]. Extended hospital stays place pressure on bed availability, staffing schedules, pharmaceutical use, and insurance cost structures. Healthcare systems already operating near capacity are particularly vulnerable to compounding burdens from environmentally mediated recovery slowdowns [25]. Moreover, increased staff absenteeism due to fatigue or illness linked to IAQ places strain on clinical teams and can reduce quality of care delivery [26].

Public institutions serve broad populations, meaning IAQ inequities may reinforce wider patterns of social inequality. Schools in low-income areas and hospitals with limited infrastructure budgets are often those with the poorest IAQ conditions, deepening disparities in health and educational outcomes [27].

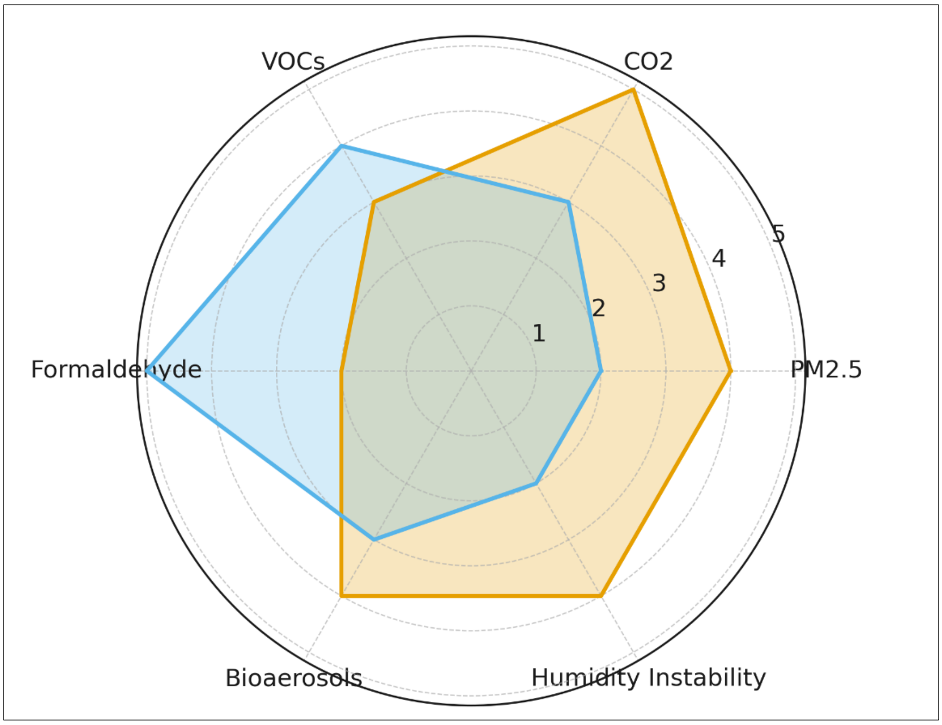

Figure 2 Comparative IAQ Exposure Profiles in Schools vs. Hospitals

This figure should visually contrast pollutant types, exposure duration, population vulnerability, and systemic consequences to highlight distinct yet interconnected IAQ priorities in both settings [28].

Recognizing IAQ as a structural determinant of societal wellbeing underscores the need for policy frameworks that treat indoor air as a public good and a foundational building block for economic resilience and population health.

5. IAQ monitoring, data challenges, and exposure assessment methods

5.1. Short-Term vs. Longitudinal Monitoring Approaches

Indoor Air Quality (IAQ) assessment approaches vary significantly in both duration and analytical intent. Short-term or “snapshot” measurements typically involve using handheld meters or periodic sampling devices to record pollutant concentrations at specific moments in time [26]. These assessments are often used during building inspections, regulatory compliance evaluations, or HVAC maintenance checks, and they provide useful data on immediate environmental conditions. However, short-term measurements may fail to capture the dynamic fluctuations of pollutant levels influenced by occupancy patterns, ventilation cycling, cleaning activities, and seasonal environmental changes [27]. As a result, critical exposure variations may be overlooked, especially those that occur outside standard working or school hours [28].

