Continental J. Applied Sciences
Oyetunde and Bello (2026) 21 (3): 73 – 88 Doi: 10.5281/zenodo.20434901

Indoor Air Quality in Built Environments: Emerging Challenges, Health Implications, and Sustainable Management Approaches

Julius Gbemiga Oyetunde[1] and Lateef Bello[2]
[1]Department of Chemical Sciences, Bamidele Olomilua University of Education, Science, and Technology, Ikere-Ekiti, Ekiti State
[2]Department of Science and Laboratory Technology, Rufus Giwa Polytechnic, Owo Ondo State

Abstract

Rapid urbanization, modifications in the design and construction of built environments, time spent indoors, and shifting exposure patterns have highlighted indoor air quality (IAQ) as a critical issue in public health and the environment. Today's populations will spend most of their lives (80-90%) indoors, making exposure inside the homes dominant in contributing to total burden. An indoor environment is a complex mixture of particulate matter (PM), volatile organic compounds (VOCs), biologic pollutants, combustion products, and gas phase pollutants from both outdoor and indoor sources. Previous studies have linked poor IAQ to respiratory disease, cardiovascular disease, neurocognitive dysfunction, allergies, reduced productivity, etc., and recently to microbial aerosols, carbon dioxide accumulation, and smart sensing technologies. In this paper, we review recent advancements in IAQ research and discuss the source and exposure routes, as well as the effects on health and new strategies in managing IAQ. Specific focus is given to sustainable building design, innovative technologies, and priorities for future research.

Keywords: Indoor air quality; particulate matter; volatile organic compounds; health risk; built environment; ventilation; sustainable buildings

Received: 15 February 2025 **Accepted: 22 May 2025**

Citation: Oyetunde, J.G. and Bello, L. (2026). Indoor Air Quality in Built Environments: Emerging Challenges, Health Implications, and Sustainable Management Approaches. Continental J. Applied Sciences, 21(3), 73-88. Doi: 10.5281/zenodo.20434901

Introduction

Today, the indoors will represent the predominant microenvironment where individuals will live, work, learn, and socialize. Previously, more regulatory focus has been on ambient air quality. However, the pollutant concentrations indoors may equal or even exceed those of outdoor environments due to lower ventilation rates and the sources of emissions indoors. IAQ is a multidimensional problem from the perspective of environmental science, engineering, epidemiology, and public health. The exposure depends on characteristics of the building, occupancy, climate, usage of fuel, and ventilation rate. Globally, it is concluded that IAQ is still an important cause of morbidity and mortality, especially for low- and middle-income countries due to persistent usage of biomass and poor housing conditions (Raju et al., 2020; Jafta et al., 2025).

However, today's buildings are designed with higher energy efficiency through increased tightness. This might lead to lower indoor air exchange rates and, therefore, higher indoor pollutants, while the population is increasingly exposed to the new generation of pollutants emitted by many consumer products, electronics, cleaning chemicals, and synthetics used.

Major Indoor Air Pollutants and Their Sources
Indoor pollution is a mixture of a number of different physical, chemical, and biological pollutants. Pollution may be generated by indoor activities, or be entering from outdoors.

Table 1. Major indoor air pollutants, primary sources, and associated health outcomes

Pollutant	Major Indoor Sources	Health Effects
$PM_{2.5}$ and PM_{10}	Cooking, smoking, burning equipment, and air infiltration.	Disease of the lungs, heart, and arteries.
CO	Human respiration, insufficient ventilation.	Impaired mental functioning, malaise.
VOCs	Paints, cleansers, furnishings.	Headaches, irritability, and potentially carcinogenic.
Formaldehyde	Construction and building materials, glues.	Lung irritation.
NO_2	Gas cooking ranges and furnaces.	Triggering of asthma.
Biological aerosols	Fungi, molds, bacteria, animals.	Allergic and infectious responses.
PAHs	Smoking tobacco and burning things.	The possibility of cancer.

ISSN: 3043-6087. Science and Education Development Inst., Nigeria

Particulate matter is one of the most researched pollutants, due to its well-known associations with ill effects. Fine particles can reach far into the pulmonary structures, pass to the systemic circulation, and initiate inflammatory and cardiovascular events (Orellano et al., 2024). The recent literature also points to indoor microbial contamination as another important but often undervalued issue, in which fungi, bacteria, and bioaerosols originating from dampness, ventilation systems, pets, occupants, etc., can significantly impact the health of occupants (Chawla et al., 2023).

