A Review of Indoor AQI in Madurai Urban Atmospheric area – an Assessment Approaches

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Abstract

The combined effect of outdoor atmospheric pollution, the features of buildings and the patterns of indoor activities are becoming more and more important as a determinant of indoor air quality (IAQ) in rapidly urbanizing areas. The review is an integration of the existing evidence of IAQ as influenced by urban atmosphere, especially in residential, public, and commercial buildings in cities of high density like those found in cities in India. Based on epidemiological, field-measurement and regulatory literature, the paper initially describes the significant indoor polluters, their causes, and the related health and material effects and shows how the urban PM, NO2, O3, and volatile organic compounds (VOCs) penetrate and react to indoor environments. It is followed by consideration of crucial elements of the environment, such as housing typology, ventilation, heating, and cooling systems, occupant behaviours as well as socio-economic aspects that do moderate pollutant concentration, particularly in a multi-family dwelling and sensitive communal places like schools, hospitals and aged care homes. The repeated patterns of pollutants can be observed in the comparative synthesis of the public utility buildings (museums, libraries, temples, offices, healthcare facilities, and care homes), yet, the sources and risk groups are situation-specific. The review also analyses standards of IAQ, guidelines and methods of assessment, such as multi-pollutant measurements, estimation of air exchange rate, and the developing role of validated low cost sensors, AI-focused platforms and tracer-gas techniques. Lastly, it determines important shortfalls in IAQ oversight and activity amid the urban ecosystem and suggests an unified model that interconnected the management of the ambiance by means of the urban environment outdoor air, building design and retrofit preparedness, and indoor source dispersion. The results strengthen the necessity to introduce IAQ as a specified element of urban health and housing as well as climate-resilient policy using the frameworks of low- and middle- income cities with long-term pollution levels and rapid growth.

Keywords

Indoor air quality; Urban atmospheric pollution; Environmental drivers; Residential buildings; Public and commercial buildings; Monitoring and assessment; Air quality standards

1. Introduction

The issue of indoor air quality (IAQ) has become a burning topic in the quickly urbanizing areas in the context of which the combination of worsening outside ambient and the intricate aspects of the internal environment has a strong impact on human exposure. The situation depicted in Urban India demonstrates this problem: due to fast population growth and high-population built environments, the level of air pollution has increased, and the concentration of particulate matter and gaseous pollutants in the air of a metropolitan area in many cases exceeds the international health-related norm.[1] These higher levels of PM10, PM2.5, NO2, SO2, and CO deteriorate the outdoor air and freely enter indoor areas, where people spend up to 90 percent of their time amplifying the risks related to them.[2]

The relevance of IAQ is that the fact that it is directly linked to respiratory, cardiovascular, and cognitive health outcomes warrant the creation of scientifically-based pollutant levels and pollution systems. The literature is consistent in showing that the level of indoor pollutant is highly influenced by the particulars of the outer atmosphere, and seasonal fluctuations (winter stagnation or summer ventilation patterns) alter the pollution transportation and storage in buildings (Chen et al., 2024). Moreover, exposure is aggravated by the increasing role of indoor sources of emissions such as building materials, Combustion activities, and bioaerosols, especially in spaces that are energy generous such as urban dwellings, which may have substandard ventilation.[3]

Development of sensing technologies has also offered new directions towards real-time IAQ measurement. Predictive systems based on AI and monitoring tools that may be integrated with IoT technologies can facilitate active mitigation as they detect the maximum level of pollution, predict the dynamics of indoor air, and provide automatic recommendations. Such systems are supplementary to the existence of health-based national regulatory indicators of PM10, PM2.5, SO2, NO2, and CO through the National Ambient Air Quality Standards of India to inform the community about the environmental situation on the ground (Central Pollution Control Board, 2009).[4]

Although such processes occur, even today, unhealthy air is still present in a significant percentage of the Indian population, and air pollution constitutes one of the most significant causes of morbidity and premature mortality, especially in densely populated and low-income urban areas .[5] The issue is not the exclusivity of India: the world inquiries have also shown that there are serious urban hubs, whose concentrations of pollutants are inclined by climate, traffic, industrial work, and urban design.[6] The results obtained underlie the necessity to consider combined IAQ models that connect indoor exposures to outdoor atmospheric challengers so as to improve building designs, ventilation, and occupant behaviour.

International tests also show the wide variety of regulatory and environmental situations affecting IAQ. Indicatively, IAQ legislative reviews demonstrate that pollutant levels, energy requirements, ventilation regulations, and moisture do coexist as determinants of the quality of the indoor environment and wellbeing of the occupants .[7] Likewise, field investigations of school and office systems, carried out on massive scales, have revealed that a combination of natural ventilation, pedestrian traffic, and occupancy considerably increase indoor levels of particulate matter and CO2, indicating the dependence on one another.[8]

As more complicated interactions, it is important to develop an in-depth organization of IAQ under urban atmospheric effects in order to progress with the effective assessment procedure and policy on human health. The review provides a synthesis of the existing knowledge on drivers of the indoor environment, behaviour of the pollutants in response to different atmospheric conditions and modern methods of monitoring and assessment of the indoor air quality as the evidence of effective IAQ management in the new urban areas.

A summary of key indoor contaminants that are of concern in the urban setting, the sources of such contaminants, and their commonly reported health effects have been served as table 1, which is based on pre-existing literature.

Collectively, the shifting building patterns, increasing urbanization and altering trends in indoor occupancy have created indoor air quality as a pivotal area of environmental health science. With the high impact of the atmospheric urban pollution, the environmental drivers and the evaluation methodologies, the current review gathers up to date the research regarding the IAQ in the urban setting with the knowledge on the interactions between the outdoors and the indoors, the measurement and evaluation of the interaction between the outdoors and the indoors, across the building types.