In contrast, longitudinal monitoring deploys continuous or regularly intervalled measurements over weeks, months, or even full-year cycles. This approach allows for the identification of recurring daily trends, seasonal influence patterns, and building usage-related exposure peaks [29]. Continuous monitoring can also detect gradual system degradation, such as declining ventilation efficiency or filter saturation, that may not be evident in isolated measurements [30]. Longitudinal monitoring networks are particularly valuable in schools and hospitals, where extended exposure durations and vulnerable populations make cumulative pollutant loads more consequential [31].

Ultimately, while short-term assessments provide immediate diagnostic information, they are insufficient for evaluating long-term cognitive and health impacts. Sustained monitoring enables holistic understanding of exposure profiles, linking IAQ to behavioral, physiological, and performance outcomes over time [32].

5.2. Sensor Networks and Spatial Data Integration

Recent advancements in sensor technology have enabled more complex and fine-grained IAQ monitoring frameworks. Low-cost environmental sensors are now capable of measuring CO_2, VOCs, particulate matter, humidity, and temperature simultaneously, enabling distributed monitoring across multiple room zones and building floors [26]. When integrated into a network, these sensors can map pollutant concentrations spatially, revealing patterns such as localized stagnation zones, high-emission material clusters, or ventilation dead spots [33].

Spatial IAQ mapping is further enhanced when coupled with building information modeling (BIM) and airflow simulation technologies. Computational fluid dynamics (CFD) models, for instance, can simulate air movement under various ventilation conditions, illustrating how pollutants circulate, accumulate, or dissipate within complex interior layouts [27]. This integration allows facility managers to identify structural or mechanical causes of exposure hotspots, informing targeted remediation such as adjusting diffuser locations, recalibrating air pressure zones, or modifying space usage patterns [28].

Moreover, time-synchronized data from networked sensors allow analysis of human behavior interactions with ventilation systems. For example, window-opening patterns, HVAC occupancy mode shifts, and door movement can all influence airflow and pollutant dispersion [31]. Real-time dashboards and automated alerts enable proactive intervention when pollutant thresholds are exceeded, reducing reliance on delayed manual inspections [34].

These combined spatial and temporal IAQ monitoring strategies support a transition from reactive responses to predictive building health management, improving both occupant well-being and operational efficiency [29].

5.3. Data Interpretation Challenges

Although sensor-based IAQ monitoring yields large and detailed datasets, interpreting this information remains complex. Pollutant levels fluctuate due to multiple interacting factors, including ventilation intensity, outdoor weather conditions, room occupancy density, cleaning schedules, and building envelope leakage variability [30]. As a result, distinguishing between structural IAQ deficiencies and temporary environmental shifts requires careful temporal trend analysis rather than reliance on single high or low readings [27].

Additionally, pollutant exposure does not always correlate linearly with concentration levels. For example, CO_2 thresholds associated with cognitive decline may occur at lower levels than those required to cause respiratory discomfort, complicating the establishment of universal exposure guidelines [31]. Seasonal variations add further complexity, as temperature and humidity shifts influence both ventilation behavior and microbial activity [32].

Table 2 IAQ Measurement Tools and Their Strengths and Limitations

Measurement Tool	Primary Parameters Measured	Strengths	Limitations	Typical Use Contexts
Handheld IAQ Meters	CO_2, temperature, humidity, sometimes VOCs	Portable, fast spot-checks, useful for inspections and classroom evaluations	Only provides momentary readings; cannot represent daily or seasonal variability	Facilities audits, classroom checks, quick workplace diagnostics
Passive Diffusion Badges / Samplers	VOCs, ozone, formaldehyde, some gases	Low-cost, silent operation, does not require power; can accumulate exposure over hours or days	Requires laboratory analysis; slower feedback; limited pollutant range	Long-duration exposure estimation, epidemiology studies, hospital environmental monitoring
Continuous Smart Sensors / IoT IAQ Nodes	CO_2, VOCs, PM2.5/PM10, temperature, humidity	Enables real-time monitoring; integration with dashboards; supports trend and anomaly detection	Data quality varies by calibration; sensors may drift over time; requires network infrastructure	Schools, offices, public buildings, long-term monitoring programs
HVAC-Integrated Air Quality Sensors	CO_2, pressure differentials, sometimes particulates	Automates ventilation adjustment; provides system-level control feedback	May not capture localized indoor hotspots; dependent on HVAC maintenance quality	Hospitals, controlled ventilation buildings, surgical and laboratory environments
Grab Air Samples with Laboratory Analysis	Wide chemical and microbiological range (e.g., mold spores, VOC speciation)	Highly accurate and specific pollutant identification possible	Resource-intensive; results not immediate; not suitable for continuous tracking	Confirmatory diagnostics, outbreak investigation, clinical environment IAQ verification