The variety of pollutants listed in Table 1 illustrates the diversity of indoor environments, suggesting that no single parameter will suffice as a surrogate for general indoor air quality. Pollutants often exist and are transformed in chemical reactions, leading to the formation of secondary pollutants, which may have different toxicological characteristics. For example, when volatile organic compounds are emitted from buildings or cleaning agents, ozone may react with them to create ultrafine particles and irritants (Gao et al., 2023). In this regard, the idea that the "mix" of air pollutants represents a more accurate exposure scenario compared to individual chemicals becomes clear.

The last dimension is associated with biological pollutants listed in Table 1. The term "different" about biological air pollutants implies their ability to reproduce, for example, under favorable conditions such as high humidity and poor ventilation. When indoor humidity is high enough, fungi and bacteria may appear indoors, increasing the likelihood of allergy sensitization and respiratory issues. According to existing studies, non-infectious adverse health effects may result from microbial diversity and indoor microbiomes (Chawla et al., 2023).

ISSN: 3043-6087. Science and Education Development Inst., Nigeria

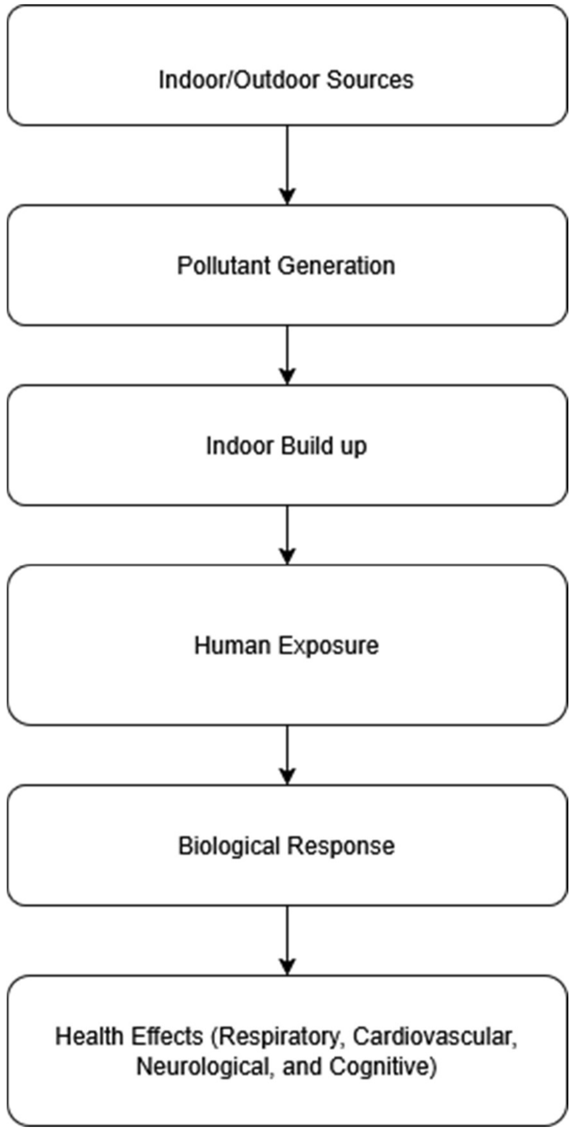

Figure 1: Conceptual framework depicting potential relationships between pollutant sources, exposure route, and health outcomes

Figure 1 illustrates the interaction between pollutant generation, indoor accumulation, exposure pathways, and resulting health consequences. The concept integrates the components presented in figure by illustrating sequential relationships among pollutant generation, exposure, and health outcomes. Indoor and outdoor emission sources contribute to pollutant accumulation within enclosed environments. Environmental characteristics such as air exchange rates, room geometry, humidity, and thermal conditions subsequently influence pollutant distribution and persistence. It further emphasizes that exposure is not solely determined by pollutant presence but by interactions among human activity patterns and indoor environmental processes. Occupant behavior affects both pollutant generation and exposure duration. Activities including cooking frequency, cleaning practices, window-opening behavior, and occupancy density alter exposure conditions considerably. The biological responses encompass inflammatory, immunological, oxidative stress, and neurological mechanisms. Pollutants entering the respiratory system may initiate cellular responses that eventually contribute to disease progression. Understanding these pathways supports development of targeted interventions and risk assessment strategies.