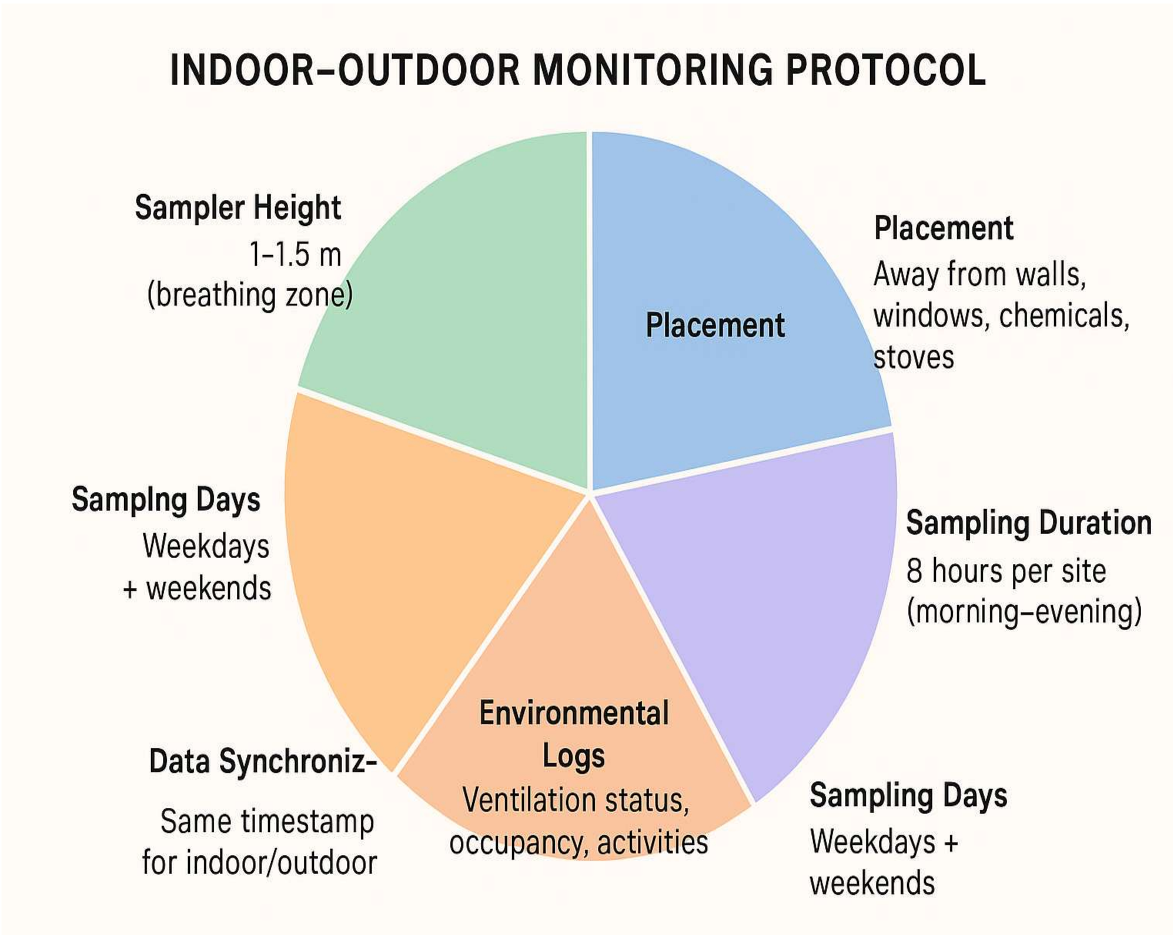

Fig:1 Indoor outdoor monitoring protocol details

2. Methodology

This review was conducted using a structured and transparent literature-based approach designed to capture the breadth and diversity of research on indoor air quality under urban atmospheric influence. Peer-reviewed journal articles, authoritative reports, and standards documents were identified through systematic searches of major scientific databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. These databases were selected to ensure comprehensive coverage of environmental science, building science, public health, and air quality research. The search strategy focused on literature published primarily between 2010 and 2025, a period that reflects rapid urbanisation, advances in IAQ monitoring technologies, and growing recognition of indoor exposure as a public health concern.

The search process employed combinations of keywords related to indoor air quality and urban pollution, including terms such as “indoor air quality”, “urban atmosphere”, “$PM_{2.5}$”, “PM_{10}”, “nitrogen dioxide”, “ozone”, “volatile organic compounds”, “residential buildings”, “schools”, “offices”, “hospitals”, “ventilation”, and “air exchange rate”. Boolean operators were used to link indoor and outdoor exposure concepts with building types and assessment approaches, allowing identification of studies that explicitly addressed the interaction between urban ambient pollution and indoor environments. Reference lists of key review articles were also examined to identify additional relevant studies not captured through database searches.

Studies were included if they presented empirical field measurements, modelling analyses, epidemiological evidence, or regulatory evaluations related to IAQ in urban or peri-urban settings. Particular emphasis was placed on research examining the transfer of outdoor pollutants into indoor spaces, the role of building characteristics and occupant activities, and the application of recognised IAQ assessment or monitoring methods. Studies focused exclusively on industrial workplaces, non-urban rural environments, or purely occupational exposures without relevance to general indoor environments were excluded. Non-peer-reviewed sources were considered only when they represented established standards, technical guidance documents, or nationally recognised regulatory frameworks.

The reviewed literature spans a wide geographical range, reflecting both India-centric urban contexts and international evidence from Europe, North America, and other rapidly urbanising regions. While Indian cities provide a central reference point due to their high pollution burdens and dense housing conditions, international studies were included to enable comparative interpretation of pollutant behaviour, building typologies, and assessment practices across diverse regulatory and climatic settings. This approach allows the identification of recurring patterns and transferable insights relevant to low- and middle-income urban regions experiencing similar environmental pressures.

Rather than conducting, the review adopts a comparative synthesis approach to integrate findings across heterogeneous studies. This method enables the identification of consistent pollutant profiles, dominant exposure drivers, and shared methodological practices across different building types and urban contexts, while acknowledging variability in study design and measurement techniques. Evidence is synthesised narratively and supported by comparative tables that map pollutant sources, building characteristics, health or material concerns, and representative studies. This qualitative integration is particularly suitable for IAQ research, where outcomes are influenced by context-specific factors such as ventilation behaviour, building age, and local atmospheric conditions.

Through this structured yet flexible methodology, the review aims to provide a coherent and policy-relevant synthesis of current knowledge on indoor air quality under urban atmospheric influence, while maintaining methodological transparency and consistency with established practices in environmental and building science review literature.

2.1. Indoor Pollution Sources and Environmental Drivers

The problem of indoor air pollution is based on the interplay between the sources of emissions, patterns of their human activity, and the specifics of structures of residential premises. In all the literature reviewed, cooking and cigarette smoking were all over and over again identified as the primary sources of indoor PM2.5 and NO2, especially in multi-family buildings where the unit volumes of the units were smaller and there was a higher air transfer between the units, illustrating a greater exposure exposure. Field measurements overseen in Massachusetts, e.g., indicated that occupants living in multi-family buildings were significantly exposed to PM2.5 in comparison with homeowners in multi-family buildings or single-family home occupants, with indoor pollution also being a factor of smoking, frequency of cooking, use of range hoods, and house size.[9] A further confirmation of the same sources causing a significant difference in pollutant concentrations in the apartments compared with the single-family houses was follow-up simulation modelling that kept the activity patterns constant where six-unit buildings had stronger accumulation of PM2.5 compared to two-unit buildings due to smaller volumes and lower dilution ability.[10]

