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REVIEW PAPER

A review of indoor air quality in heritage buildings and confined spaces: Implications for occupational safety and health

Mohamad Romizan Osman[1,2], Azman Azid[1,*], Mohd Saiful Samsudin[3], Kamaruzzaman Yunus[2], Nurul Latiffah Abd Rani[4]

[1]*School of Aquatic Science and Environment, Faculty of Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Besut Campus, 22200 Besut, Terengganu, Malaysia*
[2]*Kulliyyah of Science, International Islamic University Malaysia, 25300 Kuantan, Pahang, Malaysia*
[3]*Environmental Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia*
[4]*Faculty of Applied Sciences, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

[*]Email: *azmanazid@unisza.edu.my*

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Abstract. The quality of indoor air environments in heritage buildings and confined spaces, such as tunnels, is a critical concern for occupational safety and health (OSH). These environments often contain airborne contaminants, including particulate matter (PM2.5 and PM10), heavy metals, silica, asbestos, bacteria, fungi, and microplastics, which pose serious health risks to workers and visitors. The deterioration of building materials, inadequate ventilation, and resuspension of settled dust contribute to poor indoor air quality (IAQ), leading to long-term exposure hazards. Heritage buildings, constructed with materials such as lead-based paint, asbestos insulation, and decaying wood, release hazardous particles into the indoor environment over time. Meanwhile, confined spaces like tunnels experience high concentrations of silica dust, toxic gases, and microbial proliferation, exacerbating occupational exposure risks. Recognizing the importance of IAQ to occupational health, regulatory bodies such as DOSH Malaysia have introduced the Industry Code of Practice on Indoor Air Quality (ICOP 2010, revised 2024) to establish workplace IAQ standards. The ICOP 2010 guidelines emphasize the importance of monitoring airborne pollutants, maintaining adequate ventilation, and implementing mitigation measures to minimize health risks indoors and enclosed workspaces (DOSH, 2024). This review analyzes the sources, distribution, and health effects of IAQ degradation in historical and enclosed environments and evaluates existing regulatory frameworks, including ICOP 2010, in addressing these concerns. It compares IAQ standards with regulatory exposure limits set by organizations such as ICOP 2010, the Occupational Safety and Health Administration (OSHA), and the World Health Organization (WHO). The health effects of prolonged exposure to PM-bound heavy metals, asbestos fibres, and microbial contaminants are discussed, with particular emphasis on respiratory diseases, lung cancer, and neurological impairments. The paper also evaluates IAQ management strategies, including real-time air quality monitoring, ventilation improvements, filtration technologies, and personal protective equipment (PPE). It highlights the effectiveness of mitigation methods in reducing occupational exposure and proposes future research directions to develop sustainable IAQ solutions in heritage conservation and underground infrastructure projects. Aligning IAQ control measures with ICOP 2010 guidelines ensures that workplaces adhere to best practices for safeguarding worker health, preserving historical structures, and maintaining regulatory compliance.

Keywords: heritage buildings, confined spaces, indoor air quality, heavy metals, particulate matter, microplastics, occupational health.

Classification numbers: 3.2.1, 3.4.5, 3.6.2.

1. INTRODUCTION

The quality of indoor air environments is a crucial determinant of occupational health, particularly in heritage buildings and confined spaces such as tunnels, underground workplaces, and restoration sites. Poor IAQ has been linked to respiratory diseases, neurological disorders, and chronic exposure-related illnesses, raising significant health concerns for workers and visitors. These environments often suffer from limited ventilation and high pollutant accumulation, making air quality management more challenging compared to open workspaces. The Industry Code of Practice on Indoor Air Quality (ICOP 2010) by DOSH Malaysia provides workplace IAQ guidelines, establishing exposure limits for PM2.5 and PM10, volatile organic compounds (VOCs), carbon monoxide (CO), microbial contaminants, and heavy metals. However, despite these regulations, studies indicate that many enclosed workplaces exceed safe IAQ thresholds, increasing occupational health risks and highlighting the need for stricter air quality monitoring and control [1].

