Environmental Science: Atmospheres

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW

View Article Online
View Journal | View Issue

Cite this: *Environ. Sci.: Atmos.*, 2025, **5**, 941

Environmental health hazards attributed to deteriorated indoor air quality caused by inferior construction practices

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Accounting for nearly 5% of the global gross domestic product, the construction industry significantly contributes to environmental pollution, emitting a broad range of hazardous pollutants, including particulate matter (PM_{10}, $PM_{2.5}$), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), benzene and polycyclic aromatic hydrocarbons (PAHs). Individuals spend approximately 90% of their time indoors, where the air quality is heavily influenced by construction and demolition (C&D) activities that are carried out within or adjacent to residences. Despite regulatory interventions in the early 21st century emphasizing the importance of indoor air quality (IAQ), the contribution of C&D activities to indoor pollution remains largely underexplored, particularly to seasonal variations, extended renovation periods, and the release of case-specific pollutants. This review bridges knowledge gaps by examining the correlation between construction activities, pollutant emissions, health risks, and the efficacy of existing regulations. Key investigations include the impact of infrastructural inefficiencies and improper ventilation on IAQ, seasonal pollutant variations, and the disproportionate exposure risks faced by vulnerable populations, such as women and workers. The literature suggests that prolonged exposure prompts sick-building syndrome and ailments such as compromised immunity, bronchial allergy, asthma, and lung cancer. A survey-based data collection and analysis were conducted to gather and refine residents' practical insights across India, contributing to the development of an IAQ index. This tailored index, ranging from 22 to 100, is designed for indoor environments, incorporating building-specific and occupancy-related factors. In the long term, the index can provide actionable insights for administrators and communities to mitigate IAQ risks effectively, promoting healthier indoor environments by providing a quantitative measure of the health risks associated with exposure to poor indoor air quality in the absence of a pollutant dataset. The study enables individual households to take measures to retrofit indoor spaces by upgrading to better-quality materials or modifying the design of the building to reduce health risks and improve air exchange.

Received 19th February 2025
Accepted 23rd July 2025

DOI: 10.1039/d5ea00027k

rsc.li/esatmospheres

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Environmental significance

C&D activities release a complex list of contaminants into both indoor and outdoor environments. Due to prolonged exposure, pollutants present in indoor air pose greater risks, even at similar concentrations. This study primarily focuses on analyzing existing literature on the atmospheric chemistry of pollutants such as particulate matter, volatile organic compounds, and benzene associated with C&D activities, while investigating their formation, transformation, and interactions within indoor environments. Furthermore, global regulations were examined to highlight the negligence toward indoor air quality and its associated health risks. The study further proposes a data-driven indoor air quality index to accurately assess exposure risks. The findings provide insights into pollutant interactions, seasonal variations, and targeted mitigation strategies, supporting informed decision-making.

1. Introduction

The elevated concentration of one or more inorganic and organic gaseous pollutants within the indoor environment that can cause health and productivity-related perils to the occupants is categorized as indoor air pollution (IAP).[1] The concept of IAP and its associated detrimental impacts have long been neglected and have only gained limelight in the recent past.[2,3] Regulatory frameworks such as the Environment Protection Act,[4] along with international guidelines issued by the World Health Organization,[5] underscore the critical health risks posed by IAP, noting that the concentrations of key pollutants

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particularly $PM_{2.5}$, carbon monoxide, and volatile organic compounds (VOCs) can reach levels up to 100 times higher than those found in ambient outdoor environments, especially under conditions of poor ventilation.

Individuals generally spend about 90% of their time indoors, either at their residence or workplace.[6,7] In urban settings, indoor air quality is further compromised by infiltration of emissions from nearby vehicular traffic and industrial activities.[8] Meanwhile, rural households primarily rely on biomass-based fuels—such as wood, crop residues, dung cakes, and coal—for cooking and heating, with approximately 80% of the rural Indian population depending on such sources.[8,9] These fuels, often burned in inefficient open-stove setups, release large volumes of pollutants including CO_2, CO, SO_x, NO_x, and fine particulate matter, contributing significantly to indoor and ambient air pollution. Rohra and Taneja[9] estimated that household cooking emissions account for nearly 25% of ambient $PM_{2.5}$ concentrations in India. The accumulation of these pollutants, exacerbated by inadequate ventilation, can lead to severe health outcomes. Chronic exposure to these pollutants has been linked to respiratory disorders, cardiovascular ailments, and over four million premature deaths globally each year.[10] Moreover, the exacerbating influence of global climate change on IAQ is becoming increasingly evident, as rising ambient temperatures and altered atmospheric dynamics intensify pollutant entrapment indoors. The widespread adoption of microclimate-controlled environments characterized by mechanical heating, ventilation, and air conditioning (HVAC) systems is expected to grow at a rate of 30% annually. These enclosed and artificially ventilated spaces substantially limit natural dispersion and facilitate the recirculation and accumulation of gaseous contaminants, further aggravating indoor air toxicity.[6]

Furthermore, the accretion of these gases in the indoor environment due to the flawed ventilation design may seriously affect the health of the occupants. Short-term or prolonged exposure to IAP leads to more than 4 million global deaths per annum.[10] Long-term exposure also accounts for more than 5% of global physical disabilities and daily-adjusted life years. Unfortunately, India has the highest share of 28% air pollution-related premature mortality rate among all the developing nations. In urban settings, workers in the infrastructure sector and employees working in artificially ventilated buildings are categorized as the high-risk group. Women, being the primary cooks in rural areas, are exposed to the highest degree of threat. A recent study revealed that more than 80% of the rural female population in India is severely exposed to acute health hazards due to breathing poor-quality indoor air.[3] Inferior air quality is also responsible for more than 30% of national infant deaths and critical illnesses in adults such as chronic obstructive pulmonary disease.

While substantial research has been devoted to indoor pollution arising from combustion fuels, artificial ventilation, and domestic emission sources,[6,11] limited attention has been paid to the role of construction and demolition (C&D) activities in deteriorating indoor air quality. Studies have shown that these activities emit a wide spectrum of pollutants, including dust, PM_{10}, chlorine, ammonia, VOCs, fungal spores, and heavy metals, posing significant toxicity risks to occupants.[12–14] The present study addresses this overlooked source of indoor pollution by examining the specific contribution of C&D activities often undertaken within or adjacent to residential environments to indoor air quality degradation. This is especially relevant for rapidly urbanizing regions where renovations are frequent and often occur in occupied buildings. This study is among the first to systematically integrate empirical field data from residential occupants with existing literature to establish a quantifiable association between C&D-related emissions and IAQ deterioration in domestic environments. Furthermore, it proposes a novel exposure-responsive assessment framework to characterize IAQ risks associated with C&D activities, particularly in scenarios where

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direct pollutant monitoring data are unavailable. The findings are expected to facilitate the development of an IAQ assessment index that accounts for construction-specific variables and to guide regulatory bodies and urban planners in creating targeted mitigation strategies. This will aid in framing inclusive IAQ policies that go beyond fuel use and HVAC limitations, incorporating building renovation dynamics and localized exposure risks.

2. Types of construction and demolition waste

The construction of structures worldwide generates a considerable amount of non-biodegradable and inert materials, concrete, wood, plastic, and other harmful materials. Primarily, C&D waste is non-hazardous, but specific components of the waste that contain VOCs and heavy metals possess toxicity. It is essential to bifurcate the categories of wastes that emit toxic gases, such as CO_2, CO, and NO_x, and wastes emitting other VOCs. The waste created by mass construction projects substantially influences the air quality of surrounding areas. Compared to the waste generated during new construction, the demolition process generates considerably more waste.

The content of C&D waste varies depending on whether the structure is being constructed/erected, demolished or renovated. Due to the nature and kind of C&D activities, mode of operation, and scale of operation, such as regional, site or project-specific, the amount of C&D waste generation varies. Concrete, dirt, steel, wood, plastic, bricks, tiles and mortar are classified as C&D trash by the Central Pollution Control Board.[1] As per the Technology Information Forecasting and Assessment Council (TIFAC) and CPCB, the composition of C&D waste is portrayed in Fig. 1.

The waste can be broadly classified into four categories based on the generation source. A detailed discussion of each type of waste is provided below.

2.1 Construction/renovation waste

The typical causes of waste generated during the construction of new buildings can be listed into three categories. The first category incorporates woodwork, which accounts for 30% of waste generated while constructing new structures. The second category of waste contributors is finishing activities, accounting for about 20% of total waste generation. The third category combines concrete (13%), masonry (13%), and material handling (10%). Construction waste may be calculated depending on the project area, material consumption, and the urban population output ratio.[15]

Progressive activities such as civil and infrastructure improvements, which contribute the highest societal benefits, including roads, dams, bridges and airports, also adversely affect the environment. The construction of public and private structures creates vast amounts of waste daily since it necessitates a significant volume of material and a large geographic footprint.