Dynamics of indoor exposure

Unlike exposure outside, indoor exposures show great variability due to occupational practices and micro-environmental factors. The peak levels of pollutants resulting from activities like cooking, cleaning, burning, and humidity and density-related activities are transitory. Another factor that has an influence on the distribution of pollutants is the architectural design of the building since it includes size of rooms, ventilation design, air exchange rate, and filtration efficiency. As indicated by novel research studies on indoor exposure, the commonly applied indoor air indices do not fully represent the dynamic aspects of indoor air quality, thus indicating the requirement for context-dependent frameworks. The occupants themselves pose a major determinant in relation to exposure dynamics. Their activity behaviors and habits of opening window doors, usage of gas appliances, smoking, and using scented consumer products significantly alter exposure to indoor air pollution.

Indoor air exposure is determined by the complicated interrelationships of indoor pollutant sources, occupational conduct, circumstances inside the building, and features of the building, and this together defines human exposures at varied times. Unlike outdoors, the exposure level indoors is highly variable owing to emissions from local sources and varied conditions of the ventilation. Indoor air quality assessment is further compounded by this variable phenomenon. One of the key characteristics that defines indoor environments is the concurrent presence of several indoor air pollutant sources. Building materials, furniture, cooking devices, electronic equipment, cleaning agents, and human activity all release different types of contaminants that differ in their physical and chemical characteristics. Accordingly, the concentration of indoor pollutants varies widely over space and time in the building. Temporal variations of indoor air pollution are a major factor affecting exposure dynamics. Concentration of some indoor air pollutants, such as frying food, smoking, and usage of aerosol products, rises abruptly for short periods of time to generate levels much higher than the background concentration.

Ventilation patterns control the accumulation and removal of indoor air pollutants. Window doors and inlets of natural ventilation systems diluted the indoor air pollutant level depending on outdoor conditions, but a poor ventilation system does not allow efficient dilution and may build up concentrations of indoor pollutants. Ventilation through the mechanical ventilation system is quite complex as it depends on air distribution, efficiency of the filter, and the conditions it has been maintained in. A poorly maintained mechanical ventilation system may serve as a secondary source of microbes and fine particles as well. Building design is a strong determinant of the behavior of indoor air pollutants. It depends on room geometry, height of ceiling, material of building, segregation, and overall airflow design. Newer efficient buildings with no leakage of heat are known to have a reduced natural removal rate of indoor pollutants. Thermal conditions affect the behavior of some indoor air pollutants by varying chemical reaction rates. In higher humidity, microbes grow fast, whereas aerosols behave differently, and higher temperature usually increases emission from materials and other sources.

Human activities are responsible for various indoor air pollutant concentrations in addition to some other sources of indoor air pollutants. Indoor pollutant generation during various human activities, such as cooking and cleaning, and during the usage of personal products, varies under different circumstances. Human density is another parameter which effects exposure. Increased occupancy and crowded spaces may lead to increased concentrations of carbon dioxide and microbial particles due to human exhalation and reduced efficiency of ventilation.

Outdoor environmental pollutants also affect the indoor air quality in relation to different penetrations. Outdoor air pollutants such as traffic-related emissions, dust generated from wildfires, and the industrial sector can enter indoor environments depending upon building penetration characteristics. Particle size distributions significantly influence airborne indoor air pollutant movement and their deposition characteristics. Large particles are likely to be deposited upon the surface in a short duration, while ultrafine particles could remain suspended for a much longer period of time, and their effect can penetrate deeper inside the human respiratory system. Surface behavior affects the movement of pollutants indoors as they may stick to walls, ceiling, floor or furniture for some time and thereafter reemitted into the air. The effect of secondary emission on indoor exposure duration may last longer even after withdrawal of primary emission sources.