In addition to these structural considerations, a critical issue as covered in the literature is whether there are any systematic variations with respect to activity patterns or source prevalence between multifamily and single-family housing. There is overwhelming evidence that the inherent characteristics of multi-family housing, in particular, the existence of shared walls, ventilation, and vertical airflow, provide routes of pollutant transmission between residential units.[11] This interconnectedness implies that residents can also get exposed not just to the amount emitted in their own units but also that generated in the adjacent units. Of particular importance in this aspect is smoking, in the multi-family background, low-income families, which are overrepresented in the sample, have much higher smoking rates, which increases the risk of passing the smoking household effect on. In fact, according to a study that found that 34% of the people in multi-family housing that reported smoke-free homes still experienced SHS intrusions [12,13], national statistics F. show that these residents are at a high risk of incurring SHS morbidity and mortality. [14,15]

The exposure amounts during high-rise complexes are shown by empirical inquiries. A study conducted in New York found nicotine in not only apartments where the resident was not a smoker but also in hallways and stairwells, but at greater concentrations on higher levels, as the pressure-accelerated airflow causes SHS to migrate up the building during colder temperatures. [16,17] A bigger survey of 21 high-rise structures confirmed the existence of detectable nicotine concentrations in a majority of hallways and stairwells whereas a smaller fraction of non-smoking apartments was detected to have detectable concentrations investigators credited this difference in part to the lower levels of smoking in shared indoor spaces.[18] These observations demonstrate that there is a high level of heterogeneity in SHS infiltrations among buildings, which is caused by variations in architecture, air handling, resident behaviours, and use of smoke-free policies.

Disparities of exposure are also determined by policy landscapes. The 2018 U.S. Department of Housing and Urban Development (HUD) smoke-free mandatory decree in the public housing was a significant intervention in lessening exposure to vulnerable populations.[19] Nevertheless, the area of this regulation is comparatively small: approximately 15.5% of all residents of multi-family buildings who smoke in HUD residences[21], and numerous privately operated developments did not implement smoke-free regulations on a voluntary basis.[20] In addition, smoke free policies are not a complete way of eliminating smoking behaviours. Implementation studies showed that there were improvements after the adoption of the policy including decreased hallway smoke and less in-unit smoking, although still, a considerable percentage of residents reported intrusion multiple times a week.[22,23,24] Making this situation even more complicated, 2020 stay-at-home orders related to the pandemic caused observable rises in PM2.5 indoors in residential housing, which reflect increased smoking in the home due to experiences of greater occupational hours.[25]

In the cases where smoking is absent/or reduced, cooking is the leading source to indoor PM2.5, especially taking into consideration the short-term but strong-intensity spikes of the particles. There has been strong temporal fluctuation in indoor PM2.5 due to cooking in low-cost sensor applications in homes (Shen et al., 2021). Notably, cooking emissions are due to the use of fuel and cooking methods, whereby, pan-frying constantly causes high PM2.5 emissions that could last hours.[26] Although recent studies have not presented systematic evidence on differences in cooking practices depending on the type of housing, sociodemographic factors like the enrolment in food assistance programs, spending more time at home, or age above 65 are associated with increased hourly cooking times [27], which implies that these are indirectly related to the demographic traits of multi-family housing residents.

Respectively, all this evidence suggests that the level of indoor pollution in multi-family houses is determined by the complex of interrelationship of the aspects of the structural features, socioeconomic status, and behavioural patterns. A comparative meta-synthesis was built to produce the synthesis findings of other studies by obtaining the main contributions of the respective references to the dynamics of the exposure of indoor PM2.5 and SHS. The integrated table beneath summarizes the strength of evidence based by the type of pollutant, the type of housing, by the largest source of emission as well as capturing the effects of building design and policy interventions on exposure pathway. Placing this meta-analytic synthesis into the narrative helps to allow the section of the narrative to pass between the results of the individual studies to that of multiple studies indicating some powerful interpretative patterns that define the interior air environment of houses.[27]

Table 1: Embedded Meta-Analysis Summary Table

Study / Source	Housing Type	Dominant Indoor Pollutant Source	Key Structural / Behavioral Driver	Overall Influence on Indoor PM2.5 or SHS Exposure
Chu et al. (2021)	Multi-family vs. single-family	Cooking, smoking	Home size, range hood use	Higher PM2.5 in multi-family units due to source intensity and smaller volume

Milando et al. (2022)	Modeled apartments (2-unit vs. 6-unit)	Cooking, smoking	Reduced volume, building configuration	Higher modeled PM2.5 concentrations in smaller units
King et al. (2010); Wilson et al. (2014)	Multi-unit apartments	Secondhand smoke	Air transfer between units	High SHS incursions despite smoke-free rules
Gentzke et al. (2018); Ruhe (2019)	Affordable housing	Smoking	Enforcement of smoke-free policies	Reduced but persistent SHS infiltration
Hwang & Cho (2021)	Apartments with/without non-smoking zones	Heat-not-burn tobacco	Designated smoking areas	Mixed compliance, continued exposure potential
Garrett et al. (2019)	National cohort	Smoking prevalence	Socioeconomic status	Higher smoking rates among low-income multi-family residents
Kegler et al. (2019); Reyes-Guzman et al. (2023)	Multi-family	SHS incursions	Lack of smoke-free policies	34% report incursions; high morbidity risk
Gill et al. (2022); Anastasiou et al. (2020)	High-rise buildings	SHS	Stack effect, hallway smoking	Nicotine detected in stairwells and non-smoking units
Anthony et al. (2019); Lathen et al. (2020); Curry et al. (2022)	HUD public housing	Smoking	Policy compliance	Reductions but incomplete elimination of SHS
Gehlert et al. (2023)	Public housing during COVID-19	Smoking	Stay-at-home orders	Increased PM2.5 from intensified smoking
Shen et al. (2021)	General residential	Cooking	Cooking method, sensor detection	High PM2.5 spikes from pan-frying

Hamrick (2016)	U.S. adults	Cooking time	Age, employment, food assistance	Longer cooking times linked to sociodemographic factors

3. Indoor Air Quality in Public Utility and Commercial Buildings

3.1 Overview of Public-Use Indoor Environments

Individuals also occupy much of their conscious time at these locations in non-random ways which represent regular activities and daily schedules of institutions school, libraries, museums, offices and hospitals, temples and care centres.[28] Consequently, these micro environments may act as considerable sources of lifetime indoor air pollutants exposure, especially in poorly ventilated spaces, high emitting spaces, and highly vulnerable groups. Exposure-wise, immediate (short-term peaks) and chronic (meaning of long-term exposure) exposure is important: short spikes can cause acute sensory irritation or asthma, and the long-term exposure will determine cumulative health outcomes (ex: respiratory disease).