2.2 Demolition waste

Demolition of obsolete infrastructure is necessary to avoid safety risks, but the process generates large quantities of inert and hazardous wastes. All other demolished fractions end up at illegal dump sites except for selected components such as wood, concrete, and glass. Recycling demolition waste is one way to counter the burden of construction waste. Liu *et al.*[16] reported two possible strategies to recycle demolition waste: aggregate conversion and powder conversion. The process of aggregate conversion contributes a negative carbon emission

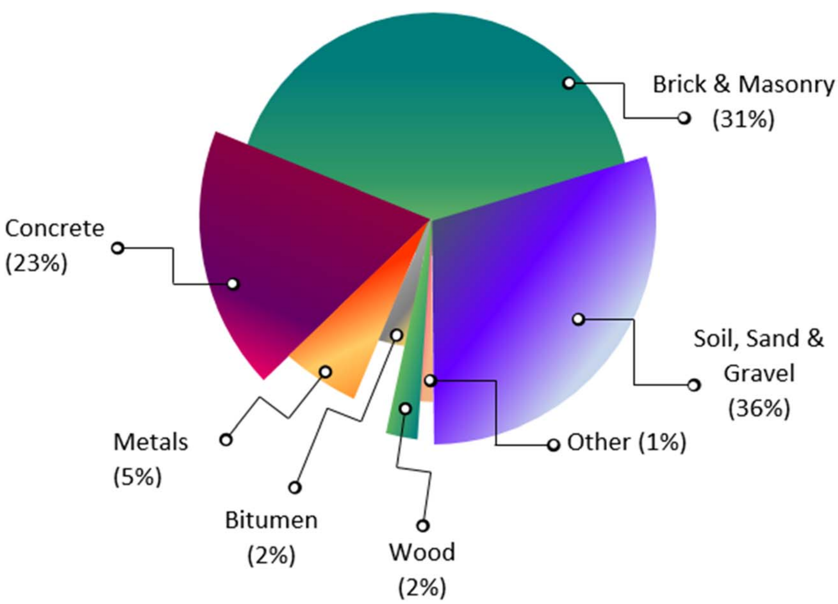

Fig. 1 Typical composition of construction and demolition waste.

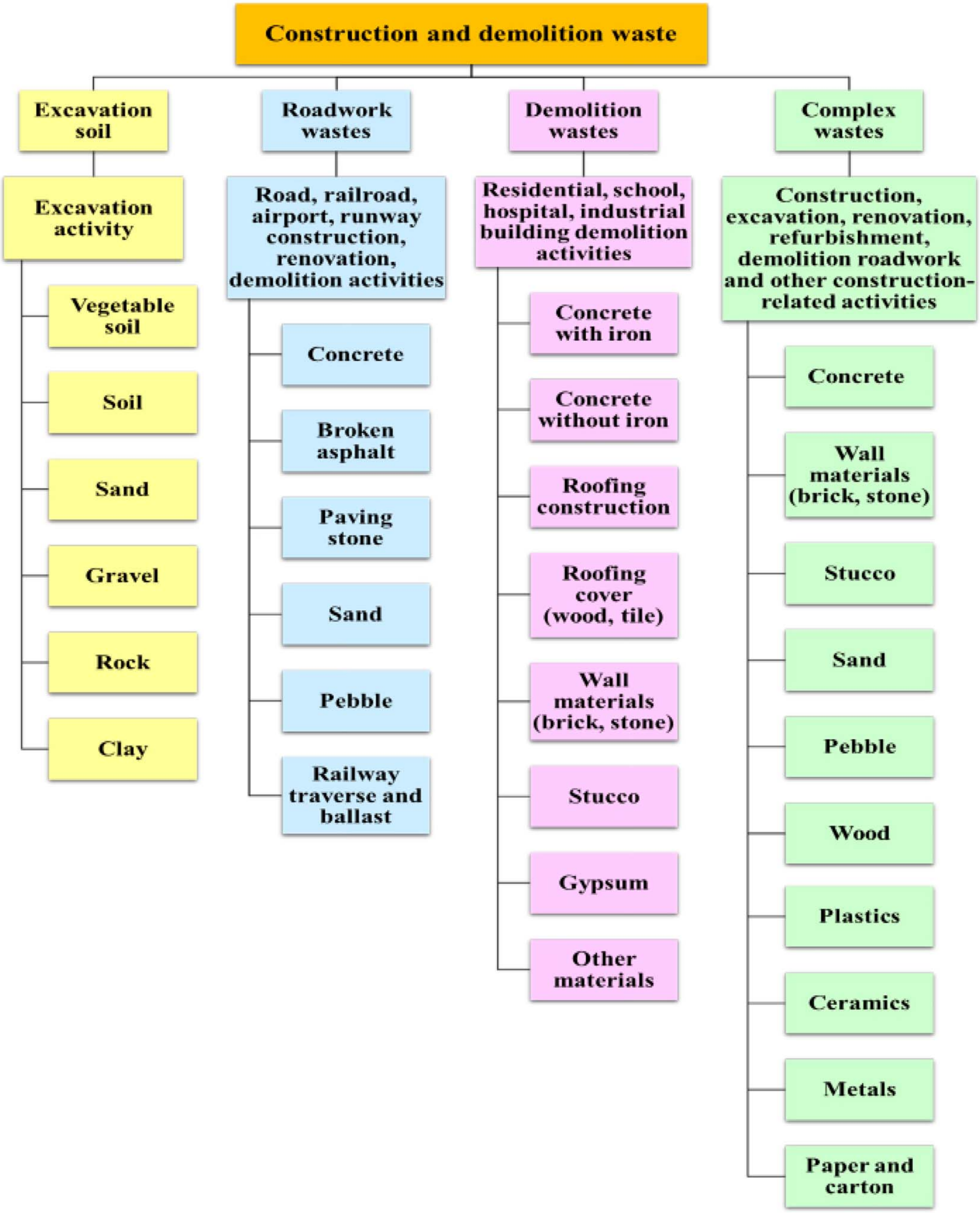

Fig. 2 Types of construction and demolition waste.

of 3.642×10^8 kg CO_2 eq., while powder conversion contributes an emission figure of -7.814×10^8 kg CO_2 eq. The researchers have identified fossil fuel requirement as the only carbon-positive phenomenon (0.163×10^8 kg CO_2 eq.) during mechanical recycling operations. However, the comprehensive waste recycling process is evaluated as vastly carbon-negative due to reduced virgin resource consumption. Furthermore, the recycling process is estimated to reduce primary pollutants such as SO_x, CO_2, PM, and NO_x by 79, 63, 53, and 50%, respectively.[17]

2.3 Waste associated with construction materials production

The production process of building materials such as cement, fly ash, slag and manufactured sand contributes significantly to the total C&D waste generation. The quantity and quality of waste generation from any specific material production unit vary mainly depending on machines' resources, process optimization strategies, and efficacy. Wimala *et al.*[18] classified these production units into three broad categories based on the small, medium, and large scales of operation. The researchers reported an inversely proportional correlation between the size

Fig. 3 Sources of construction and demolition waste.[24]

of the unit and waste generation. For instance, the percentage of waste contribution against precast concrete's overall manufacturing is calculated to be 2.96, 4.45, and 6.07% for large, medium, and small-scale operations, respectively.

2.4 Soil and road excavation waste

Excavated soil during the construction of structures, removed layers of concrete, and sections of bituminous roads during repair contribute massively to the total generation of C&D waste. In contrast, a good portion of inert C&D waste can be reused as filler and roadbed preparatory material during the construction of new roads. This practice is even more wholesome and economical when the safe bearing capacity of the soil underneath the proposed roadbed is inferior.[19,20]

TIFAC has developed a methodology to ascertain the quantity of waste beforehand, based on the classification of the activity. The quantity of waste generated for each of the three categories developed by TIFAC based on CPCB guidelines is presented below.