Indoor air chemical transformation can generate new types of secondary pollutant which may be more effective for their effects. Ozone interaction with organic matter is a possible example. Indoor biological dynamics is also very important in indoor air pollution studies. Microorganisms present in the environment, and their continuous transfer by humans, lead to an increasingly complex ecosystem inside the indoor air quality, in which the dynamics are influenced by factors like ventilation rate, humidity, and the occupation pattern. Children exhibit significantly different exposure patterns compared to adults as a result of the greater time spent in contact with the floor and hand-to- mouth behavior. This kind of interaction may result in increased exposure to pollutants like dust. The use of household fuels (biomass, kerosene) can contribute significantly to indoor air pollution, especially in developing countries. Socioeconomic status affects building conditions and the level of congestion, which may directly influence the concentration of pollutants. Workplaces may exhibit much higher or lower exposure to different pollutants as a function of occupational context, working hours, and sources that are specific to the working environment.

Real-time measurement of pollutant levels can contribute to defining the dynamic fluctuations of the indoor environment. This can be very helpful for improving exposure assessment relative to classical exposure assessments using traditional methods. Computational modeling, specifically computational fluid dynamics (CFD), can offer valuable insights concerning the dispersion pattern of pollutants indoors and the efficiency of ventilation systems. Future approaches to individual indoor exposure assessment will likely rely on combining the results of continuous monitoring with the knowledge of individual behavior.

Health effects of poor indoor air quality

Health effects caused by indoor air pollution depend on the type of pollutant and duration of exposure to it. Short-term effects usually involve irritation of the eye area and the mucous membranes, as well as headache and fatigue. Long-term effects are known to aggravate chronic diseases in general.

There is a growing body of research on particle exposure that shows that it increases the risk of mortality, cardiovascular, and pulmonary disorders (Orellano et al., 2024). The other exposures found in indoor environment that are associated with health problems are: It should be noted that the influence of indoor environment on health issues extends from the traditionally acknowledged respiratory disorders to an array of other conditions. It becomes clear now that contact with several pollutants at once in indoor environment may have profound impacts on physiology because of complicated connections between them. Asthma still remains one of the most studied effects of exposure to poor indoor environment (Conroy et al., 2025). Inhalation of particulate matter, contamination with dampness, growth of molds and mildews, and presence of substances produced during combustion processes may result in aggravating inflammation within the respiratory tract of affected people. Groups at risk include children whose lungs do not develop until maturity and breathe faster than adults.

The consequences of exposure for cardiovascular health have become a matter of growing concern. Exposure to particulate matter and combustion-derived contaminants may increase the levels of oxidative stress and induce systemic inflammation resulting in hypertensive disorder and arrhythmia development. There is emerging evidence that poor indoor environment and exposure to its adverse elements may affect cognition and neurodevelopment. High level of CO_2 concentration and insufficient ventilation with the presence of VOCs will lower attention span, decrease concentration ability, and mental capacity to resist fatigue (Bustamante-Mora et al., 2025). Poor sleep quality is also often associated with poor quality of indoor environment. Thermal discomfort, accumulation of particulate matter, lack of proper air exchange, and biological contaminants may deprive people of sleep and thus deteriorate physical and psychological state.

Effects of indoor environmental pollution on the neurological development of children have received considerable attention lately, as research indicates that such effects could cause some serious consequences from extended exposure during infancy (Luo et al., 2024). Sensitization is an allergic reaction caused by the indoor environment. Dust mites, animal hair, mold, and biotics can accumulate indoors and trigger an immune response to sensitization. Occupational areas carry a different set of risks due to the amount of time spent in artificial indoor office settings, with ventilation controlled by machines. Some of the illnesses linked with indoor air pollution in occupational settings are fatigue, headaches, and decreased productivity among workers.

A poor indoor environment may contribute indirectly to psychological well-being by negatively influencing perceived quality of life. Discomfort, odor, and environmental dissatisfaction are all part of quality-of-life considerations and could affect a person psychologically. The findings described above suggest the need for a multidisciplinary approach in evaluating the health impacts of indoor environments, involving public health and clinical practitioners along with environmental scientists. Vulnerable populations include the elderly, children, and people with existing conditions that would predispose them to ill health effects from indoor pollution due to factors such as physiological vulnerability, duration of exposure, and activity patterns. Infectious and inflammatory effects can be related to microbial contamination within indoor environments. Mold contamination in particularly high humidity conditions has repeatedly shown a strong association with respiratory outcomes and allergenic symptoms (Chawla et al., 2023).