This table should compare handheld meters, passive samplers, continuous smart sensors, HVAC-integrated monitors, and laboratory-based air sampling, highlighting cost, timescale, accuracy, and interpretive considerations [33].

Robust IAQ evaluation therefore requires not only accurate measurement but also contextual interpretation grounded in building dynamics, occupant behavior, and environmental cycles to avoid misleading conclusions [34].

6. Intervention strategies and design solutions

6.1. Adaptive HVAC and Smart Ventilation Control

Advances in building ventilation systems now make it possible to actively respond to real-time indoor air conditions. Adaptive HVAC systems integrate pollutant sensors, occupancy data, and automated control algorithms to adjust ventilation rates based on the measured concentration of CO_2, VOCs, humidity, and particulate matter rather than predefined schedules [32]. This dynamic approach ensures that fresh air supply increases during periods of high occupancy or pollutant spikes, while reducing ventilation when indoor conditions stabilize, thereby balancing indoor air quality (IAQ) goals with energy efficiency considerations [33].

Smart HVAC control platforms can also incorporate predictive modeling based on historical data, weather forecasts, and building usage patterns, allowing ventilation strategies to anticipate conditions rather than react exclusively in real time [34]. For example, in schools, systems can pre-purge classrooms before arrival periods, or in hospitals, systems can strengthen air changes in wards with immunocompromised patients before periods of increased staff movement [35].

Zonal ventilation adjustments further optimize IAQ by focusing airflow to the specific areas where pollutant levels are highest rather than applying building-wide ventilation uniformly.

Integration with Building Management Systems (BMS) enables continuous monitoring dashboards, automated alerts, and data storage for long-term evaluation. Automated filter status tracking and airflow diagnostics extend equipment lifespan and minimize inefficiencies associated with hidden mechanical degradation [36].

However, the effectiveness of adaptive HVAC systems depends on proper commissioning and continuous calibration. Without institutional commitment to monitoring and maintenance, automated systems may gradually drift away from designed performance targets [37]. Thus, smart ventilation control represents not only a technological solution but also a management practice requiring training, policy alignment, and ongoing operational oversight [38].

6.2. Material and Surface Selection for Low-Emissions Building Design

Indoor pollutant concentrations are strongly influenced by the materials used in walls, flooring, furniture, and surface finishes. Many common construction and interior products release VOCs and semi-volatile compounds over extended periods, particularly when new or exposed to heat and humidity [32]. Selecting low-emission materials is therefore a primary strategy for preventing IAQ degradation at the source rather than attempting to manage emissions after release.

Low-formaldehyde and zero-VOC paints reduce chemical off-gassing during and after application, supporting healthier indoor environments in classrooms and patient rooms [33]. Similarly, flooring choices such as natural linoleum, ceramic tile, or low-emission vinyl alternatives can substantially reduce persistent VOC loads compared to synthetic carpeting, which can trap particulate matter and re-emit absorbed compounds when disturbed [34]. Adhesives and sealants used in construction and furniture assembly are often major contributors to VOC concentration; prioritizing water-based or mechanically bonding alternatives can limit pollutant generation at installation and throughout the building's lifecycle [35].

Cleaning agents also influence IAQ. Hospitals and schools rely heavily on disinfectants that can emit strong fumes or leave aerosol residues. Selecting low-emission, fragrance-free cleaning products and providing adequate ventilation during cleaning cycles can reduce cumulative chemical exposure for both staff and occupants [36].

Material selection is most effective when considered early in the architectural design process, where lifecycle emissions and occupant sensitivity can be integrated into procurement standards, maintenance planning, and long-term environmental performance criteria [37].