Among people residing in public utility and commercial buildings, indoor air quality (IAQ) is regulated by repetitive cluster of determinants: the frequency and efficiency of air-exchange, the character of the indoors activities, the emissions that building and furnishing materials produce, the temperature and relative humidity of indoor air, the design and functioning of mechanical ventilation and filtration systems, and the quality of ambient outdoor air that gets into the structure envelope.[29] Another similarity between many of these environments and complex indoor chemistry is that the ozone or nitrogen oxides and the volatile organic compounds (VOCs) can be combined to form secondary pollutants including aldehydes and organic acids, which can be more irritating or toxic than either the oxides or the precursors .[29] The underlying driving factors have broad similarities, but each type of building has unique source profile, mixture of pollutants, and context of risks that are summarised narratively below and synthesised comparatively in Table 3.

3.2 Museums and Galleries

Uniqueness of the museums and galleries among the buildings of the population is that not only the health of human beings depends on the chemical content of the air in the internal space but also the maintenance of highly sensitive collections. Nitrogen dioxide (NO2), sulphur dioxide (SO2), acetic and formic acid, formaldehyde, leather, paints, wood, metals, leather, composite materials, wood, and textiles that consist of paper and various materials can be destroyed by gases that promote corrosion, fading or embrittlement of substances as time progresses (Morrison and Nazaroff, 2002). These are pollutants which are external and internal. Outdoor smog of the photochemical and the traffic pollutants can be deposited through cracks and open windows, doors, and mechanical ventilation whereas the indoor production is achieved via building products, display cases, wooden furniture, and office or conservation equipment.

The European museums have demonstrated that location and building envelope determine the mixtures inside the building. As an illustration, a museum, which was close to an airport, a busy highway, and a park, had measurable indoor concentration of BTEX (benzene, toluene, ethylbenzene, xylenes), naphthalene, and benzoic acid related to traffic emissions, and limonene connected to biogenic sources of the surrounding vegetation.[30] Long-term monitoring in a historical museum in Antwerp showed that SO 2 and O3 in indoors were significantly lower than in outdoors, whereas NO 2 in indoors was frequently of comparable or even higher levels, which showed selective uptake and reaction of SO2 and O3 on indoor surfaces including wood-based material.[31] High concentrations of organic acids were also associated with those emissions during wooden showcases and shelving, which supports the suggestion that the storage temperature of sensitive wooden exhibits should be kept to the lowest possible level and the number of wooden fixtures with the highest emissions should be reduced to limit the development of VOC and secondary pollutants.[31] The combined results highlight the fact that museum IAQ should be controlled with regard to occupant safety and preventive conservation, the main attention should be paid to ventilation, filtration, choice of materials, and microclimatic conditions.

3.3 Libraries and Archives

Another dual IAQ concern is seen in libraries, whose purpose is to protect the occupants and preserve the paper- and parchment-based materials, when dealing with the rare and historical collections. Whereas it is instinctively true to expect books to be the main source of the emission themselves, it has been shown that furnishings and finishes are in many cases more significant sources of the VOCs. In Florence, Italy, measurements of libraries and archives revealed the preponderance of the emissions of furniture, shelving, floor covers, and wall finishes (wood, composites, coatings, adhesives) in the VOC profile, which also comprised of aldehydes and other organics of conservation concern.[32]

Conservatively, gas-phase oxidants, including NO 2 and O3, in particular in conditions of increased relative humidity, hasten the deterioration of cellulose fibres, resulting in yellowing, brittle and mechanically weak aged historic paper collections. These mechanisms are aggravated by the presence of acidic gases or organic acids which further reduce the pH of the paper and enhance the chemical ageing.[33] As a historical library revealed, seasonal NO2 and O3 were higher in the summer season than in the winter season, which was moderated by humidity variations and ventilation configuration, which requires consideration of outdoor pollution, indoor sources, and microclimate regulation during a IAQ management strategy design.[33]

As a result, the library IAQ strategies are often combined to filtrate outdoor air, use low-emission IA interior materials, maintain a consistent temperature-humidity level, and select conservation treatment and cleaning agents carefully not to add another volatile or reactive chemical.[32]

3.4 Temples and Churches

Indoor settings unique to religious buildings, the ritual practices of religious buildings dominate the pollutant profiles of these buildings. Complex mixtures of particles and VOCs are created during the combustion of candles, incense, oils and other ritual substances. Studies conducted in European churches have indicated fairly low levels of inorganic gases like SO2 indoors yet escalated concentrations of NO2 around altars, which has been propelled partly by constant burning of candles, infiltration of outside gases of combustion as a result of heating seasons .[34] Being carried into the indoor air by outdoor urban air, Ozone reacts with wooden structures, including pews, beams, and carvings; ozone reactions are intensified by high temperatures associated with summertime, causing depletion of Ozone indoors but also creating the possibility of long-term effects of ozone on wooden surfaces.[35]

In post and south Asia temples, an incense burning is a key contributor to indoor pollutants. It was found that formaldehyde and BTEX levels were often exceeding WHO guideline values in Chinese temples, particularly during peak performance moments, and the highest levels were measured in the location of incense burners and in inner sanctum rooms.[45] Other studies such as in Indian religious contexts have demonstrated that the burning of mixtures of natural and synthetic materials, such as cow dung, ghee, wood, leaves, oils and camphor, can result in large amounts of VOC, however the intensity and composition is highly dependent on the fuel mix and the conditions of combustion. The relationship between temples that have a higher proportion of cleaner material, including cotton wicks and vegetable oils, and those in which mixed solid fuels are the principal ones will show that the overall VOC emissions will be less than in the latter.

All these studies point out to the fact that IAQ in temples/churches is not the victim of only ventilation and outdoor air quality, but it depends on the specifics of combustion practises in the culture, so the context-specific interventions including the use of cleaner fuel, better exhaust, or space separation of combustion areas in particular are particularly significant.

3.5 Schools and Educational Buildings

School structures are extremely sensitive IAQ environments since children spend a large amount of time in classrooms each day and are more physiologically susceptible to respiratory irritants and allergens. The exchange of air in most schools that are older or smaller and do not have a mechanical ventilating system is largely explained by the opening of windows and doors, which means that the level of indoor pollutants is very dependent on the quality of the air outside and the behaviour of occupants. Besides the emissions caused by furniture, flooring and wall material, special teaching exercises, including art classes using paints, solvents and adhesives, may result in short-term spikes in the VOC levels.