For new construction: 40–60 kg m^{-2}

For building repair: 40–50 kg m^{-2}

For building demolition: 300–500 kg m^{-2}

Fig. 2 and 3 depict various categories of waste generated during new construction and demolition of the existing infrastructures. Each of the categories mentioned releases considerable toxic gases into the atmosphere, which leads to the deterioration of the air quality in the external surroundings and indoor building components.[1]

3. Area-specific impact and indoor air quality

The generation of C&D waste can be reduced if the best quality materials and construction techniques are used. The comprehensive C&D waste generation in India in 2016 accounted for nearly 150 million tons. According to Jain *et al.*,[21] this generation can go up to 431 million tons by 2030 if inferior quality construction materials and practices are continued. At the same

Table 1 Pollution potential of various biomass fuels[29–31]

		Intensity of contribution based on the category of fuel					
Pollutant	Range of contribution	Cow dung cake	Wood	Kerosene	Mixed fuel	LPG	PNG
PM_{10}	2000–7000 μg m^{-3}	Very high	High	Moderate	Moderate	Low	Low
$PM_{2.5}$	1750–5200 μg m^{-3}	Very high	High	Moderate	Moderate	Low	Low
CO	1000–22 000 μg m^{-3}	Very high	Moderate	Moderate	High	Moderate	Low
NO_x	65–125 μg m^{-3}	Very high	Very high	Moderate	Moderate	Very high	Low
PAHs	4–28 μg m^{-3}	High	Very high	Very high	Low	Low	Very high
VOC	25–900 ppb	Very high	High	Moderate	Moderate	Low	Low
Benzene	13–500 ppb	Very high	Very high	Moderate	Moderate	Low	Low

time, mandatory compliance with standard construction practices and usage of recommended material quality can restrict this quantity to 289 million tons. Bricks have also been identified as potential sources for generating vast amounts of C&D trash, especially in rural regions. The same study also highlighted that the volume of C&D waste generated in rural areas against independent activities is substantially higher than that generated in urban areas. Wimala *et al.*[18] identified CO_2, SO_x, NO_x, and PM as the most prevalent gaseous pollutants from C&D sites. These pollutants conveniently travel greater distances before dispersion owing to the environmental lapse rate and may critically deteriorate the ambient air quality and subsequently affect the IAQ. Fatal illnesses such as stroke, pneumonia, lung cancer, and heart disease could be caused by the elevated concentration of PM_{10} in the indoor atmosphere. Furthermore, moisture dampening, mostly caused by cracks developed during the demolition of adjacent structures, stimulates the growth of fungus and specific pathogens on the wall surface, resulting in microbial pollution of the interior air. Generally, the indoor concentration of VOCs is significantly higher than outside. Indoor VOCs are usually made of construction items such as paints, thinners, and furniture, which may stay indoors for a longer period of time.[22–24]

3.1 Area-specific impacts

Good ambient air quality is an essential requirement for all humans, which differs according to the area, season, and local contribution of gaseous pollutants. A healthy adult human requires 10–20 m^3 of pure air daily, which is also considered a fundamental right.[25] Researchers investigated that indoor air, in which the population spends 90% of their time, is more likely to get polluted.[26] Besides, it could also be said that indoor air is more vulnerable to pollutants and toxic substances emitted from paints, furniture, and construction materials. Therefore, ensuring healthy IAQ is essential but complex. In homes, workplaces, and institutions, inferior IAQ often results in reduced productivity, compromised cognitive functioning, and unexplained pulmonary sickness in humans.[27] Al-Rashidi *et al.*[7] claimed a steady correlation between severe deterioration of IAQ and surrounding pollution. The study concluded a higher degree of correlation between the pollution sources and IAQ compared to the association with ambient air quality. A study by the WHO reveals that 99% of the global population (both urban and rural) lives in places where air consists of critical pollutants in concentrations that exceed WHO guidelines, and therefore, the area-specific impacts have been further scrutinized as rural, urban, and suburban impacts.[5]

3.2 Comparison of air pollution impacts between rural, urban and suburban areas

3.2.1 Impact on rural regions. As rural areas are often considered pollution-free, air quality in rural areas has always been an overlooked topic. Contrarily, rural places' IAQ, especially in developing nations, is far worse than in urban areas. Spraying chemicals such as herbicides, insecticides, and fungicides and burning agricultural residues such as wheat, paddy straw, and stubble contribute to outdoor air pollution. Furthermore, activities such as cooking and lighting with biomass fuels cause havoc with IAP. The generated smoke contains significant quantities of PM and benzo(*a*)pyrene (BaP), one of the most notorious polycyclic aromatic hydrocarbons with high carcinogenicity. In India, the exposure of BaP is estimated at about 4 μg m^{-3} while cooking with biomass fuels.[2,28] Rural regions' most common indoor air pollutants are sulfur oxides, nitrogen dioxide (NO_2), carbon monoxide, PM_{10}, $PM_{2.5}$, formaldehyde, and polycyclic organic matter. Gautam *et al.*[8] reported cow dung as the most polluting rural energy source with the highest amount of PM contribution, followed by wood, kerosene, mixed fuel, liquefied petroleum gas (LPG), and piped natural gas (PNG). The details of emission load and the pollution potential hierarchy of various biomass fuels are presented in Table 1.

Due to PAH's extreme carcinogenicity, there is no safe level that has been assessed or prescribed to existing standards and protocols. The smoke generated by using biomass/coal for

Table 2 A typical concentration range of most prominent suburban air pollutants

Pollutant	Unit	Concentration
PM_{10}	μg m^{-3}	14–23
$PM_{2.5}$	μg m^{-3}	2–15
O_3	ppb	0.015–20
NO_2	ppb	0–20

cooking significantly impacts the IAQ of rural localities in developing nations, leading to various respiratory disorders such as tuberculosis and asthma. Women are identified as the worst sufferers of indoor pollution as they spend more time with the primary point source of IAP.[29,30]

In the Indian context, rural air quality is one of the least explored areas. Presently, out of 804 manually operated air quality monitoring stations and 274 continuous ambient air quality monitoring stations, about 96% are placed in Tier-1 and Tier-2 cities. Only 26 manually handled stations are in rural areas, of which 24 are in the state of Punjab alone. So, better public sector advocacy and supervision are required to address this neglected issue.[31]

3.2.2 Impact on urban areas. The ambient air quality in urban areas is much inferior compared to rural settings. Unlike rural areas, urban cities are more vulnerable to air pollution. Studies revealed that air in Class-I cities in India, such as Delhi, contains 500 m^3 per day of total PM.[32] In cities, outdoor pollution is mainly caused by vehicular emissions, burning fossil fuels, industrial stack emissions, and various C&D activities. In contrast, IAP is mainly caused by poorly ventilated kitchens, flawed structural designs of the house, usage of paints, and some electronic appliances such as air conditioners, refrigerators and air blowers. The primary indoor air pollutants in urban areas are VOCs, CO, CO_2, NO_2 and some amounts of PM.[33] Studies revealed that low-income groups in urban areas still depend on biomass-derived fuels for cooking, which aggravates the concentration of various air pollutants.[34,35]

3.2.3 Impact on suburban areas. Suburban areas have a smaller population on the city's outskirts. The primary air pollutants in the suburbs are ozone, NO_x, and PM, but in lesser concentrations than in urban areas. A typical range of these pollutants in suburban ambient air is presented in Table 2.[36,37]

4. Seasonal variance of air pollutants

According to the report of WGBC,[38] around 8 million people die each year in developing nations because of air pollution, with 4.2 million fatalities attributable to outdoor pollution and 3.2 million deaths due to indoor air pollution. These deaths are caused by short-lived climate pollutants (SLCPs), including PM and greenhouse gases such as methane. These SLCPs are linked to respiratory ailments, cancer, strokes, and heart diseases. Carbon dioxide is a primary greenhouse gas generated *via* building materials, fossil fuel combustion, and other sources, accounting for 40% of global warming with a 100-year atmospheric lifetime. The quantity of carbon released at present will impact the future climate. Greenhouse gases such as methane, SLCPs and hydrofluorocarbons account for 45% of global warming and have significant environmental and health consequences. The PM also causes significant damage to the environment and human health. Airborne coarse and fine PM can change the global balance of incoming solar energy, distort the albedo effect, and react with other pollutants. The seasonal variation of these prominent pollutants for indoor and outdoor environments is portrayed in Table 3.

The anomalous rise in temperature in tropical and subtropical countries, including India, often prompts higher usage of air-conditioning systems. Consequently, a local microclimatic warming impact is created due to the expulsion of hot air, exacerbating the urban heat island effects. By 2050, worldwide energy consumption for air conditioners is anticipated to increase by three times, further increasing the detrimental impact on global air quality. The predominant pollutants that diversify or change due to climatic variations include benzene, PM and NO_x.[44]

In the context of seasonal variance, it is essential to mention that IAQ deteriorates much more severely in rural settings

Table 3 Seasonal variation in the concentration of various indoor and outdoor air pollutants[39–43]

	Concentrations in various seasons, μg m^{-3}					
	Summer		Monsoon		Winter	
Parameters	Range	Mean	Range	Mean	Range	Mean
PM_{10} (interior)	70–165	99	59–145	87	80–190	120
PM_{10} (exterior)	90–200	137	35–216	141	100–190	140
$PM_{2.5}$ (interior)	50–100	68	7–31	18	50–150	85
$PM_{2.5}$ (exterior)	50–110	79	6–43	25	55–110	81
CO (interior)	0.1–2	0.6	0.07–0.8	0.45	0.5–3.0	1.6
CO (exterior)	0.2–2.5	1.2	0.1–1.67	0.8	0.5–2.5	1.5
CO_2 (interior)	460–680	558	480–1000	705	500–970	692
CO_2 (exterior)	400–520	451	315–460	383	400–520	454
NH_3 (interior)	0.012–0.05	0.0285	0.02–0.05	0.015	0.01–0.03	0.08
NH_3 (exterior)	32–384	74	25–106	53	69–402	84
NO_2 (interior)	0.06–0.08	0.03	0.01–0.09	0.085	0.01–0.022	0.02
NO_2 (exterior)	33–82	55	30–75	48	31.2–86.8	60
H_2S (interior)	0–0.001	0.0024	0–0.003	0.013	0	0
H_2S (exterior)	0.01–3.70	0.20	0.3–2.2	0.40	0.02–4.30	0.93
SO_2 (interior)	0.01–0.02	0.012	0.02–0.05	0.03	0.04–0.09	0.03
SO_2 (exterior)	27.8–59.3	39	10.5–42	23	33.7–65	41