6.3. Occupant Behavior Modeling

Even in buildings equipped with sophisticated ventilation and low-emission materials, occupant behavior significantly influences IAQ. Window-opening habits, door-holding patterns, and room-use densities can either support or undermine ventilation strategies [32]. For example, in naturally ventilated schools, windows may remain closed during cold or hot seasons, allowing CO_2 and VOC concentrations to rise faster than anticipated by system models [33]. In hospitals, staff may prop doors open to facilitate workflow efficiency, unintentionally weakening pressure differentials designed to isolate airborne contaminants [34].

Seasonal patterns also affect behavior; heating periods often lead to reduced ventilation and lower humidity, while rainy seasons increase moisture levels that encourage mold growth [35]. Understanding these behavioral cycles enables IAQ management to shift from building-only solutions to combined socio-environmental strategies.

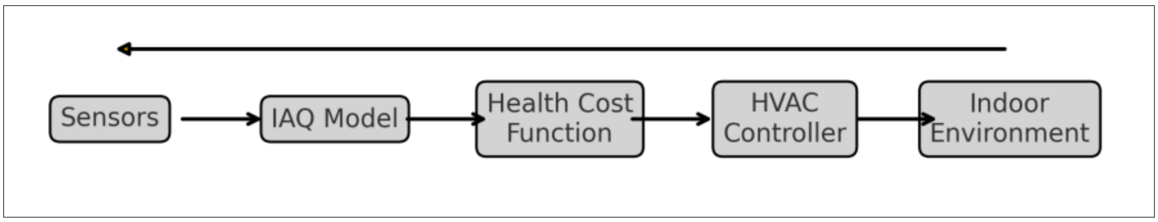

Figure 3 Integrated IAQ-Health-Energy Optimization Model

This figure should illustrate the interaction between building systems, material choices, and occupant behaviors as interconnected drivers of air quality outcomes [36].

Behavior modeling frameworks support targeted education campaigns, signage, and automated prompts that encourage ventilation-supportive activities without imposing behavioral burdens on occupants [37].

6.4. Cost-Benefit Implications of IAQ-Focused Design

Although IAQ-focused ventilation, material selection, and monitoring systems require upfront investment, long-term economic benefits often outweigh initial costs. Improved IAQ reduces absenteeism, increases workplace performance efficiency, enhances learning outcomes, and shortens patient recovery times, yielding measurable financial returns for schools and healthcare systems [32]. Energy-optimized ventilation strategies can also limit operational cost increases associated with higher air exchange rates [33]. Preventative environmental health measures are therefore more cost-effective than reactive medical or remediation responses, demonstrating that IAQ-centered design enhances both human health and institutional sustainability [34].

7. Future directions and sustainability implications

7.1. Policy Needs and Regulatory Gaps

Current IAQ regulatory frameworks often emphasize short-term exposure thresholds rather than the cumulative impacts that develop over months and years in continuously occupied buildings [36]. Most standards focus on momentary pollutant concentrations, overlooking how long-duration exposure influences cognitive development, immune system sensitivity, and chronic disease risk in children, patients, and workers [37]. Furthermore, regulatory oversight tends to be fragmented across building codes, occupational safety guidelines, and environmental health directives, creating gaps in enforcement and accountability [38]. Schools and hospitals, despite housing highly vulnerable populations, often lack mandatory continuous monitoring requirements and instead rely on periodic inspections that may miss sustained IAQ deterioration [39]. Effective policy reform requires integrating IAQ targets into ventilation design standards, occupant density regulations, maintenance protocols, and material procurement guidelines [40]. Additionally, policy must support funding mechanisms that allow public institutions to upgrade ventilation infrastructure rather than rely on temporary mitigations [37].