ISSN: 3043-6087. Science and Education Development Inst., Nigeria

CO_2 as an Indoor Air Quality Indicator

Traditionally, carbon dioxide is used as a surrogate marker of the adequacy of ventilation. An accumulation of high indoor carbon dioxide is indicative of poor outdoor air exchange and has been correlated with the buildup of other indoor contaminants. There has been a growing shift in the interpretation of carbon dioxide readings toward it being a measure of ventilation adequacy related to the number of people within the space rather than solely of toxicity. Optimal values of carbon dioxide vary among buildings and guidelines (Mendell et al., 2024).

Recent studies suggest that elevated levels of carbon dioxide may have the potential to alter cognitive function and decision-making performance under specific circumstances, although further study into mechanisms is needed (Mendell et al., 2024). The measure of carbon dioxide (CO_2) is one of the most common indicators of indoor air quality. It is a product of the human respiratory system, and when the ventilation level is low, CO_2 accumulates fast in indoor environments where there are many people, for example, classrooms, offices, lecture halls, and vehicles. Although CO_2 is found in ambient air, it has become generally accepted practice to use it as a marker of ineffective ventilation and possible accumulation of other substances produced indoors by occupants, including bioaerosols and volatile organic compounds. Contrary to other chemicals, which require specialized laboratory equipment for measuring, CO_2 is relatively easy to measure through various inexpensive devices.

The popularity of CO_2 measurement as a ventilation surrogate has led to thorough research. However, in recent years, there has been growing recognition of CO_2 as an important ventilation indicator rather than a substance that poses harm. At this time, it would be more appropriate to see CO_2 not as a toxin but as an indication of proper ventilation in relation to occupancy. Such an explanation would be based on a contextual understanding of building occupancy, purpose, and activity patterns instead of using arbitrary cut-off points that do not consider variations. Effects of increased CO_2 levels on cognitive performance and function have received a lot of attention from both science and the clinical community. Studies conducted in laboratory settings show evidence that higher concentrations of CO_2 levels have been found to negatively affect cognitive functions such as attention span, problem-solving ability, and resistance to fatigue (Mendell et al., 2024). Such findings become highly relevant in situations where there are high demands on cognitive functions, such as classrooms and workplaces.

Another application of measuring CO_2 levels is its role in enhancing infection prevention. High CO_2 levels could imply an increase in the risk of spreading infectious diseases via airborne particles (Ha et al., 2022; Oswin et al., 2025). Fast monitoring of CO_2 levels can provide information about the rate of air exchanges in potentially infectious environments. Real-time integration of CO_2 sensors with HVAC systems makes possible automatic demand-controlled ventilation approaches. Such systems control ventilation according to CO_2 levels in order to save energy associated with excessive introduction of fresh air from outside while providing satisfactory indoor air quality at any occupancy level. Uneven distribution of CO_2 inside a building could be used to assess airflow dynamics and possible stagnation areas where people will experience higher than average exposure to particular indoor pollutants. Uneven spatial CO_2 distribution is always indicative of some ventilation system malfunction that should be corrected by modifying air distribution through building rooms.

It appears that indoor CO_2 concentrations vary seasonally and are determined by the necessity to heat/cool the premises, which prevents windows from being open. Even in tropical regions, use of air conditioning results in accumulation of high indoor CO_2 levels in the absence of natural ventilation (Mendell et al., 2024). Indoor CO_2 measurements and its effects on cognitive performance and learning are common in educational facilities because there is a high concentration of people in them throughout the day (Sember et al., 2025). Moreover, it was discovered that excessive concentrations of CO_2 are common in such facilities. The problem of proper ventilation also arises in health care facilities. It is important to make sure that an optimal air exchange takes place because the health status of people depends on it (Ha et al., 2022; Oswin et al., 2025).

Limitations of CO_2 use as a single parameter: As noted above, some sources other than the person's body emit air pollution indoors. Hence, indoor CO_2 can be satisfactory while indoor pollutants that do not come from humans, such as VOCs, still stay present. It is also important to ensure calibration and maintenance of the sensing units for the case of monitoring, since sensor drift, interference from the environment, and placement errors can all affect the accuracy of measurement, if quality assurance is not ensured. Mobile and wearable monitoring units are expected to further increase the scope for personal exposure assessment. This is likely to result in more information regarding individual exposures to the indoor environment in different microenvironments. It is anticipated that the use of CO_2 sensing units will eventually merge with that of artificial intelligence and forecasting technologies. Such intelligent systems would then be able to determine if ventilation was poor before becoming a problem.