Table 4 Studies on IAQ due to the construction/demolition activities

No.	Summary of the study	Key findings	Source
1	The outcomes associated with asbestos removal without negative pressure systems were examined. Generally, asbestos fibre concentrations in the working environment were relatively low. However, the leakage in barriers designed to restrict the work zone increased asbestos concentration in the surrounding areas of the renovated buildings Such contamination can spread throughout the entire building. This leads to the long-term retention of asbestos fibres in the work zone, even after the completion of the asbestos removal process	These findings reveal short-term pollution near the building, extending to a depth of 15 meters. It was observed that during the removal of non-friable asbestos-cement sheets, indoor air pollution increased to levels as high as 3000 fibres per cubic meter (f m^{-3}) outside the work zone. For the same type of buildings, these concentrations significantly exceeded the average values typically observed during regular use (<300–400 f m^{-3})	46
2	$PM_{2.5}$, temperature and humidity were measured in a newly renovated office building	The $PM_{2.5}$ concentrations were higher in the cafeteria compared to other areas	11
3	During building renovation, various pollutants, including PM and its components, including chlorides, nitrates, sulfates, lead, and fungal spores in the air and the fungi, reached higher levels	It has been observed that the average suspended dust level reached 6.1 mg m^{-3}, surpassing both the Egyptian indoor air quality standard of 0.15 mg m^{-3} and the occupational exposure limit of 5 mg m^{-3} The detection of species such as *Epicoccum*, *Trichoderma*, *Exophiala*, *Aureobasidium*, *Paecilomyces*, *Scopulariopsis* and *Ulocladium* indicates the signs of moisture in the buildings If precautionary measures are not taken properly, the particulate matter infiltrates into the working zone/occupied zones	12
4	The immunotoxicological activity and microbial flora of filter samples collected from two buildings for remediation were reviewed and analyzed. It also compared the moisture-damaged samples collected before and after the renovation of the building. These results match the outdoor air quality and reference the building's air quality	It has been observed that at location 1, the immunotoxicological activity of the damaged building decreased due to renovation. Furthermore, a slight difference in fungi concentration has been observed. In contrast, at location 2, the immunotoxicological effects were not observed. Moreover, a decrease in the fungi concentration was detected	47
5	Studied the release of particulate matter due to various activities such as successive drilling and cutting of hardened concrete and the mixing of fresh concrete	It has been observed that while mixing of concrete, $PM_{2.5-10}$ fraction emitted around 52–64% of the total mass. In contrast, due to activities such as cutting (97%) and drilling (95%), more particulates were released. However, the ultrafine particles oppressed the total particle number concentrations (PNCs)	13
6	Various experiments were conducted in the civil engineering laboratory, including crushing aggregates using a jaw crusher, preparation of the concrete, sieve analysis of silt specimens, Proctor compaction test, dynamic triaxle compression test and cleaning a mixture sieve with an air compressor, periodically measuring various sizes of the particle concentrations	It has been observed that the concentration reached the maximum level when compared to the indoor air quality standards. To control the PM values, mitigation strategies were applied in the laboratory	48
7	Different operations on the building for the maintenance and protection of the asbestos products, asbestos removal and accidental damage to the asbestos due to these asbestos fibres were studied	It has been identified that the average increase in pollution in buildings and dozens, after removal of the asbestos beyond the work zones, ranged from ≈ 1700–2700 f m^{-3}, and these concentrations were observed within two years	46
8	The resuspension dust concentration in the various stages, such as reinforcement and demolition of a reconstruction project, was studied	It has been observed that, in the demolition stage, dust particles have reached a maximum concentration of 0.96 mg m^{-3}. In contrast, maximum dust concentration evolved in the concrete and mortar mixing during the reinforcement activity	49
9	Various activities such as remodelling and renovation using ultrasonic extraction and anodic stripping voltammetry (UE-ASV) measured the lead concentration and the paint chip samples	The lead in air filter samples analyzed by Ultrasound-Enhanced Anodic Stripping Voltammetry (UE-ASV) has been correlated with lead measurement by the Ultrasound-Enhanced Atomic Absorption (UE-AA) method	50

during winter than in urban settings. Factors such as the size of the home, availability of cross ventilation and environmental lapse rate govern IAQ.[45]

5. Studies on indoor air quality due to construction activities

Numerous studies in recent years have investigated indoor air quality across diverse global environments, including laboratories utilizing construction equipment, renovated residences, and similar settings. Table 4 summarizes these studies, focusing on the specific microenvironments and the associated health impacts of air pollutants within these indoor spaces.

The studies reveal that the confinement of the indoor air pollutants generated due to activities such as construction and demolition, coupled with faulty designs, has resulted in elevated concentrations, contributing to various health risks and hazards. Although many studies have investigated indoor air quality in various microenvironments under normal conditions, the impact of renovation, construction and demolition has not been investigated widely. Although renovation and infrastructural activities are typically conducted over relatively short durations, the health risks associated with exposure to pollutants released during these activities can be significant due to their prolonged and intermittent release and high toxicity. Hence, the health hazards associated with these air pollutants must be investigated in detail.

6. Health hazards associated with indoor air quality

For several years, outdoor and occupational air pollution driven by the excessive release of gaseous pollutants has drawn scientists' attention. In contrast, the contamination of indoor air and its associated health hazards is a lesser-explored phenomenon. Most third-world countries do not have regulatory standards or norms to monitor IAQ. Organic pollutants are the main reasons for IAP. Regular and prolonged exposure to unhealthy air poses significant health risks and perilous illness. At present, one-third of heart disease-related deaths globally are caused by breathing polluted air. Airborne particles emitted from carpentry activities, such as hardwood silica dust, impose