European schools were studied in large numbers with indoor/outdoor (I/O) concentrations ratio being used to differentiate between indoor and infiltrated compounds. The I /O ratios of d-limonene, formaldehyde, and acetaldehyde were very high, which indicated the strong sources of these compounds indoors, but an I /O ratio of nearly unity of benzene indicated the predominance of air exchange outside structures.[37] The greatest levels of the VOC were detected in the art classes as they were actively using the chemical products.[37]

The next issue that has been a common concern in schools is the high VOC load in new buildings or those that had been refurbished in the recent past. A new school in Seoul was observed to exhibit the highest levels of VOCs initially during the period of system commissioning and dropped off slowly over several months, leading to the suggestion of a phase of seasoning of the building by increased ventilation and controlled heating to evacuate emissions prior to full occupancy.[38] Those measures can minimise the risk of having sick building syndrome (SBS)-like symptoms (headache, fatigue, mucosal irritation) in students and staff .[16]

Taken altogether, it can be indicated that IAQ in schools is to be controlled via the classification of low-emission materials and appropriate ventilation planning and control of source-specific phenomena caused by activities particularly in special classes.

3.6 Offices and Administrative Workplaces

The most commonly researched microenvironment of VOC exposure related to public/commercial environments consists of offices and administration. Patients usually spend a significant time on a regular basis and air quality is very much related to comfort, productivity, and symptom reporting. BTEX and other aromatic hydrocarbons, chlorinated solvents, glycol ethers and aldehydes have also been pivoted out as recurrent contaminants of office-type structures through investigations into office building-related pollution and these problems originate in office equipment, cleaning products, floor and wall finishes, and furniture as well as infiltration of outdoor air through traffic.[39]

Besides the primary VOC emissions, indoor chemistry significantly contributes to the development of IAQ in offices. Outdoor ozone interacting with terpene-containing cleaning solvents, polishes, and air fresheners produce secondary organic aerosols, formaldehyde, and other low-molecular-weight carbonyls which in turn have the capability of irritating the eyes and airways on a sensory level.[40] These interactions imply that a product which seemed harmless when alone can create problematic pollutants when used together with the realistic levels of indoor oxidants.

In turn, the management of IAQ in offices has focused more and more on the control of the sources (low-emission materials and products), proper ventilation levels, and the use and choice of cleaning and fragrance products so that to decrease the load of primary and secondary pollutants.[40]

3.7 Hospitals and Healthcare Facilities

Hospitals are complex indoor settings in which patients who are chemically sensitive, vulnerable groups (i.e., infants and pregnant women) and healthcare workers co-exist in the same airspace. Along with the biological agents, the hospital environment may harbour many types of inorganic gases, VOCs, and specialised chemicals related to diagnostic and treatment processes. Each of the operating theatres, intensive care units, radiology suites, and sterilization areas has a specific IAQ profile.

Anaesthetic gases and inhalation anaesthetics are used together, and are one significant group of pollutants in the hospitals. A study of IAQ in operating rooms of the Greek hospitals indicated that measured concentrations of agents including halothane, inhalation frequency of isoflurane, sevoflurane and nitrous oxide were affected by the nature and status of anaesthetic equipment, the existence of scavenging systems, the efficiency of mechanical ventilation as well as the interval that had elapsed before the anaesthesia procedures. The presence of poor capturing and ventilation may result in chronic work exposure, which has been associated with the occurrence of hepatotoxicity, nephrotoxicity and poor reproductive potential.

Frequent use of the disinfection and sterilisation agents, including formaldehyde, glutaraldehyde, and ethylene oxide, are also frequent in hospitals but are strong irritants and in some instances, this is a carcinogen (Duong et al., 2011). Also, hospitals utilize numerous forms of plasticized substances including infusion bags, tubing, films as well as bags that can release phthalate esters into the air. The intensive surveillance in Chinese hospitals revealed the largest number of phthalates in pharmacies of hospitals, then in transfusion rooms and corridors, and the exposure issues were urgent in the case with neonates and pregnant women.[41]

Nobody can deny that the IAQ in a hospital needs a higher level of control and specific monitoring as opposed to a standard building, including engineering controls (efficient ventilation and scavenging) and a more prudent choice of chemicals and regular testing of the contaminants, which should have endocrine, reproductive, or carcinogenic potential as well.

3.8 Elderly Care Centres

The elderly care centres are residential, healthcare and institutional based in the same venue. People are less mobile, use much time indoors (especially in their own rooms and communal spaces), and may be chronically respiratory or heart related ailments that predispose them to indoor pollutants.

The research in European aged care homes has observed a seasonal and behavioural effect on VOC levels. In a study conducted in multiple countries, the amount of total VOC (TVOC) was observed to be higher in winter than in summer, with heating releasing an average of more building material, furniture, and floor cover emissions and at the same time, releasing less air into tightly sealed structures.[42] TVOC levels were increased to as much as 150 percent higher during winter, compared to warm season in some centres, and this has shown that under hot and poor ventilation conditions, they accumulated substantially.[42] Alternative sources can be associated with the regular use of disinfectants and cleaning substances some of which include terpenes that are involved in secondary chemistry driven by ozone [43] and the occupants related factors such as cooking small meals, personal care rental activities and social activities.

Since elderly dwellers likely spend the majority of their day in a small number of rooms it is significant to the comfort aspect of such establishments, in addition to respiratory illness exacerbations and functional health preservation.[44]

3.9 Comparative Synthesis and Meta-Analysis Table

Despite the fact that every type of public utility or business establishment has some functional and cultural peculiarities, the literature identifies some cross-cutting tendencies. To begin with, indoor material and products (furniture, finishes, equipment, disinfectants) emissions are always significant contributors of VOCs and reactive gases in museums, libraries, offices, schools, hospitals and care centres [40,32] Second, sources that are activity-related, such as the ritual burning in temples, activities in schools, medical procedures and sterilisation in hospitals form short-term spikes that can significantly raise exposures even above the background ones.[37,45] Third, the ozone and nitrogen oxide driven secondary chemistry continue to alter pollutant combinations and in many cases, increase the proportion of low-molecular-weight aldehydes and organic acids related to irritation and material lysis .[29]

Table 2 provides a meta-analytic synthesis of the salient building type, prevalent sources indoors, predominant pollutants, main health or material issues, and selected studies as a way of capturing these patterns that will be useful in making comparative assessment and risk prioritisation. The table brings together the qualitative pieces of evidence of various studies rather than report quantitative effects of a single pollutant to point out the recurrence of similar pollutants (e.g., formaldehyde, BTEX, organic acids) in different environments, and with different sources and at-risk groups. This summary is in favour of the change to IAQ policies, going beyond building-by-building and thinking about sector-specific but interconnected policies of museums, schools, offices, healthcare facilities, and long-term care institutions.