Technological Advancement of Indoor Environment Monitoring

Recent technological advancements have changed the way that IAQ can be measured and assessed. These are seen in the form of inexpensive sensor networks, smart devices, artificial intelligence, and real-time measurement and alerting systems. Modern IAQ systems increasingly incorporate a combination of:

Modern IAQ systems are combining sensors, communication networks, and analysis tools to create sophisticated and networked monitoring platforms that replace periodic sampling with continuous monitoring and faster, data-driven decisions. Particulate matter sensors are one of the most common included measurements because fine particulate matter has a significant effect on health outcomes. $PM_{2.5}$ sensors and PM_{10} sensors provide information about a pollution event when cooking, smoking, or an outside air pollution event occurs. Carbon dioxide sensors provide a metric of indoor environmental conditions because the indoor CO_2 level correlates with outdoor air and indoor activity; high CO_2 may indicate a lack of ventilation and accumulation of pollutants. Volatile organic compound sensors provide information about indoor conditions because emissions can come from furniture, construction materials, or cleaning products. These sensors are not as accurate or reliable as others yet, but they provide useful trend information. Temperature and humidity sensors provide useful information because many pollutant behaviors are affected by these variables. In addition to having direct effects on the indoor environment, temperature affects water activity and hence may affect the ability of microbial growth. Humidity also has an effect on aerosol dynamics and occupant comfort. Occupancy sensors are a technology that will increasingly be found in smart building applications. Motion detectors and smart software will help monitor space occupancy so that ventilation and temperature can be managed as needed. Wireless networks provide the means for the different sensing technologies to share data. Internet-of-things technology allows information to be sent to and accessed from various locations, for instance, using cloud technology.

Visualization of data from sensing equipment through dashboards and smartphone apps can make environmental measurements more accessible to building occupants. Artificial intelligence and smart software will interpret sensing data, identify problematic conditions, and predict when problems may arise, e.g., predicting pollution events. Heat and cooling systems may be automatically controlled based on sensor readings to ensure comfortable conditions with minimized energy use. Ultimately, such systems will facilitate the creation of smart buildings that optimize health protection with energy efficiency and sustainability concerns addressed. These systems will enable better estimation of exposure and prediction analysis. However, inexpensive sensor technology can be flawed. Problems with sensor calibration and accuracy, as well as sensor drift, can affect measurements. Consumer monitoring system experiences have demonstrated a high degree of variation in sensor accuracy (Nalakurthi et al., 2024).

ISSN: 3043-6087. Science and Education Development Inst., Nigeria

Table 2. Emerging mitigation strategies for indoor air quality improvement

Strategy	Mechanism	Advantages	Limitations
Improved ventilation	The dispersion rate has increased, thus diluting the pollutants.	Instantaneous reduction of pollutants	Energy effects
HEPA filtration	Particles have been separated.	Good for PM elimination	Maintenance
Source control	The sources have been removed.	Proactive measures	Possibly need behavior modifications
Smart sensing systems	There is continuous monitoring.	Real-time actions	Problems with calibration/cost
Green building design	The whole environment is being managed in an integrated manner.	Sustainable solutions	Implementation costs

The other approaches to mitigation listed in Table 2 target different phases within the exposure pathways. While both increased ventilation, which dilutes pollutants by bringing fresh air into an indoor environment, and filtration systems that capture physical particles from the air fall within the exposure pathway categories of reducing the environment or removing pollutants, source control represents a preventative measure. The further upstream, the better, about exposure control: while source control may not be as long-term effective, reducing pollutants at their source will generally be more effective over time as a solution than dealing with them after they have already permeated the air. Also listed in Table 2, technology, through the development of smart monitoring systems and the creation of integrated building management systems, plays an increasingly important role in controlling indoor environments; control will not just be about statics in the future but dynamic and responsive, using sensor readings to determine when to increase the rate of ventilation, balancing its energy use with other requirements like the comfort of occupants.