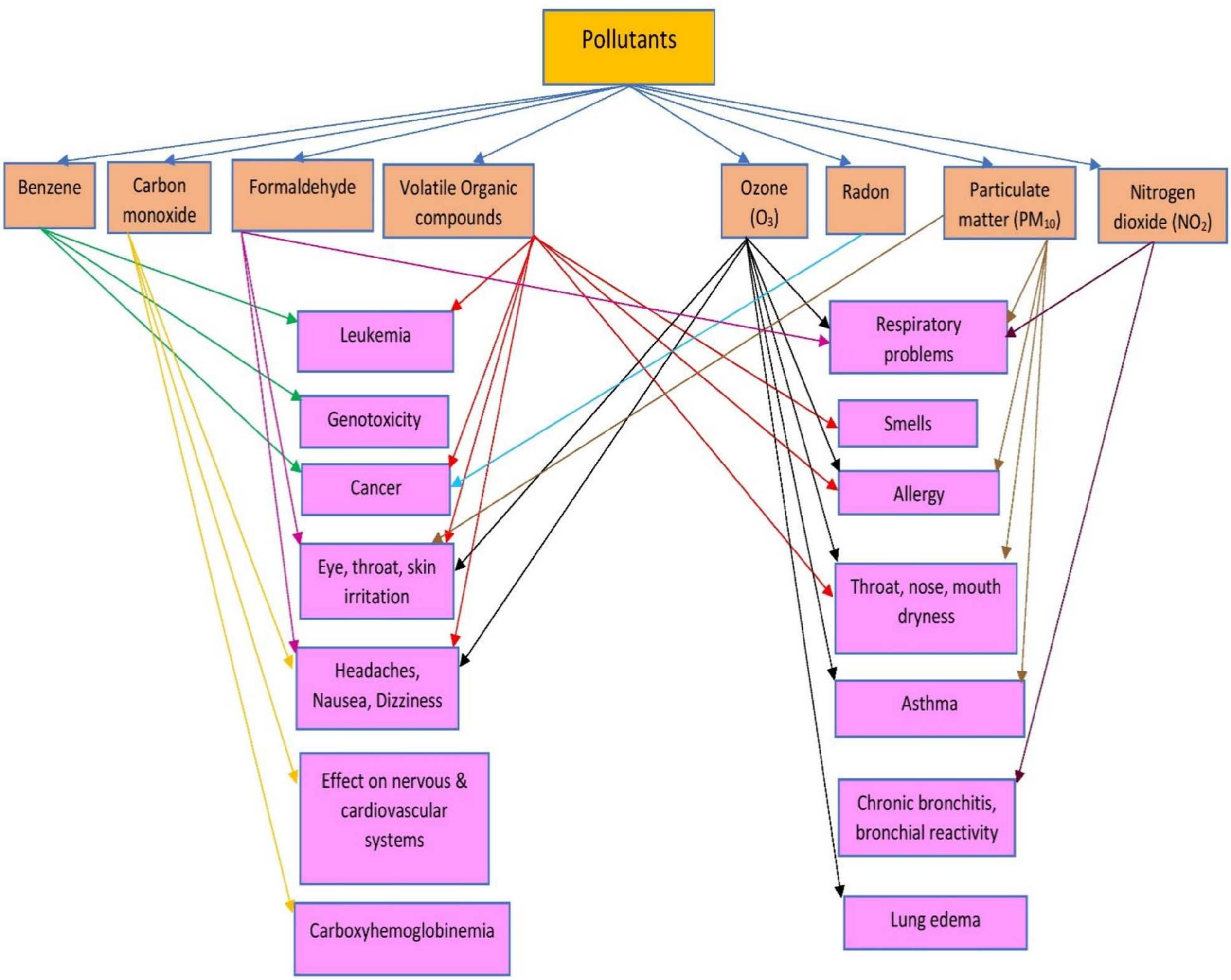

Fig. 4 Possible health effects of protuberant indoor pollutants.

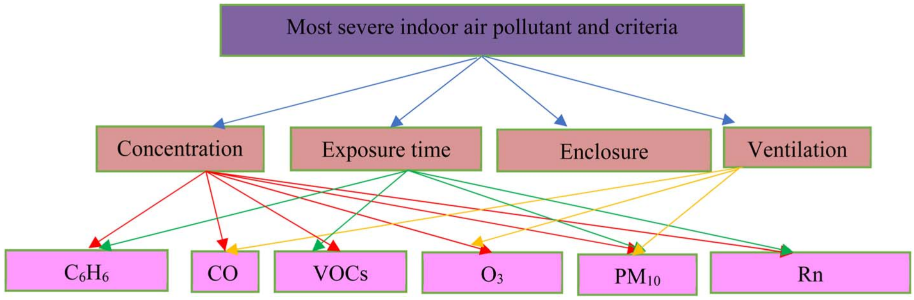

Fig. 5 Analytic hierarchy process to identify the most severe indoor air pollutant.

Table 5 Pairwise comparison using AHP analysis

Category	Priority	Rank	(+)	(−)
C_6H_6	46.2%	1	20.2%	20.2%
CO	26.2%	2	9.1%	9.1%
VOC	14.0%	3	5.1%	5.1%
O_3	7.3%	4	3.0%	3.0%
Rn	4.0%	5	1.6%	1.6%
PM_{10}	2.3%	6	1.3%	1.3%
Category	**Priority**	**Rank**	**(+)**	**(−)**
Pollutant concentration	59.9%	1	15.9%	15.9%
Exposure time	25.9%	2	4.7%	4.7%
Ventilation	9.8%	3	2.1%	2.1%
Dimension of the enclosure	4.4%	4	1.5%	1.5%

severe health impacts, such as respiratory diseases (asthma and silicosis) and heart-related diseases.[38,51] A pollutant's effect on human health depends on various factors such as concentration, duration of exposure, age, and gender. Some airborne chemical pollutants such as VOCs cause a range of ear, nose, and throat-related health effects, creating nausea and headaches. In the case of prolonged exposure to indoor air pollutants, dwellers may be affected severely or at least develop a higher degree of irritation due to these pollutants. This situation is referred to as "Sick Building Syndrome". A detailed correlation between various gaseous pollutants and their associated health impacts is portrayed in Fig. 4.[25,52–54]

Furthermore, there is an impeccable need to assess the exposure-based severity for each pollutant mentioned above and its associated health hazards. Based on the available data of various indoor air pollutants and attributed severity in terms of health

Table 6 Decision matrix using AHP analysis

	1	2	3	4	5	6
1	1	3.00	5.00	7.00	9.00	8.00
2	0.33	1	3.00	5.00	9.00	7.00
3	0.20	0.33	1	3.00	7.00	5.00
4	0.14	0.20	0.33	1	5.00	3.00
5	0.11	0.11	0.14	0.20	1	0.33
6	0.12	0.14	0.20	0.33	3.00	1

	1	2	3	4
1	1	3.00	9.00	7.00
2	0.33	1	7.00	3.00
3	0.11	0.14	1	0.33
4	0.14	0.33	3.00	1

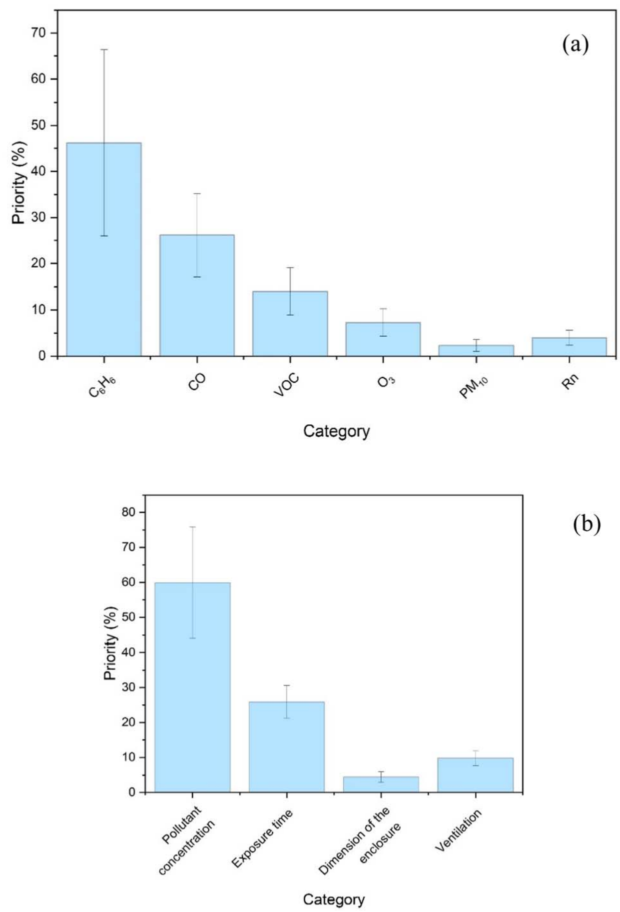

Fig. 6 Consolidated results for decision-making on (a) the pollution potential of key indoor air pollutants and (b) the factor governing their degree of severity.

Table 7 Simplified and interpreted representation of various global bylaws/regulations related to IAQ[58]

No.	Law(s)	Analysis	Source
1	Exposure guidelines for residential indoor air quality	• Provides information about the maximum allowable 8 hours and/or 1-hour average threshold concentration for $PM_{2.5}$, nitrogen dioxide, sulfur dioxide, radon (Rn), naphthalene, CO_2, CO, formaldehyde, O_3, and relative humidity • The standard does not furnish any information related to pollutants such as PM_{10}, trichloroethylene, tetrachloroethylene, PAHs, and benzene • Except for radon (*i.e.* 800 Bq m^{-3} @ 12 months avg.), the standard mainly focuses on short-term exposures, which is a significant drawback of the Canadian standard	59
2	Guidelines for good indoor air quality in office premises	• Provides information about the maximum allowable 8-hour threshold concentration for CO_2, CO, formaldehyde, O_3, relative humidity and PM_{10} • The standard does not provide information about pollutants such as benzene, $PM_{2.5}$, nitrogen dioxide, PAHs, sulfur dioxide, radon, tetrachloroethylene, or naphthalene • A local adaptation of the WHO standard, citing local atmospheric conditions. The highest allowable PM_{10} level of 150 μg m^{-3} in office spaces is a matter of concern. The value is three times higher than the value recommended by WHO (*i.e.* 50 μg m^{-3} @ 24 hours avg.)	60
3	Goals for maximum permissible levels of pollutants in indoor air	• Provides information about the maximum allowable average threshold concentration only for CO_2, CO, formaldehyde, O_3, PM_{10}, and sulfur dioxide • The standard does not furnish information about pollutants such as benzene, $PM_{2.5}$, nitrogen dioxide, PAHs, radon, tetrachloroethylene, naphthalene, relative humidity, and trichloroethylene • The prescribed values are either stringent or comparable to those recommended by the other bylaws	61
4	Indoor air quality-related standards in China	• Provides information about the maximum allowable 24-hour average threshold concentration for benzene, CO_2, CO, formaldehyde, nitrogen dioxide, O_3, sulfur dioxide, and PM_{10} • The standard does not furnish any information related to pollutants such as $PM_{2.5}$, PAHs, radon, tetrachloroethylene, naphthalene, relative humidity, and trichloroethylene • Contrary to the WHO statement of no safe exposure level for benzene, the Chinese standard offers the highest allowable 1-hour average exposure limit of 90 μg m^{-3}	62
5	NIOSH pocket guide to chemical hazards	• Provides information about the maximum allowable 8 hours or 15-minute average threshold concentration for CO_2, CO, formaldehyde, nitrogen dioxide, sulfur dioxide, and O_3 • The standard does not furnish any information related to pollutants such as benzene, $PM_{2.5}$, PM_{10}, relative humidity, PAHs, radon, tetrachloroethylene, and naphthalene • This standard fails to provide the maximum allowable concentration for prolonged exposure. Instead, it focuses on offering safe concentration for short-term exposure, though occupants spend most of their time indoors	63
6	Typical indoor air pollutants	• Provides information about the maximum allowable average threshold concentration only for $PM_{2.5}$, nitrogen dioxide, sulfur dioxide, CO_2, CO, formaldehyde, O_3, and PM_{10} • The standard does not provide information about pollutants such as benzene, naphthalene, PAHs, trichloroethylene, tetrachloroethylene, relative humidity, or radon • The highest allowable threshold concentration of 800 ppm for CO_2 is highly ambitious and incomparable with the other existing standards	64
7	Guidelines for indoor air quality: selected pollutants	• Benzene, formaldehyde, nitrogen dioxide, carbon monoxide, polycyclic aromatic hydrocarbons, and carbon dioxide have been enlisted as the most significant indoor air pollutants • Their threshold concentrations, maximum allowable exposure time, each pollutant's ill effects, *etc.*, are depicted profoundly • The standard does not furnish information about pollutants such as O_3, relative humidity, sulfur dioxide and radon • The WHO standard identified benzene as one of the most toxic indoor gaseous pollutants and recommends a zero-exposure limit	25