One of the most concerning IAQ pollutants in heritage buildings and confined spaces is particulate matter (PM), which serves as a carrier for toxic substances such as heavy metals, silica, asbestos, and microbial contaminants. PM2.5 consists of fine inhalable particles smaller than 2.5 micrometers, while PM10 includes coarser particles up to 10 micrometers in size [2]. Research indicates that PM concentrations in historical buildings and underground tunnels often exceed outdoor air levels, primarily due to dust resuspension, poor ventilation, and material degradation. A study on railway tunnels and industrial underground sites found that PM2.5 levels exceeded WHO and OSHA exposure limits, increasing risks of respiratory diseases, cardiovascular conditions, and toxic metal accumulation in workers [3]. Given the ability of PM to serve as carriers of hazardous substances, exposure to airborne particles is not only a respiratory issue but also a major source of heavy metal contamination in enclosed environments. In addition to PM pollution, heavy metals such as aluminum (Al), lead (Pb), cadmium (Cd), and arsenic (As) are prevalent in indoor dust, originating from degrading paint, corroding metal fixtures, and industrial emissions [4].

Long-term exposure to aluminum has been associated with neurotoxicity and cognitive impairment, with studies linking aluminum accumulation in the brain to neurodegenerative diseases such as Alzheimer’s and Parkinson’s [5, 6]. Similarly, exposure to lead from lead-based paints and deteriorating building materials increases the risk of neurological dysfunction, cardiovascular diseases, and immune suppression [7]. Studies on underground workplaces and industrial tunnels have found that cadmium and arsenic contamination often exceeds occupational exposure limits, further exacerbating risks of lung and kidney diseases [2]. Despite ICOP 2010 requiring periodic IAQ assessments, many heritage sites and confined spaces lack enforcement, leading to prolonged and unregulated exposure to these toxic airborne metals.

Beyond heavy metals, silica dust and asbestos exposure remain significant hazards in historic building restorations and underground workspaces. Crystalline silica, released from rock cutting, drilling, and concrete processing, is a well-documented cause of silicosis, lung cancer, and chronic obstructive pulmonary disease (COPD) [8]. Tunnel workers and restoration specialists frequently experience silica exposure due to poor ventilation and long working duration, increasing their risk of developing severe respiratory conditions. Similarly, asbestos contamination in old insulation and roofing materials continues to pose hazards to IAQ, with prolonged inhalation leading to asbestosis, lung cancer, and mesothelioma [9]. Although ICOP 2010 mandates asbestos control measures such as encapsulation and the use of personal protective equipment (PPE), many heritage restoration projects lack proper asbestos risk management, leaving workers vulnerable to airborne fibre inhalation [1]. Apart from chemical and particulate pollutants, microbial contamination poses another major threat to IAQ in enclosed spaces. Studies conducted in historical and enclosed heritage environments have detected elevated levels of fungal spores and bacterial communities, particularly in humid spaces with limited air circulation [10]. Prolonged exposure to airborne microorganisms has been linked to respiratory infections, allergic reactions, and autoimmune disorders, increasing the burden of occupational illnesses.

The ICOP 2010 standard establishes bacterial count limits at 500 CFU/m^3 and fungal counts at 1000 CFU/m^3, yet research shows that many heritage buildings exceed these values due to mold growth, water leaks, and ventilation issues [1]. In some cases, Legionnaires' disease outbreaks, caused by *Legionella pneumophila*, have been traced back to stagnant water and poorly maintained air-conditioning systems in underground workplaces, further underscoring the health risks of poor IAQ [11–13]. An emerging area of concern in IAQ research is microplastic contamination, which originates from synthetic fibres, paint coatings, and degraded construction materials. Studies indicate that airborne microplastics are present in indoor environments at levels comparable to outdoor air in polluted urban areas, raising concerns about chronic inflammation, immune dysfunction, and respiratory complications [14, 15].