Sustainable Management and Future Directions

Future control of the indoor environment requires a combination of engineering techniques and public health interventions. Design of sustainable buildings should focus on energy efficiency, occupant health, or both. The priority areas for future research include the following:

ISSN: 3043-6087. Science and Education Development Inst., Nigeria

Despite recent progress, several important gaps remain in our understanding of indoor air quality science and our ability to characterize exposures and inform effective interventions. A priority research area for improved indoor air quality studies remains the standardization of metrics used to describe IAQ. Currently, many studies utilize a variety of measurement protocols, measures of pollutant levels, and ways of defining exposure, which can limit comparison across different investigations. Development of a unified way to characterize indoor environments and their pollutants is a necessary step toward building a synthesized evidence base. Another priority research area is long-term exposure. Most studies measure short periods or have a cross-sectional design and provide inadequate measures of chronic exposure. Longitudinal studies are also necessary to adequately understand chronic impacts and variable exposure over time. In the field of indoor bioaerosols research is relatively scarce, yet there is increasing recognition of their importance in health impacts. Indoor microbial populations vary as a result of moisture in the environment, the building, and occupant activity; understanding the mechanics of these populations can help inform interventions to improve health.

Artificial intelligence and machine learning can provide significant tools for this work in the future: models that can anticipate episodes of high pollution and control system operations in response are a promising area for IAQ research; in addition, smart monitoring could work hand-in-hand with adaptive building systems to customize IAQ control to individual needs. Building-specific modeling is an area that also warrants significant research since each building has its own unique air pollutant profile based on building materials and occupancy levels. Vulnerable populations should also be addressed by factors like age, socioeconomic status, health, and housing conditions, which impact both the magnitude of exposure as well as the susceptibility to ill health effects of the exposure. Research into indoor environmental justice remains understudied; the poorest may face inadequate housing conditions and subsequent pollution exposure more frequently. Future research should seek to integrate monitoring of the indoor environment with measures of health outcomes and human behavior, since controlling environmental exposures is likely not sufficient in and of itself. Policy-oriented research to facilitate the implementation of effective indoor air quality controls is still necessary for the translation of science into action. Climate change and future building practices will continue to create uncertainties, which require research. Countries that are still developing should receive emphasis due to continued use of household fuel combustion, inadequacy of housing, and poverty, which lead to significant exposures (Emetere et al., 2024)

ISSN: 3043-6087. Science and Education Development Inst., Nigeria

Conclusion

Indoor air quality has become a critical issue in public health, requiring significant research, an interdisciplinary approach to management, and policy development. Both occupant behavior and changing building technology create complexities that hinder thorough exposure characterization and the reduction of risks. The health impacts of a mixture of indoor pollutants may go far beyond traditional respiratory outcomes to also impact cardiovascular health and cognitive function, among other issues. Smart technologies and sustainable building design practices can offer ways to improve indoor air quality.

References

Bustamante-Mora, A., Diéguez-Rebolledo, M., Zegarra, M., Escobar, F., & Epuyao, G. (2025). Environmental Conditions and Their Impact on Student Concentration and Learning in University Environments: A Case Study of Education for Sustainability. *Sustainability*, *17*(3), 1071. https://doi.org/10.3390/su17031071

Chawla H, Anand P, Garg K, Bhagat N, Varmani SG, Bansal T, McBain AJ and Marwah RG (2023) A comprehensive review of microbial contamination in the indoor environment: sources, sampling, health risks, and mitigation strategies. Front. Public Health 11:1285393. doi: 10.3389/fpubh.2023.1285393

Conroy, E. R., Phipatanakul, W., & Banzon, T. M. (2025). The Impact of the Indoor Environment on Childhood Asthma. *Current Allergy and Asthma Reports*, *25*(1), 11. https://doi.org/10.1007/s11882-025-01193-x

Emetere M, Olaniyan I, Fadiji J, et al. Indoor Air Pollution: A Review on the Challenges in Third World Countries. *Air, Soil and Water Research*. 2024;17. doi:10.1177/11786221241239891

Gao, Y., Zhang, M., Wang, H., & Xiong, J. (2023). Experimental Investigation on the Reaction Characteristics between Ozone and Vehicle Cabin/Furniture Materials. *Atmosphere*, *14*(5), 769. https://doi.org/10.3390/atmos14050769