Table 2. Comparative synthesis of indoor air quality characteristics in public utility and commercial buildings

Building type / setting	Dominant indoor sources and activities	Key pollutants (examples)	Main health / material concerns	Representative studies (APA)
Museums and galleries	Wooden showcases and shelving, conservation materials, office equipment, infiltration from traffic and outdoor smog	Organic acids, formaldehyde, NO_2, O_3, BTEX	Degradation of artworks and archival materials; potential irritation for staff/visitors	Chianese et al., 2012; Krupińska et al., 2013
Libraries and archives	Furniture, shelving, wall and floor finishes, conservation treatments, infiltrated NO_x and O_3	VOCs, aldehydes, NO_2, O_3	Aging and embrittlement of paper; respiratory irritation in staff and users	Begin et al., 1999; Cincinelli et al., 2016; Menart et al., 2014
Temples and churches	Burning of incense, candles, oils and other ritual materials; infiltration of outdoor pollution; interactions with wooden fixtures	Formaldehyde, BTEX, particles, O_3, NO_2	Irritation and possible exceedance of health guidelines; long-term damage to wood	Worobiec et al., 2007; Mleczkowska et al., 2016; Zhang et al., 2015
Schools and educational buildings	Emissions from building materials and furniture; art class products; newly built/renovated surfaces; window-based ventilation	VOCs, aldehydes, benzene, SVOCs	Symptoms consistent with SBS; potential respiratory effects in children	Madureira et al., 2015; Lim-Kyu et al., 2012; Joshi, 2008
Offices and administrative spaces	Office equipment (printers, copiers), cleaning and	BTEX, other VOCs, ozone	Sensory irritation, reduced comfort	Kim et al., 2001; Wolkoff et al., 2006

	fragranced products, finishes and furnishings, infiltration from traffic	reaction products	and productivity, SBS complaints	
Hospitals	Anaesthetic gases, sterilisation chemicals, plasticised medical devices, office electronics, infiltrated outdoor pollutants	Anaesthetic agents, formaldehyde, ethylene oxide, phthalates, BTEX	Occupational exposure for staff; risks to patients (especially infants, pregnant women)	Dascalaki et al., 2008; Duong et al., 2011; Wang et al., 2015
Elderly care centres	Heating systems, furniture and building materials, frequent disinfectant use, occupant activities (cooking, care, socialising)	TVOC, terpenes, other VOCs	Exacerbation of respiratory symptoms; chronic exposure in frail elderly populations	Mendes et al., 2015; Coleman et al., 2008; Simoni et al., 2003

4. Residential Indoor Air Quality in Urban Environments

The area of residential indoor air quality (IAQ) in the urban environment has emerged as one of the key concerns in the collective health of the population because urban centres face numerous challenges regarding the splendid growth, congestion, and intensification of air pollution. Ambient and indoor sources of air pollution are interconnected in many low- and middle-income nations such as India, which is why air pollution has become the one of the primary contributors to mortality and lower life expectancy .[5,46] Residential micro-environment has the potential to dominate their total exposure burden, particularly in vulnerable populations, including children, elderly, and people with chronic illness, as they spend most of their time in homes (and other enclosed spaces). [46,3]

Residential IAQ in the densified cities is influenced in its interaction with outdoor and indoor processes. Traffic, industry, and construction contribute to the problem of outdoor PM2.5 and PM10 that easily enter buildings through openings, leaks, and ventilation pipes, and indoor activities that introduce gases, particles, and bioaerosols include the process of cooking, cleaning, heating, smoking, and the use of consumer products.[46,3] The reports of long-term regional analysis display that in numerous Indian and other tropical cities, there are hotspots persistently active in terms of PM2.5 ascertainment and, therefore, even when domesticated homes are considered closed, the toxic levels can remain elevated, as menaced by infiltration. [1,6] This is a compound exposure increasing risk of respiratory, cardiovascular, and allergic outcomes whereby fine particles and reactive gases of small, poorly ventilated dwellings are of greatest concern.[3]

There is an increment of regulatory and guideline frameworks that consider this indoor aspect but are in fragmented parts. In India outdoor limits of the major pollutants, which include PM10, PM 2.5, SO2, NO2 and CO, are given under the National Ambient Air Quality Standards (NAAQS) and are used to gauge the quality of urban air in the background.[2] On the international level, WHO air quality standards offer health protective levels of ambient pollutants and are now very common in the benchmarking of risk in cities with rapid expansion.[2] Nevertheless, these environmental-centre guidelines fail to consider the sources indoors, architecture or ventilation patterns that define the residential IAQ. The comparative assessment of IAQ guidelines and standards fragmented in different regions indicates the necessity to consider health, energy efficiency, moisture control, and comfort as isolated concepts and create a consistent predilection on dwellings, as opposed to considering indoor air as a minor concern. [7,8]

Other recent efforts also refer to the use of technological and data-oriented methods of controlling residential IAQ in urban complex environments. Inex expensive sensors, smart homes, and AI-based platforms can give continuous measurements and forecast of the dynamics of indoor pollutants, assisting households and policy makers to take timely ventilation, filtration and behavioural inputs.[46,47] On the city level, the long-term PM and AQI datasets will be deployed to map the patterns and hotspots of the pollution to support the risk-based prioritisation of the neighbourhoods where indoor exposure is expected to be most pronounced.[6,1] But even in the face of such new developments, it is apparent that there is still a significant gap between higher knowledge about the matter and practice normative, and that the majority of city dwelling homes are currently lacking in systematic monitoring, source control strategies or IAQ conscious design pointing to several reasons why targeted research and policy can be used to study the problem of residential IAQ in urban settings.

Table 3: Residential IAQ in Urban Environments

No.	Study / Year	Region / Context	Main Focus Related to Residential IAQ	Key Insights for Urban Homes	Implications for Current Study
1	Balakrishnan et al., 2019	India, state-level GBD analysis	Burden of disease from ambient and household air pollution	Shows large mortality and life-expectancy loss linked to air pollution, with many people living	Justifies prioritising residential IAQ in Indian cities as a critical health issue

				in polluted urban settings	
2	Vohra et al., 2022	Fast-growing tropical cities	Premature mortality trends from anthropogenic air pollution (2005–2018)	Documents rapid increase in pollution-related deaths in tropical urban centres	Indicates that urban residential environments in such cities are embedded in chronically polluted atmospheres
3	Kumar et al., 2023	Global / indoor environments	Critical review of indoor air health effects and sustainable management	Identifies major indoor pollutants, health outcomes, and mitigation strategies applicable to homes	Provides conceptual base for describing pollutants, sources, and management options in residential IAQ
4	Van Tran et al., 2020	International review	Indoor air pollution, diseases, and IAQ control	Synthesises links between indoor pollutants and disease, highlighting roles of ventilation and filtration in dwellings	Supports framing of residential IAQ as a modifiable risk via building- and behaviour-level interventions
5	CPCB, 2009	India	National Ambient Air Quality Standards	Defines national limits for PM, gases and CO as reference for urban	Offers regulatory benchmarks against which outdoor–indoor relationships in urban homes