This study aims to examine IAQ degradation in heritage buildings and confined spaces, focusing on the sources and health impacts of PM, heavy metals, silica, asbestos, microbial contaminants, and microplastics. In addition, the study evaluates the effectiveness of IAQ improvement strategies, including ventilation enhancements, real-time air quality monitoring systems, and the implementation of PPE, while assessing compliance with the ICOP 2010 and relevant international standards. By improving the understanding of IAQ risks in enclosed workplaces and heritage sites, this review provides evidence-based recommendations for strengthening occupational safety, enhancing IAQ management practices, and reducing potential health risks among workers and visitors.

2. APPROACH OF LITERATURE REVIEW

This review study assesses the indoor air quality (IAQ) in heritage buildings and confined spaces, focusing on key pollutants such as particulate matter (PM2.5, PM10), heavy metals, silica dust, asbestos fibres, microbial contaminants, microplastics, volatile organic compounds (VOCs), carbon dioxide (CO_2), and carbon monoxide (CO). The IAQ monitoring is essential in environments like heritage sites and underground tunnels, where pollutants from deteriorating materials and confined space conditions pose serious implications for health. Studies have employed various monitoring devices and analytical techniques, and this review synthesizes the methods used to assess these pollutants and evaluate their impact on human health.

Particulate matter (PM), particularly, the PM2.5 and PM10, remains a major concern in IAQ studies due to its significant health consequences. According to the World Health Organization (WHO), exposure to the PM2.5 is associated with millions of premature deaths annually due to cardiovascular disease, chronic respiratory illness, stroke, and lung cancer [16]. Its fine particle size enables deep penetration into the pulmonary system, triggering systemic inflammation and oxidative stress. These risks make PM2.5 a central focus in indoor air quality assessments, especially in enclosed and poorly ventilated environments such as heritage buildings and underground spaces. Many studies have used real-time aerosol monitors such as the DustTrak™ DRX Aerosol Monitor (Model 8533, TSI Inc.) to measure airborne particulate concentrations. These instruments operate using laser photometry, providing real-time data on particle concentration and size distribution. Additionally, high-volume air samplers like the TE-PM10-2.5-300 from Tisch Environmental have been employed to collect PM-bound heavy metals on Teflon filters, which are subsequently analyzed for toxic metal content using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) [17]. This method allows for direct measurement of pollutants, thereby allowing accurate and reliable data collection. Heavy metals such as aluminum (Al), lead (Pb), cadmium (Cd), and arsenic (As) are of particular concern, as they are often bound to the PM and can accumulate in indoor air. Studies have focused on the detection of these metals using ICP-MS, which offers high sensitivity for detecting trace metals in indoor environments [4, 17].

Among emerging pollutants, airborne microplastics are gaining increasing attention due to the absence of regulatory thresholds and growing evidence of health impacts. Microplastics have also emerged as a growing concern in IAQ research, with Raman Spectroscopy (Thermo Fisher DXR3) being widely used to identify and quantify plastic fibres in air samples [14, 18]. Although the ICOP 2010 does not currently regulate microplastic exposure, the increasing presence of microplastics in enclosed spaces has raised significant health concerns. The term “high microplastic levels” in indoor environments remains undefined in regulatory standards. For silica dust exposure, personal air samplers like the Casella Apex2 are commonly used to collect respirable crystalline silica (RCS). These samplers include cyclone separators that allow for accurate measurement of fine particles in the inhalable size range, and the collected filters are then analyzed via Fourier Transform Infrared Spectroscopy (FTIR), a method that detects crystalline silica with high specificity [8, 19].

Similarly, asbestos exposure in heritage buildings is measured using high-volume air samplers such as the SKC AirCheck XR5000 pump. After the air is sampled, Phase Contrast Microscopy (PCM) and Transmission Electron Microscopy (TEM) are used to identify asbestos fibres, following the NIOSH 7400 and 7402 methods [20]. The asbestos fibres in indoor air can cause serious respiratory diseases, making their detection critical in renovation projects. Recent advancements, such as deep learning-based semantic segmentation models, have automated the asbestos analysis process, reducing turnaround times from hours to minutes while improving the efficiency and accuracy of asbestos fibre detection using SEM images integrated with EDS [21]. While Transmission Electron Microscopy (TEM) remains the gold standard for accuracy, combining it or SEM with automation enhances efficiency for large-scale studies [22].