Ha, W., Zabarsky, T. F., Eckstein, E. C., Alhmidi, H., Jencson, A. L., Cadnum, J. L., & Donskey, C. J. (2022). Use of carbon dioxide measurements to assess ventilation in an acute care hospital. *American Journal of Infection Control*, *50*(2), 229–232. https://doi.org/10.1016/j.ajic.2021.11.017

Jafta, N., Shezi, B., Buthelezi, M., Muteti-Fana, S., & Naidoo, R. N. (2025). Household air pollution and respiratory health in Africa: persistent risk and unchanged health burdens. *Current Opinion in Pulmonary Medicine*, *31*(2), 89–97. https://doi.org/10.1097/MCP.0000000000001126

Karmakar, P., Pradhan, S., Chakraborty, S. (2023). Exploring Indoor Health: An In-depth Field Study on the Indoor Air Quality Dynamics. arXiv: 2310.12241. https://doi.org/10.48550/arXiv.2310.12241

King, C. (2025). Commentary: Air pollution and neurodevelopmental disorders: a cause for concern in an urbanising world. Global Public Health. 20(1), https://doi.org/10.1080/17441692.2025.2492234

Kumar, P., Singh, A.B., Arora, T., Singh, S., Songh, R. (2023). Critical review on emerging health effects associated with the indoor air quality and its sustainable management. Science of The Total Environment, Volume 872, 10 May 2023, 162163. https://doi.org/10.1016/j.scitotenv.2023.162163

Luo, H., Hu, H., Zheng, Z. *et al.* (2024). The impact of living environmental factors on cognitive function and mild cognitive impairment: evidence from the Chinese elderly population. *BMC Public Health* 24, 2814 (2024). https://doi.org/10.1186/s12889-024-20197-2

Mendell MJ, Chen W, Ranasinghe DR, Castorina R, Kumagai K. Carbon dioxide guidelines for indoor air quality: a review. *J Expo Sci Environ Epidemiol.* 2024;34(4):555–569. doi:10.1038/s41370-024-00694-7.

Nalakurthi, N. V. S. R., Abimbola, I., Ahmed, T., Anton, I., Riaz, K., Ibrahim, Q., Banerjee, A., Tiwari, A., & Gharbia, S. (2024). Challenges and Opportunities in Calibrating Low-Cost Environmental Sensors. *Sensors (Basel, Switzerland)*, *24*(11), 3650. https://doi.org/10.3390/s24113650

Orellano, P., Kasdagli, M. I., Pérez Velasco, R., & Samoli, E. (2024). Long-Term Exposure to Particulate Matter and Mortality: An Update of the WHO Global Air Quality Guidelines Systematic Review and Meta-Analysis. *International Journal of Public Health*, *69*, 1607683. https://doi.org/10.3389/ijph.2024.1607683

Oswin, H.P., Glachant, L., Lekamge, S.A., Alinaghipour, B., Khan, S.B., Morawska, L. (2025). Using indoor CO_2 concentration thresholds to understand and improve the air quality of public buildings: A practical approach. Energy and Buildings. Volume 347, 10.1016/j.enbuild.2025.116254

Raju, S., Siddharthan, T., & McCormack, M. C. (2020). Indoor Air Pollution and Respiratory Health. *Clinics in Chest Medicine*, *41*(4), 825–843. https://doi.org/10.1016/j.ccm.2020.08.014

Sember, V., Jurak, G., Starc, G., Kovač, M., Bardid, F., & Morrison, S. A. (2025). One decade of school environment monitoring and its influence on providing adequate opportunities for engaging in physical activity from the Active Healthy Kids Global Alliance Global Matrices 1.0 to 4.0. *Journal of Exercise Science and Fitness*, *23*(4), 480–486. https://doi.org/10.1016/j.jesf.2025.10.007

Yavuz, V. (2024). Variations in Air Pollutant Concentrations on Dry and Wet Days with Varying Precipitation Intensity. *Atmosphere*, *15*(8), 896. https://doi.org/10.3390/atmos15080896

Zhivkov, P., & Fidanova, S. (2026). Machine Learning Calibration Transfer for Low-Cost Air Quality Sensors: Distance-Based Uncertainty Quantification in a Hybrid Urban Monitoring Network. *Atmosphere*, *17*(4), 335. https://doi.org/10.3390/atmos17040335.

ISSN: 3043-6087. Science and Education Development Inst., Nigeria