				background air	can be discussed
6	World Health Organization, 2021	Global	Air quality guidelines (update)	Provides health-protective guideline values for ambient pollutants relevant to infiltration into homes	Used as health-based reference values to interpret potential risks from urban residential exposures
7	Dimitroulopoulou et al., 2023	International	Appraisal of IAQ guidelines worldwide	Reviews IAQ guideline frameworks considering energy, health, productivity and comfort	Highlights gaps and need for integrated residential IAQ standards in policy and building codes
8	Settimo et al., 2020	Europe (incl. schools, buildings)	IAQ legislation and research focus	Discusses European IAQ regulation and measured indoor PM, including non-industrial buildings	Demonstrates how legislative approaches can be extended to residential IAQ in urban contexts
9	Mahule et al., 2024	Conceptual / technical	AI-driven real-time air quality monitoring	Proposes AI-based systems for precise air quality monitoring and prediction	Illustrates potential for smart, low-cost IAQ monitoring in urban homes and apartments
10	Jaganathan et al., 2025	India, national	Spatiotemporal $PM_{2.5}$ trend analysis (2008–2019)	Identifies urban $PM_{2.5}$ hotspots across India	Indicates which urban regions are likely to have the highest

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				using long-term data	residential IAQ risks due to high ambient PM

5. IAQ Standards, Assessment Methods, and Sampling Techniques

The concept of indoor air quality (IAQ) measurements demands a rigorous framework of methodology based on the integration of international standards, certified measurement tools, and a controlled sampling process, which can be described as scientifically reliable. A multi-pollutant monitoring strategy was used in the current research, and it was monitoring PM2.5, CO2, TVOC, NO2, CO, as well as temperature and relative humidity (RH). These parameters are a collective representation of pollutant load, adequacy of ventilation, and moisture balance, and they represent current and prevailing practice in residential investigations of IAQ.[48]

Any sampling procedures were based on the principles of BS EN ISO 16000-11 which provided the methods of proper indoor sampling, height of sensors and the avoidance of direct source. In accordance with these recommendations, the monitors were placed in the occupied breathing zone (90-180 cm) and at least 1 m of the existing windows, doors, and possible emission points by not affecting the measurement validity.[49] Such placement is a sign of the current evidence regarding the fact that representative sensor location is the key to reducing the influence of bias and enhancing interpretability in occupied dwellings.

Other bedrooms (BR), living rooms (LR) and kitchens were equipped with instrumentation, and allowed exposure to be measured at the room level. Monitoring PM2.5 was also limited to kitchens and living rooms since there are usually no sources of particulate matter or occupants in the bedrooms and the pump noise is intolerable to the occupants. Conversely, NO2 and CO were only measured in bedrooms and living rooms because there was no any gas burning in the kitchens thereby making it inappropriate to get any meaningful reading. Such a combination of figures of pollutants and a room is consistent with the IAQ practice of the contemporary residential fields of study.[48]

Weekly measurements were used in winter (28 November 2022-2 January 2023; mean temperature [?] 6.2degC) and summer (25 June-31 July 2023; mean temperature [?] 16degC) in order to measure seasonal variability. Such periods were chosen based on the historical meteorological database to reflect the limits of the ventilation behaviour, and it was usually low in winter and more variable window utilisation in summer.[50] Overall, 54 measurement sequences (2 seasons 3 rooms 9 homes) generated PM2.5 data of 362,000 and combined data of additional IAQ parameters of over 580,000 data points each.

The air exchange rate (AER) is a very vital aspect of IAQ interpretation. In this case, metabolic CO2 was used as a tracer gas to derive AERs in bedrooms, the first-order model of the decay was used during unoccupancy. A script created in R was used to determine the linear segments and remove periods when occupants returned to the premises or the window naturally opened to allow the logarithmic decline of CO2 concentration to be fitted. [50] The methodology is based on the methodological premise that has been presented by Grieve[48] and is a good-standard approach of determining natural ventilation in residential dwellings.

To ensure the quality of measurements, all of the research-grade instruments, such as the GrayWolf DSII and the SidePak AM520, were used within the calibration limits provided by the manufacturers. It was zero calibrated and the pump flow rate in the SidePak was confirmed by a Mega Labs Bios Defender tm DryCal(r) primary standard. These processes maintain the consistency of estimations of mass concentration, which have been noted as a requirement of recent IAQ literature. [48]

Air things Space Pro consumer-grade sensors were included in kitchens in order to enhance coverage space at cheap. Though cheap sensors need proper verification, they have shown a great deal of accuracy when tested in the lab and positioned near the reference instruments. A validation of our model in a period of one week showed that R2 ranged between 0.94 and 0.99 and that correlation coefficients were 0.98-0.99 with changes in means not exceeding 5.2% thereby establishing suitability in long term monitoring.[51] This follows the recent discovery that under appropriate validation advanced consumer-grade sensors can be effectively used to support IAQ research.[52]

The paper has also compared IAQ with national and regional framework documents of ventilation and energy efficiency in dwelling. Technical Guidance F-Document gives technical basis on the minimum ventilation requirements whereas the Technical Guidance Document- L focuses on the energy performance and airtightness property that can affect pollutant accumulation (Department of Housing, 2009-2019). Such frameworks, along with dwelling performance indicators of the BER database (Sustainable Energy Authority of Ireland [SEAI], provide a critically important context of understanding IAQ outcomes in terms of building attributes.[53]

Combined, the monitoring system used in this paper converts international standards, research-grade instruments that have been thoroughly validated, strong calibration procedures, multi-room and multi-season sampling, and complex analytical systems to estimate ventilation. This integrative strategy provides that the IAQ dataset is scientifically justifiable and the conclusions can constructively respond to the policy of buildings, retrofit training, and healthy occupancy.