Moreover, particulate and chemical contaminants, along with microbial contamination, are significant factors in IAQ. Microbial air quality has been studied using BioStage® Single-stage Impactor Samplers, which collect airborne bacterial and fungal spores on agar plates. The collected samples are cultured and analyzed to determine microbial levels in the air, with results typically reported in Colony Forming Units per cubic meter (CFU/m^3). These results are compared to the ICOP 2010 standards for microbial contamination, which set acceptable limits of 500 CFU/m³ for bacteria and 1000 CFU/m³ for fungi [23]. High levels of microbial contamination are often found in moist environments, which are prevalent in historical buildings with inadequate ventilation [24].

For the analysis of VOCs, CO_2, and CO, a range of real-time air quality monitors have been employed, including the MultiRAE Pro (RAE Systems) and the Q-Trak™ IAQ Monitor (TSI Inc.). These devices are equipped with electrochemical and infrared sensors, allowing for the detection of gases such as formaldehyde, benzene, carbon dioxide, and carbon monoxide [25]. The VOCs, typically emitted from paints, adhesives, and furniture, can have significant health impacts, including respiratory irritation, neurological disorders, and cancer, while carbon dioxide and carbon monoxide pose immediate risks due to poor ventilation in confined spaces [26].

To ensure a comprehensive review, studies were selected based on their relevance to IAQ in enclosed environments. Sampling methodologies were compared across different studies to assess the effectiveness of IAQ monitoring techniques and to determine whether regulatory limits were exceeded. Data from previous field studies were analyzed using SPSS Statistics (Version 28) to examine correlations between pollutants and exposure risks. Meanwhile, the XLSTAT 2024.3 (Addinsoft, Paris, France) is a statistical software package that integrates with Microsoft Excel and provides over 250 statistical analysis features to support data visualization, multivariate analysis, and interpretation of environmental datasets [27].

The findings were then compared against ICOP 2010, OSHA, and WHO guidelines to evaluate compliance levels and regulatory enforcement gaps. To address the regulatory context of IAQ management, the guidelines issued by key bodies are compared. Indoor air quality (IAQ) standards vary between regulatory agencies, with each emphasizing different health protection thresholds and occupational limits. Malaysia's ICOP 2010 (revised 2024) provides specific microbial, gas, and particulate limits for workplaces, whereas the WHO sets broader public health-oriented guidelines. The OSHA, on the other hand, enforces legally binding permissible exposure limits (PELs) for occupational settings in the United States. Table 1 summarizes the key differences in selected IAQ parameters, highlighting gaps and alignment opportunities for better policy integration.

Table 1. Comparative summary of selected IAQ parameters in ICOP 2010, WHO, and OSHA guidelines.

Parameter	ICOP2010 (Malaysia)	WHO guidelines	OSHA (USA)
PM2.5 (24h avg)	35 µg/m³	15 µg/m³	Not specifically regulated
CO_2	1000 ppm (comfort level)	1000 ppm	Not regulated
CO (8h avg)	10 ppm	9 ppm	50 ppm (PEL)
Bacteria (CFU/m³)	500	Not specified	Not specified
Fungi (CFU/m³)	1000	Not specified	Not specified
VOCs (total)	3 ppm	0.3 – 0.5 ppm (indicative)	Not regulated
Asbestos	Zero tolerance	Zero exposure	0.1 f/cc (8h TWA)
Formaldehyde	0.1 ppm	0.08 ppm	0.75 ppm (8h TWA)

This comparison indicates that the ICOP 2010 provides clear limits for microbial and gaseous pollutants within Malaysian workplaces. In contrast, the WHO guidelines generally adopt lower thresholds with a greater emphasis on protecting public health. The OSHA regulations, on the other hand, are designed for industrial enforcement and often permit higher exposure levels.

These differences suggest the importance of contextualising IAQ standards based on the type of indoor environment, particularly in complex settings such as heritage buildings and confined spaces.