Table 7 (*Contd.*)

No.	Law(s)	Analysis	Source
8	Workplace exposure limits	• Provides information about the maximum allowable average threshold concentration for only CO_2, CO, formaldehyde, nitrogen dioxide, and O_3 • The standard does not provide information about pollutants such as benzene, naphthalene, PAHs, trichloroethylene, $PM_{2.5}$, sulfur dioxide, radon, tetrachloroethylene, relative humidity, and PM_{10} • The standard offers a confusing portrayal of the highest permissible exposure limit. The maximum allowable 8-hour CO concentration of 11.6 ppm is 3.0 ppm higher than the value recommended by the WHO. In contrast, the 15-minute average exposure standard of 15 000 ppm for CO_2 is 85 000 ppm, which is less than the highest value permitted by the WHO	65
9	Interim Guidelines for indoor air pollution in India	Along with the interim guidelines for IAQ in India, the document has provided recommendations for IAQ-related studies and has also provided road maps for various stakeholders, including the government/monitoring agency/health audit level, the industry level, the research/academia level and the NGO/NPOs/Civil society level	66

impacts, an analytical hierarchy process (AHP) evaluation has been performed to determine the priority of concern[55,56] (Fig. 5).

Fig. 5 depicts the correlation between the goal, general criteria, and alternatives. Furthermore, to identify the most severe indoor air pollutants and associated criteria, two individual priority matrices have been formulated (Table 5). Table 6 depicts the resulting weights formulated based on the principal Eigenvector of the decision matrix. It reveals benzene as the most harmful indoor air pollutant, and the concentration of the pollutant has the most significant impact on the individual (Fig. 6). Priority values were ascertained against the consistency

Table 8 IAQ management plan flowchart[72]

Process	Working principle	Benefits
Ventilation	Effectively designed cross ventilation maximizes the inflow of outdoor air	Crossflow of air minimizes the concentration of indoor air pollutants
Control at source	Eliminate or minimize the emission from the indoor point sources	Generation of indoor pollutants from sources such as air conditioners, curtains and rags can be diminished by effective and periodical cleaning
Filtration	Decomposition of organic compounds using ultraviolet germicidal irradiation or similar methods	Disinfection of organic compounds ensures zero smell and contamination-free air
Humidity control	Maintain the indoor humidity of the establishment by ensuring effective cross ventilation or using a dehumidifier	Lower humidity results in the restriction of malodor and allergic substances indoors
Indoor plantation	Several plants such as English ivy, dragon trees, bamboo palms, peace lily and spider plants help minimize IAP	Plants typically convert carbon dioxide to oxygen and absorb synthetic compounds such as benzene and formaldehyde, thereby minimizing the risk of respiratory/lung diseases
Dust-mite proof covers	The covers prevent the development of dust mites in bedding	Minimizes the risk of allergic infection and asthma
Zero tobacco smoking	Maintain zero smoking habits to ensure zero discharge of highly toxic gases such as carbon monoxide and hydrogen cyanide	No smoking habit can prevent the spread and accumulation of certain hazardous gases in indoor air and curtail the risk of passive smoking
Regular and timely disposal of garbage	Segregate wet and dry waste, store it in covered containers, and ensure timely disposal	The primary benefits include suppression of malodor and minimization of harmful insect infestation
Salt lamps	It emits negative ions while burning, thereby neutralizing the harmful cations in the indoor air	Anions released during the burning neutralize positively charged pollutants and allergy-causing contaminants
Eco-friendly cleaning products	Use natural cleaning agents such as neem, lemon or vinegar to ensure zero toxins are left behind	Lowers indoor dust and pollutants that cause allergies

ratio and principal Eigenvalue of 7.5% & 6.468, and 3.6% & 4.099, respectively, for pollutants and criteria.

7. Existing global bylaws/standards and infrastructure assessment related to indoor air quality

The compromise of IAQ has recently gained the limelight and is considered a significant factor that may impact human well-being. IAP is the elevated concentration of toxic elements inside a building that can cause direct or indirect illness to the occupants.[57] The understanding and highest allowable limits of various gaseous pollutants in indoor air vary globally. A comprehensive analysis of various regulations, policies, and standards practiced globally is depicted in Table 7.

7.1 Building assessment system and sustainability rating authorities

Several environmental assessments and rating schemes were introduced for new and renovated infrastructure because of the growing concern over IAQ. Post-thorough assessment, certification is issued against mandatory IAQ compliance, and the details of crucial globally accepted bodies are furnished below.

7.1.1 BREEAM (building research establishment's environmental assessment method). It is an evaluation method for rating sustainable buildings following the protocol developed in-house by the building research establishments. The assessment criteria are based on the design proficiency of the structure to curb the entry of outdoor pollutants and achieve efficient cross ventilation. The rating is also influenced by the measures adopted to eliminate pollutants such as VOCs and formaldehyde from indoor air.[67]

7.1.2 WELL (WELL Building Standard®). It was introduced in 2015 to enhance the air quality of residential and commercial establishments. Overall, there are 29 areas covered in this standard, inclusive of parameters such as proper ventilation, air purification and pollutant reduction.[67]

7.1.3 LEED (leadership in energy and environmental design). The US Green Building Council has launched this certification program. The criteria for arriving at a particular building rating using the system include architectural design, construction materials and the quality of operation and maintenance.[67–70]

7.2 Control strategies for mitigating air pollutants in the indoor environment

Strategies for reducing air pollutants and mitigating them in the indoor environment depend on the type of pollutant, origin,