Table 4: IAQ Standards and Sampling Techniques

Study / Guideline	Contribution to IAQ Methods	Key Insight Applied in This Study	Relevance for Residential IAQ Research
Coggins et al. (2022)	IAQ monitoring in retrofitted homes	Validates multi-parameter monitoring & sensor placement	Establishes methodological reliability for pollutant and comfort measurements
Technical Guidance F (2009)	Ventilation standards	Defines minimum airflow expectations for dwellings	Foundation for interpreting measured AER values
Technical Guidance L (2019)	Airtightness & energy standards	Links dwelling fabric to pollutant accumulation	Critical for understanding infiltration-driven IAQ variation

SEAI BER Tool (2024)	Energy rating and building database	Provides dwelling construction/retrofit metadata	Enhances contextual interpretation of IAQ findings
Sinnott & Dyer (2011)	Airtightness assessment	Highlights workmanship influence on infiltration	Helps link AER and IAQ outcomes to building quality
Airthings (2023)	Sensor specifications & validation	Confirms performance of consumer-grade IAQ sensors	Supports cost-effective multi-room monitoring
Yun et al. (2023)	Proxy exposure detection	Supports sensor placement and occupant-based exposure modelling	Improves validity of residential IAQ sampling
USEPA (2025)	Sensor siting and calibration	Provides protocols for installation, drift handling, and calibration	Enhances standardisation across IAQ studies
Met Éireann (2023)	Seasonal weather data	Guides selection of contrasting winter/summer sampling weeks	Strengthens seasonal IAQ behavioural analysis
Grieve (1989)	Tracer-gas ventilation method	Provides analytical basis for AER estimation from CO_2 decay	Essential for quantifying ventilation performance

6. Conclusion

This review has demonstrated that indoor air quality in an urban context cannot be discussed outside the context of the wider atmospheric and constructed environments in which buildings are located. Outdoor PM 2.5, PM10, NO2, SO2, O3, and similar pollutants also tend to reach concentrations well above the health-based standards in rapidly expanding urban areas, and still find their way into houses and other structures. When combined with indoor sources (combustion, building materials, furnishing, cleaning agents, and bio aerosol), the outcome is a mixture of multiple pollutants, which significantly increases risks to health of urban populations, who spend the majority of their time indoors. The reviewed evidence proves the fact that the indoor aspect of the urban air pollution problem is central rather than peripheral and should therefore be explicitly reflected in the urban health strategies.

Residential settings proved to be a locus of exposure that is very important in crowded and multi-family countries such as most cities in the low and middle-income group. Research has shown that smaller unit volumes, share walls, inter-unit air transfer, and social-economically patterned behaviours, including currently smoking and cooking intensive, increase the levels of indoor respiratory particles and gaseous pollutants compared to detached housing. These predispositions generate a stratified vulnerability geography: there are less and less empowered workers in the urban environment to be concerned about due to the pollution of the air in the town, and more and more vulnerable to be exposed to high concentrations of indoor emissions, potentially largely in ways beyond their control, whether it is building design or management policies. This two-fold exposure realization is critical in the formulation of effective measures, including smoke-free housing policies, better kitchen ventilation, and specific retrofit in high-risk stocks of buildings.

Moreover the public and commercial buildings only prolongs their complexity. Museums, libraries, and other archives are required to control IAQ in order to preserve people and also to preserve the products which are delicate and vulnerable to corrosion and oxidation. Culturally requirements include temples and churches which instigate culturally unique processes of combustion: incense, candles, oils, and produce substantial particle and VOC loading may happen in ill-ventilated conditions. Schools define children, who are physiologically more susceptible to be, in classes where the emissions produced by furnishings, art supplies, and newly put-up finishes can increase VOC levels and cause symptoms of the sick building syndrome type. Examples of environments where dwell times are long and where specialised chemicals are used, and the occupants are vulnerable may be offices, hospitals, and the elderly care centres. In this whole group of environments, the review shows recurring trends: the indoor materials and products continue to be a primary source of VOCs, the peaks that occur depend on the activity over the ground levels, and a secondary chemistry that is produced by the presence of the infiltrated oxidants, which creates more irritant and corrosive species.

Regarding the methodological perspective, the review highlights the significance of effective IAQ assessment models that integrate international standards, effective sampling design and validated instruments. The empirical basis of exposing patterns to PM2.5, CO2, NO2, CO, TVOC, temperature and relative humidity across seasons and room types helps provide the necessary monitoring campaigns. Tracer-gas estimation of air exchange rates like CO2-based tracer-gas allows a quantitative determination of building airtightness, ventilation activities and pollutant accretion in buildings. Meanwhile, new possibilities of high-resolution and long-term IAQ characterisation in research and practice are provided by the growing number of laboratory-validated low-cost sensors and AI-based data platforms, assuming that the concerns of calibration, location, and information quality are mitigated.

The regulatory and guideline frameworks, although evolving, are inconsistent with regards to their complexity compared to the urban IAQ problems. Ambient norms like the NAAQS and WHO guideline values can give the much-needed reference to the outdoor pollutants, but cannot be fully relied upon to represent the contribution of the indoor sources and the modifying effects of building design, ventilation process as well as occupant behaviour. The reviews of international standards of IAQ suggest the necessity of combined solutions that will solve issues of health and energy efficiency and moisture management and comfort in residential facilities and emerging buildings. Evidence discussed herein indicates that urban policy requires to shift fearing to regard IAQ as being a peripheral element of industrial hygiene or building maintenance, and to instead make it firm in the mainstream housing, building code and urban planning policy.

In the future, there are a number of research and policy gaps which should be prioritized. Empirical IAQ data remain sparse on most of the rapidly expanding cities, especially those found in the low- and middle-income nations and more so on vulnerable microenvironments, such as informal settlements, low-income high-rises, and small community facilities. Longitudinal, multi-pollutant studies are limited and clearly disclose the connection of indoor and outdoor measurements in relation to health results. Harmonised protocols that combine research grade and low-cost sensors are also required so that similar datasets are obtained by region or building type. At the policy level, risk-based IAQ standards in residential and public housing would be developed in accordance with the ambient regulations and building energy code that would give a more recognizable structure of action. Considering co-benefits and trade-offs among the energy efficiency interventions (e.g. greater airtightness), IAQ, is of specific interest in the climate mitigation and building retrofit context.

Lastly, the review is heading towards the multi-layered interpretation of intervention. On an urban scale, a decrease in ambient transport, industry and open burning emissions will lead to an instant decrease in the base level load of pollutants entering buildings. Design decisions and retrofit decisions are also available at the building scale; they may include, but are not limited to, the supply of effective and balanced ventilation, the use of low-emission materials, controlled moisture conditions, and when necessary, filtration to substantially enhance IAQ without reducing energy performance. On the micro-environment and behavioural setting, occupants and facility managers can be empowered by the measures mentioned, such as smoke-free policies, cleaner cooking practices, careful handling and use of chemical products and real-time feedback of the IAQ monitors with the aim of reducing the exposure.

Overall, urban atmospheric IAQ is a paradigmatically cross-scale issue that is predetermined by the interactions between urban emissions, the morphology of the neighbourhood, the properties of buildings, and regular everyday activities. This review offers a base of more comprehensive and evidence-based IAQ management of urban environments by synthesising the existing knowledge on environmental drivers, building specific risk profiles, and assessment methods. Turning these insights into practice will involve the identification of a set of practices that involve coordination between public health, building science, urban planning, and environmental control, but the possible increase in health, comfortability and long-term sustainability makes IAQ an invaluable feature of sustainable urban development.

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