7.2. Digital Twins and Predictive Indoor Exposure Modeling

Emerging computational approaches are reshaping how IAQ is monitored and managed. Digital twin systems create real-time virtual models of buildings that simulate pollutant movement, ventilation dynamics, occupancy behaviors, and material emissions simultaneously [33]. When combined with machine learning algorithms, these digital models can forecast periods of elevated pollutant exposure before they occur, enabling proactive HVAC adjustments and targeted ventilation interventions [36]. Such predictive capability is particularly valuable in high-density settings like classrooms and surgical wings, where even moderate changes in airflow patterns can alter exposure distribution [23]. By integrating sensor network inputs, weather data, and historical behavioral trends, digital twins allow building managers to test hypothetical scenarios such as altered window-use patterns or modified cleaning schedules to evaluate IAQ outcomes without physical trial-and-error [34]. However, these systems require sustained investment in data infrastructure, technical expertise, and institutional readiness to ensure accurate interpretation and responsible deployment [25].

7.3. Addressing Climate and Equity Dimensions

IAQ challenges intersect with equity and climate vulnerability. Aging public buildings, limited ventilation investment, and higher urban pollution exposure disproportionately affect low-income communities and children [40]. Climate-driven heat and humidity extremes further compound pollutant persistence, emphasizing the need for IAQ strategies that prioritize both environmental justice and long-term resilience [40].

8. Conclusion

Long-term exposure to indoor air pollutants must be recognized as a central determinant of public health and cognitive functioning rather than a secondary comfort or maintenance concern. The evidence presented highlights that schools, hospitals, and other public buildings are environments where cumulative exposure effects are particularly pronounced, influencing children's learning trajectories, patient recovery outcomes, workforce productivity, and general wellbeing. Addressing IAQ therefore requires a shift from reactive, short-duration measurement approaches toward integrated strategies that combine adaptive ventilation systems, low-emission material selection, continuous monitoring networks, and informed occupant practices. At the same time, policy frameworks must evolve to reflect the realities of chronic exposure, establishing standards that safeguard vulnerable populations and incentivize proactive building health management. By aligning building design, operational practices, and regulatory oversight, IAQ can be effectively positioned as a core component of sustainable public infrastructure protecting human development potential as well as environmental performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Zhou J, Wang H, Huebner G, Zeng Y, Pei Z, Ucci M. Short-term exposure to indoor PM2. 5 in office buildings and cognitive performance in adults: An intervention study. Building and Environment. 2023 Apr 1;233:110078.

[2] Qiu Y, Yang FA, Lai W. The impact of indoor air pollution on health outcomes and cognitive abilities: empirical evidence from China. Population and Environment. 2019 Jun 15;40(4):388-410.

[3] Midouhas E, Kokosi T, Flouri E. Outdoor and indoor air quality and cognitive ability in young children. Environmental Research. 2018 Feb 1;161:321-8.

[4] Adeyanju BE, Bello M. Storage stability and sensory qualities of Kango prepared from maize supplemented with kidney bean flour and alligator pepper. IOSR Journal of Humanities and Social Science (IOSR-JHSS). 2022;27(1, Series 3):48-55. doi:10.9790/0837-2701034855

[5] Tzivian L, Winkler A, Dlugaj M, Schikowski T, Vossoughi M, Fuks K, Weinmayr G, Hoffmann B. Effect of long-term outdoor air pollution and noise on cognitive and psychological functions in adults. International journal of hygiene and environmental health. 2015 Jan 1;218(1):1-1.

[6] Omogiate PM. Designing automated audit mechanisms to evaluate compliance of generative AI platforms with federal authorship and ownership disclosure requirements. International Journal of Science and Research Archive. 2023;10(2):1536–1549. doi:10.30574/ijsra.2023.10.2.1099.

[7] Śmiełowska M, Marć M, Zabiegała B. Indoor air quality in public utility environments—a review. Environmental Science and Pollution Research. 2017 Apr;24(12):11166-76.

[8] Rajagopalan P, Andamon MM, Woo J. Year long monitoring of indoor air quality and ventilation in school classrooms in Victoria, Australia. Architectural Science Review. 2022 Jan 2;65(1):1-3.

[9] Afolabi OS. Load-Bearing Capacity Analysis and Optimization of Beams, Slabs, and Columns. Communication In Physical Sciences. 2020 Dec 30;6(2):941-52.

[10] Wargocki P, Wyon DP. Providing better thermal and air quality conditions in school classrooms would be cost-effective. Building and Environment. 2013 Jan 1;59:581-9.