Compared to modern buildings, heritage buildings often present distinct IAQ challenges due to their age, structural limitations, and construction materials. These buildings typically lack mechanical ventilation systems, relying instead on natural air flow, which may be insufficient in enclosed or windowless areas such as underground tunnels or sealed galleries. Furthermore, older materials such as lead-based paints, wood preservatives, and asbestos insulation may degrade over time and contribute to airborne pollutant levels. In contrast, modern buildings generally incorporate HVAC systems with filtration capabilities and adhere to updated building codes that restrict the use of hazardous materials. As a result, occupants in heritage settings may be at a higher risk of exposure to pollutants like mold, particulate matter, and volatile organic compounds released from decaying materials. These differences highlight the need for customized the IAQ assessment and control strategies tailored to the architectural and historical constraints of heritage buildings.

To complement the regulatory discussion, Table 2 summarizes the sampling approaches and analytical instruments used across IAQ studies. These IAQ analysis methods provide insights into pollutant measurement techniques, instrumentation, and regulatory references used in IAQ research. Different studies have employed various types of monitoring instruments, such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Fourier Transform Infrared Spectroscopy (FTIR), and Transmission Electron Microscopy (TEM), each offering distinct sensitivity, specificity, and detection limits. These differences influence pollutant quantification accuracy and affect the comparability of IAQ data across different studies. Therefore, understanding the capabilities and limitations of each instrument is critical for interpreting the variability in IAQ findings.

To support the analysis, this review incorporates descriptive and comparative evaluations of findings from selected IAQ studies. The SPSS Statistics (Version 28) is used to tabulate and visualize descriptive parameters such as mean concentrations, standard deviations, and pollutant frequency across different study sites. Meanwhile, the XLSTAT 2024 is applied for exploratory multivariate analysis, including principal component analysis (PCA) and correlation matrices, to identify pollutant interrelationships and common sources. Although raw datasets from previous studies were not always accessible, this review reorganizes published results into structured tables to enable consistent cross-comparison of IAQ parameters, exposure levels, and compliance with regulatory standards.

Table 2. IAQ pollutants, sampling methods, and devices.

Pollutants	Sampling method	Device/Instrument used	Refs
Heavy metals (Al, Pb, Cd, As)	High-volume air sampling	PerkinElmer NexION 2000 ICP-MS	[4, 17]
Silica dust (RCS)	Personal air sampling	Casella Apex2 Personal Sampler, FTIR	[8, 19]
Microplastics	Glass fibre filter sampling	Thermo Fisher DXR3 Raman Spectrometer	[14, 18]
Asbestos fibres	High-volume air sampling	SKC AirCheck XR5000 Pump, PCM & TEM microscopy	[20–22]
Microbial contaminants	Bioaerosol sampling & culture analysis	BioStage® Impactor Sampler	[23, 24]

VOCs, CO_2, CO	Real-time gas detection	MultiRAE Pro, Q-Trak™ IAQ Monitor	[25, 28]
PM2.5, PM10	Real-time air monitoring	DustTrak™ DRX Aerosol Monitor (TSI Inc.)	[29]

3. SYNTHESIS OF LITERATURE FINDINGS

The quality of indoor air environments in heritage buildings and confined spaces presents significant occupational safety and health challenges, particularly due to the accumulation of airborne pollutants and limited ventilation. Numerous studies have identified particulate matter (PM), volatile organic compounds (VOCs), heavy metals, silica dust, asbestos fibres, microbial contaminants, and airborne microplastics as key pollutants that contribute to a variety of health issues [28, 30]. The presence of these contaminants has been linked to respiratory diseases, cardiovascular conditions, and cancer, with statistical data confirming substantial morbidity and mortality rates among exposed individuals [16]. To further illustrate the sources and health risks associated with indoor air pollutants in confined spaces, Table 3 provides a comprehensive summary. It highlights the primary pollutants, their sources, and the associated health effects.

Table 3. Summary of indoor air pollutants, sources, and health risk.