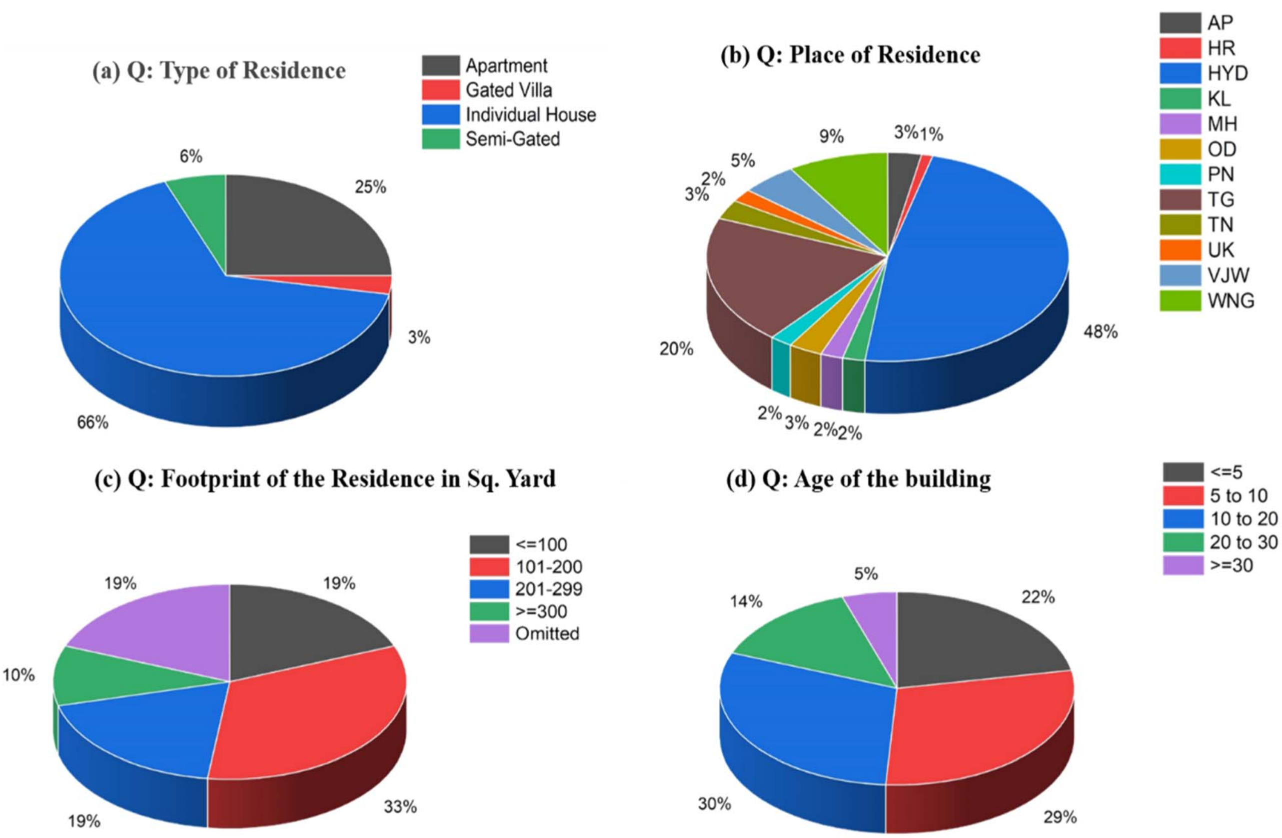

Fig. 7 Opinions of Indian commuters on various factors influencing indoor air quality due to fugitive outdoor dust originating from construction activities in the vicinity of residences. *AP: Andhra Pradesh, HR: Haryana, Hyd: Hyderabad, KL: Kerala, MH: Maharashtra, OD: Odisha, PN: Punjab, TG: Telangana, TN: Tamil Nadu, UK: Uttarakhand, VJW: Vijayawada, and WNG: Warangal.

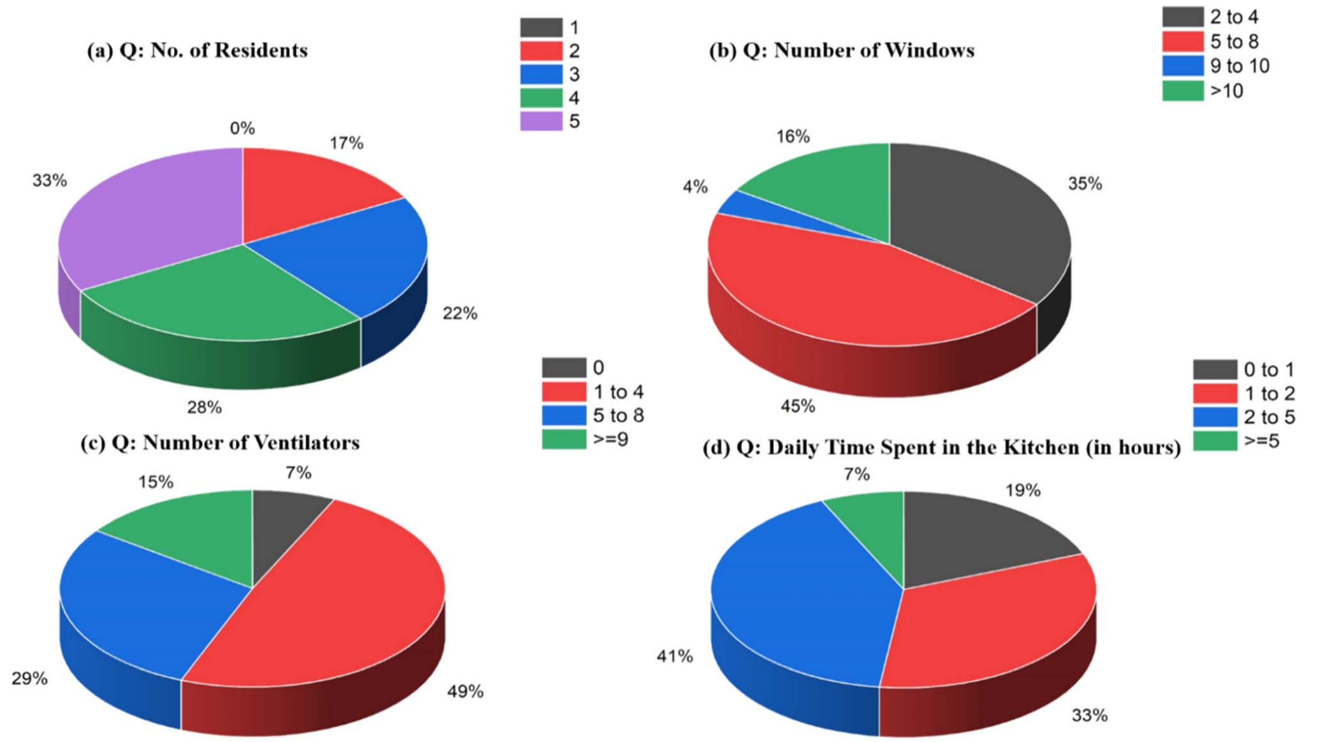

Fig. 8 Distribution patterns of key parameters affecting indoor air quality.

and activity source. Some simple techniques, such as providing complete ventilation, will lead to the dilution and removal of the polluted indoor air, but these are not complete solutions, and they are low-cost simple techniques.[4,71] A comprehensive IAQ management plan is outlined in Table 8.

8. Capacity building and human exposure to pollutant sources in the indoor environment

8.1 Commuter opinion through online survey

A commuter opinion survey was carried out online by asking various questions related to day-to-day activities and the type of residence to understand pollutant sources in the indoor environment. The responses collected from various residents nationwide help us understand some aspects of indoor air quality. However, a comprehensive overview of the severity of IAQ may not be obtained. Hence, an index to interpret such data sets for more straightforward understanding has been formulated (Fig. 7–9).

9. Development of an IAQ index for households

An indoor air quality index has been developed to make the residents aware of the ill effects of poor indoor air quality. Indoor air quality depends upon the construction practices implemented and the nature of the building's occupancy. The factors considered for the IAQ index include the type of flooring, type of residential locality, number of windows/ventilators, age of the building, duration indoors, problems with construction in the neighbouring areas, and residents' occupancy.

The IAQ index developed may have a maximum value of 100 and a minimum value of 22.

The factors that are linked to the construction practices and their corresponding indexing values are explained below.

9.1 Occupancy

A larger number of occupants in a relatively smaller area will eventually increase indoor air pollution problems due to the excessive release of CO_2 and enhanced transmission of microbes from person to person. Hence, more weightage has been given to the indoor space with maximum occupancy and minimum floor area. The remaining areas and occupancies were given scores proportionally. The scores allotted are presented in Fig. 10.

9.2 Type of flooring material

It has been observed that asbestos and wood flooring may have more impacts when compared to granite and marble flooring due to properties such as reactivity and degradability. Hence, a score of 2 was given for granite and marble, and scores of 8 and 10 were allotted to wood and asbestos, respectively. The scores allotted are depicted in Table 9.