[11] Fleming R, Purandare N. Long-term care for people with dementia: environmental design guidelines. International psychogeriatrics. 2010 Nov;22(7):1084-96.

[12] Rumbidzai Derera. HOW FORENSIC ACCOUNTING TECHNIQUES CAN DETECT EARNINGS MANIPULATION TO PREVENT MISPRICED CREDIT DEFAULT SWAPS AND BOND UNDERWRITING FAILURES. International Journal of Engineering Technology Research & Management (IJETRM). 2017Dec21;01(12):112–27.

[13] Calderón-Garcidueñas L, Calderón-Garcidueñas A, Torres-Jardón R, Avila-Ramírez J, Kulesza RJ, Angiulli AD. Air pollution and your brain: what do you need to know right now. Primary health care research & development. 2015 Jul;16(4):329-45.

[14] Bamidele Igbagbosanmi John. CROSS-FUNCTIONAL ENGINEERING LEADERSHIP COORDINATING MULTIDISCIPLINARY TEAMS TO ACHIEVE SYNCHRONIZED EXECUTION, TECHNICAL ALIGNMENT, AND CONSISTENT OPERATIONAL IMPROVEMENT IN MANUFACTURING. International Journal Of Engineering Technology Research and Management (IJETRM). 2022Dec21;06(12):161–77.

[15] Oudin A, Forsberg B, Adolfsson AN, Lind N, Modig L, Nordin M, Nordin S, Adolfsson R, Nilsson LG. Traffic-related air pollution and dementia incidence in northern Sweden: a longitudinal study. Environmental health perspectives. 2016 Mar;124(3):306-12.

[16] Clements N, Zhang R, Jamrozik A, Campanella C, Bauer B. The spatial and temporal variability of the indoor environmental quality during three simulated office studies at a living lab. Buildings. 2019 Mar 11;9(3):62.

[17] Onyechi VN. Modern Reservoir Optimization Techniques: Data-Guided Field Development Strategies for Improving Hydrocarbon Recovery and Reducing Operational Uncertainty. International Journal of Computer Applications Technology and Research. 2019;9(12):465–474. doi:10.7753/IJCATR0912.1014.

[18] Chen H, Kwong JC, Copes R, Hystad P, van Donkelaar A, Tu K, Brook JR, Goldberg MS, Martin RV, Murray BJ, Wilton AS. Exposure to ambient air pollution and the incidence of dementia: a population-based cohort study. Environment international. 2017 Nov 1;108:271-7.

[19] Voyer P, Verreault R, Azizah GM, Desrosiers J, Champoux N, Bédard A. Prevalence of physical and verbal aggressive behaviours and associated factors among older adults in long-term care facilities. BMC geriatrics. 2005 Nov 10;5(1):13.

[20] Kelly FJ, Fussell JC. Air pollution and public health: emerging hazards and improved understanding of risk. Environmental geochemistry and health. 2015 Aug;37(4):631-49.

[21] Otoko J. Multi-objective optimization of cost, contamination control, and sustainability in cleanroom construction: A decision-support model integrating Lean Six Sigma, Monte Carlo Simulation, and Computational Fluid Dynamics (CFD). Int J Eng Technol Res Manag. 2023;7(1):108.

[22] Parkinson T, Parkinson A, de Dear R. Continuous IEQ monitoring system: Context and development. Building and Environment. 2019 Feb 1;149:15-25.

[23] Ibitoye JS. Securing smart grid and critical infrastructure through AI-enhanced cloud networking. International Journal of Computer Applications Technology and Research. 2018;7(12):517-529. doi:10.7753/IJCATR0712.1012.

[24] Enyiorji P. Blockchain-enforced data lineage architectures with formal verification workflows enabling auditable AI decision chains across regulated fintech compliance regimes and supervisory reporting. International Journal of Science and Research Archive. 2023;9(2):1201–1217. doi:10.30574/ijsra.2023.9.2.0559.

[25] Tang X, Misztal PK, Nazaroff WW, Goldstein AH. Volatile organic compound emissions from humans indoors. Environmental science & technology. 2016 Dec 6;50(23):12686-94.