Pollutant	Sources	Health risks	References
Silica	Construction activities, mining, restoration work	Silicosis, chronic obstructive pulmonary disease (COPD), lung cancer	[8]
Asbestos	Old building materials (insulation, pipes, roofing)	Asbestosis, mesothelioma, lung cancer	[9, 31, 32]
Microplastics	Synthetic textiles, plastic degradation, indoor dust accumulation	Respiratory inflammation, potential toxic chemical exposure, unknown long-term effects	[14, 15, 33, 34]
Biological contaminants	Mold, bacteria, viruses, dust mites, pollen	Respiratory infections, asthma, allergies	[24, 35, 36]
Volatile organic compounds (VOCs)	Paints, cleaning products, tobacco smoke, furniture, adhesives	Eye, nose, throat irritation, headaches, dizziness, organ damage	[26, 28]
Particulate matter (PM2.5, PM10)	Combustion processes, outdoor air infiltration, dust resuspension	Respiratory diseases, cardiovascular diseases, lung cancer, premature mortality	[16]
Heavy metals (e.g., Al, Pb, Cd, As)	Industrial emissions, mining, contaminated water and soil, paints	Neurotoxicity, kidney damage, anemia, cancer, developmental disorders	[37, 38]
Carbon monoxide (CO)	Incomplete combustion of fuels (wood, coal, gas stoves, vehicle emissions)	Reduced oxygen transport in blood, dizziness, death at high levels	[28]
Carbon Dioxide (CO_2)	Human respiration, combustion sources, poor ventilation	Headaches, dizziness, cognitive impairment, suffocation at high levels	[39]

3.1. Particulate matter (PM) exposure and health risks

As summarized in Table 2, exposure to fine particulate matter (PM2.5) has been extensively linked to increased mortality risks and the worsening of cardiovascular and respiratory diseases. A comprehensive global study found that long-term exposure to PM2.5 has been associated with increased mortality risks, particularly from cardiovascular and respiratory diseases [40]. Cardiovascular and respiratory diseases, including stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD), and lung cancer, remain the primary contributors to PM-related deaths [40]. Their Global Exposure Mortality Model (GEMM) estimated that 8.9 million premature deaths worldwide were attributable to PM2.5 exposure in 2015, suggesting that the true burden of air pollution-related mortality is significantly higher than previously reported [41].

The World Health Organization (WHO) reports that 3.2 million premature deaths occur annually due to household air pollution, primarily caused by the incomplete combustion of solid fuels and kerosene used for cooking. Indoor air pollution, largely driven by the burning of solid fuel sources such as firewood, crop waste, and dung, poses a major health risk for the world’s poorest populations. In poorly ventilated environments such as heritage buildings and underground tunnels, where air circulation is limited, particulate matter and toxic gases can accumulate, increasing exposure risks. Indoor air pollution is widely recognized as a major environmental health risk globally [16, 42].

Furthermore, ambient air pollution trends indicate a concerning trajectory. According to the Institute for Health Metrics and Evaluation (IHME), although death rates from air pollution have declined by 46 % from 1990 to 2021, the total number of deaths caused by PM2.5 exposure has increased by 93 % over the same period. This suggests that while medical advancements and air quality regulations have mitigated mortality risks in certain regions, increasing outdoor air pollution levels, coupled with confined environments in heritage sites and tunnels, has amplified the global burden of PM-related diseases [41, 43]. A meta-analysis conducted in the Asia-Pacific region found that long-term PM2.5 exposure is directly associated with increased risks of cardiovascular diseases, type 2 diabetes, kidney diseases, and stroke [44].

In addition, short-term exposure studies indicate that every 10 $\mu g/m^3$ increase in PM2.5 correlates with a rise in daily hospital admissions for respiratory and cardiovascular issues [45]. Chronic exposure has also been linked to an increased risk of hospitalization and potential long-term effects such as dementia later in life [46]. These findings highlight the need for urgent interventions in confined spaces, especially heritage buildings and tunnels with poor ventilation, where pollutant accumulation exacerbates public health risks. Effective regulatory policies, improved ventilation strategies, and widespread adoption of clean energy sources could help mitigate the health burden of PM exposure [47, 48]. Continuous air quality monitoring in high-risk environments is also necessary to safeguard public health and ensure long-term cultural preservation [29, 49–51].