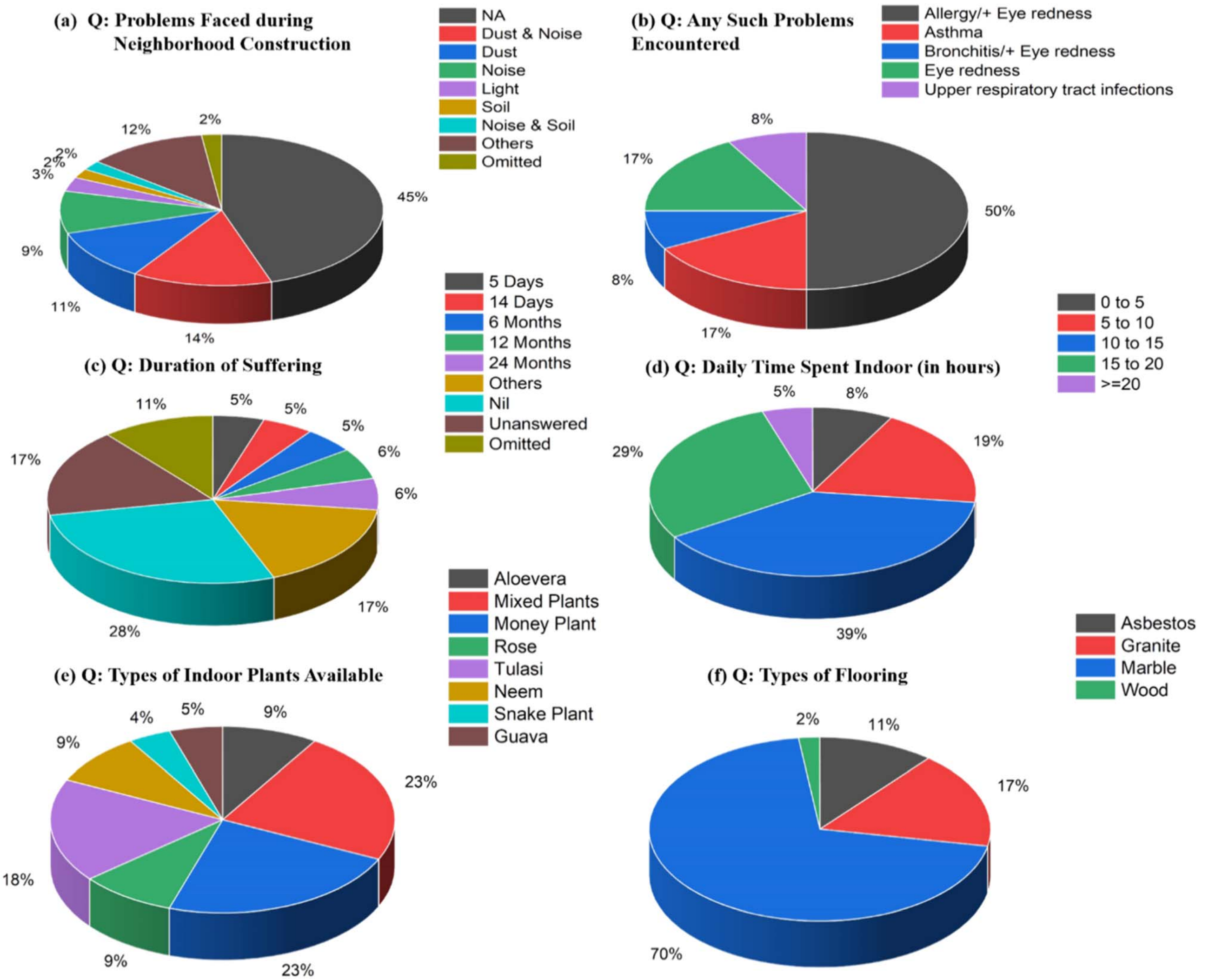

Fig. 9 Comprehensive analysis of environmental and health factors affecting indoor air quality.

9.3 Type of residence

A house located on the ground floor may have more indoor transmission of microbes from the surrounding open space, resulting in the exposure to more indoor pollutants from outside. In contrast, buildings such as apartments have a lesser effect from ground-level sources of indoor air pollutants, and hence, higher scores were allotted to independent/individual houses, and lesser scores were allotted to the indoor spaces in multi-storied apartments. The scores for the other communities were allotted proportionally. The scores allotted are given in Table 9.

9.4 Area of residence

It has been observed that the floor area may significantly impact the dispersion of pollutants indoors and from indoors to outdoors and *vice versa*. Hence, the lower the floor area, the more the impact of indoor air pollution will be. Subsequently, a higher score of 10 has been allotted for an area <100 sqm, and a score of 2 is allotted for an area >300 sqm. The areas in between were allotted scores proportionally. The scores allotted are given in Table 9.

9.5 Windows

According to the WHO, more than 90% of the Indian air is polluted.[5] Hence, more windows often result in the entrainment of outdoor pollutants indoors. Hence, more windows in a house were given higher scores than fewer windows. The scores allotted are given in Table 9.

9.6 Age of the house

It has been observed that old houses need more maintenance, resulting in frequent retrofitting and the introduction of additives such as paints, *etc.*, to the walls. This leads to the addition of more artificial materials and subsequent release of gaseous

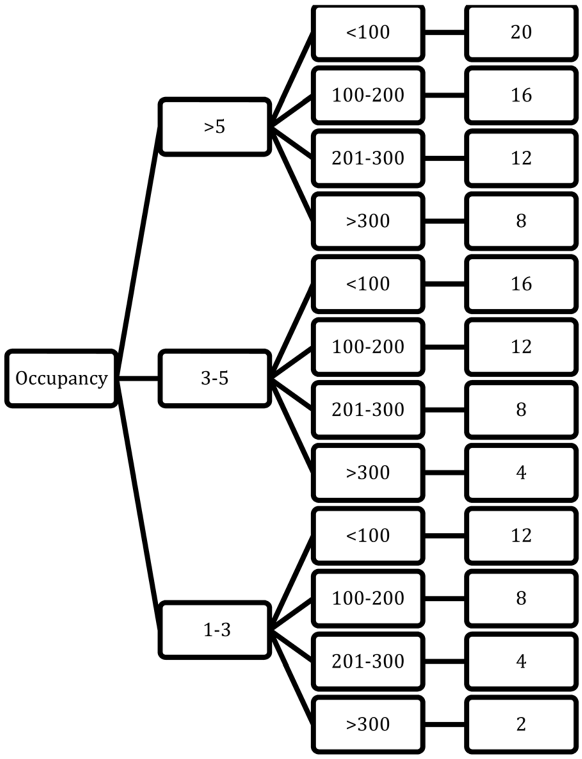

Fig. 10 IAQ scores for combined occupancy and the area of the house.

vapours into the indoor environments. Hence, buildings with a higher age (>30 years) were allotted a score of more than 10, and those with an age of less than 5 years were allotted a score of 2 units. The scores were proportionally allocated based on the building age for the intermediate ages of the buildings. The scores allotted are presented in Table 9.

9.7 Hours spent indoors

It has been observed that indoor exposure to pollutants is proportional to the residence time indoors, and hence, the scores were allotted proportional to the number of hours an occupant stays indoors. The scores allotted are presented in Table 9.

9.8 Impact of neighborhood construction activities

Various cases may be observed during construction activity in the neighborhood. First, the presence of noise and dust in the residential area indicates that the construction activity is occurring close by, and the pollutant concentration/migration of the pollutants towards the residence is extremely high; hence, the maximum score is allotted to this case. Furthermore, the presence of strong noise indicates the presence of a fuel-based machine that releases air pollutants. Hence, indoor pollutant concentrations may rise subsequently. Proportionally, the scores were allotted to the other scenarios. The scores allotted are given in Table 9.

Table 9 IAQ scores for various factors (a) materials, (b) type of house, (c) area, (d) windows, (e) age of house (f) number of hours spent indoors and (g) impact of neighborhood construction activities

a

Material	Score
Asbestos	10
Wood	8
Marble	2
Granite	2

b

Type of house	Score
Individual	10
Apartment	6
Semi-gated	4
Gated	2

c

Area (m^2)	Score
Less than 100	10
100–200	8
201–300	6
>300	2

d

Windows	Score
>10	10
9–10	8
7–8	6
5–6	4
2–4	2

e

Age of house	Score
30 years or more	10
20–30	8
10–20	6
5–10	4
Up to 5	2

f

Number of hours	Score
>20	10
16–20	8
10–15	6
5–10	4
Less than 5	2

g

Impact	Score
Noise and soil	20
Dust and noise	16
Dust	8
Noise	4
No impact	2

10. Conclusion

The study solicits a uniform focus to assess the primary factors contributing to IAP, the influence of geographic and seasonal variances, health hazards, and possible precautionary measures, especially those from construction and demolition activities. The identified primary factors contributing to the deterioration of IAQ are flawed structural designs, the size of the structures, and poorly ventilated indoor spaces. Moreover, it has been observed that pollutants such as benzene, CO, VOCs, O_3, Rn, and PM are the critical indoor air pollutants released from these activities that pose the highest health risks, including nausea, irritation, carboxy hemoglobinemia, leukaemia, lung cancer, and other cardiovascular diseases.

The study also correlated the pollutant's health risk with seasonal variation, exposure time, space, and ventilation. The analytical hierarchy process concluded that benzene is the most fatal indoor air pollutant. The study has also ascertained and enlisted various control measures, including source administration and elimination, humidity maintenance, timely waste removal and cleaning, and incorporation of air filters. Additionally, the slightest exposure to the pollutant had the highest potential to cause a health hazard, as ascertained based on the criteria-driven simulation model. Considering the globally established various IAQ bylaws and the associated health impacts, efforts were made to quantify the impacts of indoor air quality by developing an index for indoor air quality based on the building- and occupancy-related factors, which can enable users to estimate the degree of indoor air pollution. In the future, studies may be conducted by further modifying the methodology and apportioning the activity/source of the pollutant and its contribution to health risk to mitigate the same. Studies may also be conducted on identifying the various combinations of approaches that may be the most sustainable for the given indoor space. As air exchange is always associated with energy costs, combining the same with temporary pathway reduction approaches and implementing source control approaches at the generation of the construction dust may be examined.

Conflicts of interest

There are no conflicts to declare.

Data availability

The required data that support the findings of this study have been included in the article.

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