[26] John BI. Data-driven resource optimization approaches enhancing capacity planning, labor utilization, material efficiency and continuous improvement across manufacturing project lifecycles. GSC Advanced Research and Reviews. 2023;17(3):220–236. doi: https://doi.org/10.30574/gscarr.2023.17.3.0467

[27] Mendell MJ, Heath GA. Do indoor pollutants and thermal conditions in schools influence student performance? A critical review of the literature. Indoor air. 2005 Jan 1;15(1):27-52.

[28] Omogiate PM. Designing automated audit mechanisms to evaluate compliance of generative AI platforms with federal authorship and ownership disclosure requirements. International Journal of Science and Research Archive. 2023;10(2):1536–1549. doi:10.30574/ijsra.2023.10.2.1099.

[29] Broberg AG, Wessels H, Lamb ME, Hwang CP. Effects of day care on the development of cognitive abilities in 8-year-olds: A longitudinal study. Developmental psychology. 1997 Jan;33(1):62.

[30] Ghaffarianhoseini A, AlWaer H, Omrany H, Ghaffarianhoseini A, Alalouch C, Clements-Croome D, Tookey J. Sick building syndrome: are we doing enough?. Architectural Science Review. 2018 May 4;61(3):99-121.

[31] Atanda ED. EXAMINING HOW ILLIQUIDITY PREMIUM IN PRIVATE CREDIT COMPENSATES ABSENCE OF MARK-TO-MARKET OPPORTUNITIES UNDER NEUTRAL INTEREST RATE ENVIRONMENTS. International Journal Of Engineering Technology Research & Management (IJETRM). 2018Dec21.;2(12):151-64.

[32] Riemersma-van Der Lek RF, Swaab DF, Twisk J, Hol EM, Hoogendijk WJ, Van Someren EJ. Effect of bright light and melatonin on cognitive and noncognitive function in elderly residents of group care facilities: a randomized controlled trial. Jama. 2008 Jun 11;299(22):2642-55.

[33] Giles LV, Koehle MS. The health effects of exercising in air pollution. Sports Medicine. 2014 Feb;44(2):223-49.

[34] Smith KR, Mehta S, Maeusezahl-Feuz M. Indoor air pollution from household use of solid fuels. Comparative quantification of health risks: global and regional burden of disease attributable to selected major risk factors. 2004;2:1435-93.

[35] Hutter HP, Moshammer H, Wallner P, Kundi M. Subjective symptoms, sleeping problems, and cognitive performance in subjects living near mobile phone base stations. Occupational and environmental medicine. 2006 May 1;63(5):307-13.

[36] Calderón-Garcidueñas L, Solt AC, Henríquez-Roldán C, Torres-Jardón R, Nuse B, Herritt L, Villarreal-Calderón R, Osnaya N, Stone I, García R, Brooks DM. Long-term air pollution exposure is associated with neuroinflammation, an altered innate immune response, disruption of the blood-brain barrier, ultrafine particulate deposition, and accumulation of amyloid β-42 and α-synuclein in children and young adults. Toxicologic pathology. 2008 Feb;36(2):289-310.

[37] Passchier-Vermeer W, Passchier WF. Noise exposure and public health. Environmental health perspectives. 2000 Mar;108(suppl 1):123-31.

[38] Feng Z, Liu C, Guan X, Mor V. China's rapidly aging population creates policy challenges in shaping a viable long-term care system. Health Affairs. 2012 Dec 1;31(12):2764-73.

[39] Derera R. Machine learning-driven credit risk models versus traditional ratio analysis in predicting covenant breaches across private loan portfolios. International Journal of Computer Applications Technology and Research. 2016;5(12):808-820. doi:10.7753/IJCATR0512.1010.

[40] Hodgson MJ, Morey P, Leung WY, Morrow L, Miller D, Jarvis BB, Robbins H, Halsey JF, Storey E. Building-Associated Pulmonary Disease From Exposure toStachybotrys chartarum and Aspergillus versicolor. Journal of Occupational and Environmental Medicine. 1998 Mar 1;40(3):241-9.