3.2. Heavy metal contamination and occupational health hazards

Heavy metals such as aluminum (Al), lead (Pb), cadmium (Cd), and arsenic (As) are significant indoor air pollutants, particularly in heritage buildings and confined spaces. These metals are often bound to particulate matter (PM) and originate from deteriorating lead-based paints, corroding metal structures, and industrial emissions. Studies have reported the presence of these metals in enclosed environments, raising concerns regarding occupational exposure and associated health risks. For instance, studies conducted in heritage buildings in Romania reported the presence of lead (Pb) contamination in indoor environments, raising concerns regarding occupational exposure and health risks [4]. Similarly, aluminum exposure in industrial workplaces, particularly in metal machining environments, has raised concerns regarding occupational health risks [52]. In underground tunnel environments, elevated concentrations of heavy metals such as cadmium have also been reported, particularly in poorly ventilated confined spaces [2]. These findings highlight the disproportionate accumulation of heavy metals in confined spaces compared to outdoor environments, with indoor levels often being higher due to poor ventilation and the resuspension of settled dust [14, 53].

The health impacts of heavy metal exposure are substantial. Lead exposure from degrading paints in heritage buildings is strongly associated with cognitive decline, memory impairment, and increased risk of neurological disorders, including Alzheimer's disease [5, 37]. Similarly, the aluminum has been linked to neurotoxicity, with evidence of accumulation in the brain contributing to Parkinson's and Alzheimer's diseases [6, 38]. Respiratory health is also severely affected by cadmium and arsenic exposure. The cadmium, frequently found in industrial and underground environments, has been shown to cause lung irritation, reduced lung function, and pulmonary fibrosis when concentrations exceed 5 $\mu g/m^3$ [8, 54]. Meanwhile, the arsenic inhalation has systemic effects, leading to cardiovascular diseases, immune suppression, and even skin lesions in workers exposed to confined environments with high levels of PM-bound arsenic. Epidemiological studies have indicated that prolonged exposure to heavy metals in confined environments may increase the risk of chronic respiratory diseases and lung cancer among exposed workers [16, 55].

These findings highlight the urgent need for stricter monitoring and mitigation measures to address heavy metal contamination in indoor environments. Real-time air quality monitoring, combined with enhanced ventilation systems and regular dust removal protocols, can significantly reduce the health risks associated with these pollutants. Additionally, the use of personal protective equipment (PPE) such as respirators should be prioritized, particularly for workers in heritage restoration projects and underground spaces. Future research should focus on developing cost-effective technologies for heavy metal filtration and evaluating the cumulative health effects associated with long-term exposure to multiple heavy metals in confined environments.

3.3. Silica dust and asbestos-related diseases

Construction activities in underground tunnels and heritage restorations frequently release respirable crystalline silica (RCS) and asbestos fibres, both classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC). Recent studies have reported substantial mortality associated with silica dust exposure, particularly due to silicosis and related complications such as chronic obstructive pulmonary disease (COPD) and lung cancer [31, 56]. Data from the Occupational Safety and Health Administration (OSHA) indicates that nearly 2.3 million workers in the United States are exposed to silica dust annually, with many working in confined spaces such as underground construction sites [9, 57].

Furthermore, asbestos exposure continues to be a significant concern in heritage buildings, as deteriorating insulation and roofing materials release fibres into poorly ventilated spaces [32]. The asbestos remains a leading cause of mesothelioma, a rare but fatal cancer, with thousands of new cases reported globally each year. The World Health Organization (WHO) has reported that approximately 125 million people worldwide are exposed to asbestos in occupational settings, with 107,000 deaths annually attributed to related diseases such as asbestosis, lung cancer, and mesothelioma [9]. Studies show that exposure in confined environments like tunnels amplifies risks, as the lack of ventilation exacerbates fibre concentration [46, 58]. Workers involved in heritage restoration projects face particularly high risks due to the deterioration of older building materials that historically contained asbestos before its widespread ban in many countries.

To mitigate these health risks, stricter enforcement of permissible exposure limits (PEL) and implementation of advanced dust control measures are critical. Regular air quality monitoring, the use of personal protective equipment (PPE), and proper training for workers can significantly reduce exposure risks in confined and restoration settings [16, 59–61].

3.4. Biological contaminants and infectious diseases

Poor indoor air quality has been closely associated with increased risks of respiratory and systemic infections caused by microbial contamination in enclosed environments. According to the Centers for Disease Control and Prevention [35], Legionella pneumophila outbreaks associated with contaminated HVAC systems have increased substantially over recent decades in indoor environments. Legionnaires' disease, caused by this bacterium, leads to severe pneumonia and affects thousands annually, especially in poorly ventilated buildings or heritage sites with aging infrastructure. Similarly, fungal spores such as *Aspergillus*, frequently found in damp indoor spaces, are a major cause of aspergillosis and contribute to a substantial global disease burden among immunocompromised patients [36].

The WHO [62] highlights that excessive dampness and mold remain common problems in indoor environments, significantly increasing the risk of fungal and bacterial infections. Furthermore, outbreaks of respiratory infections like influenza and RSV are exacerbated in poorly ventilated indoor environments, emphasizing the critical need for improved air quality management and regular microbial assessments.

3.5. VOCs, CO_2, and CO: Indoor gas exposure risks

Volatile organic compounds (VOCs), carbon dioxide (CO_2), and carbon monoxide (CO) are significant indoor air pollutants that contribute to severe health risks, particularly in confined spaces such as heritage buildings, tunnels, and industrial workplaces. The VOCs, including benzene, formaldehyde, and toluene, are commonly emitted from aging paints, adhesives, and furniture. These compounds are widely recognized for their toxic and carcinogenic properties. A global review by Manisalidis *et al.* [25] reported that prolonged exposure to the VOCs is associated with increased risks of respiratory diseases and certain cancers. Additionally, benzene exposure has been associated with leukemia and other adverse health effects [16]. Studies have shown that indoor concentrations of formaldehyde in poorly ventilated buildings can reach 150 $\mu g/m^3$, exceeding the WHO’s safe limit of 80 $\mu g/m^3$, increasing the risk of respiratory irritation and long-term carcinogenic effects [63].

The CO is an odorless, colorless gas that poses immediate health risks through oxygen displacement in the bloodstream. The CO poisoning remains a significant public health concern and is associated with numerous emergency department visits and fatalities annually in the United States. Industrial workplaces and enclosed areas with combustion sources have reported elevated CO concentrations, which may exceed OSHA’s permissible exposure limit (PEL) of 35 ppm and lead to acute symptoms such as headaches, dizziness, and loss of consciousness [28]. Prolonged exposure, even at lower levels of 10–20 ppm, has been linked to cardiovascular diseases and an increased risk of premature death, particularly in vulnerable populations such as the elderly and individuals with pre-existing conditions.

The CO_2, a common marker of poor ventilation, can accumulate to harmful levels in confined environments. The WHO and IAQ guidelines commonly recommend maintaining indoor CO_2 concentrations below 1,000 ppm; however, studies in heritage buildings, classrooms, and underground workspaces have recorded concentrations exceeding 2,500 ppm, increasing risks of fatigue, headaches, and respiratory stress [28, 39]. Poor ventilation and the accumulation of indoor pollutants such as VOCs and CO_2 may negatively affect occupant comfort and overall indoor environmental quality [64].

These findings highlight the importance of proper ventilation in maintaining indoor air quality and reducing health-related risks. The presence of VOCs, CO_2, and CO in indoor environments poses substantial risks to both immediate and long-term health. Acute exposure to VOCs can cause symptoms such as eye and throat irritation, headaches, dizziness, and nausea, while chronic exposure is linked to an increased prevalence of asthma and chronic obstructive pulmonary disease (COPD), particularly among individuals in occupational settings [14].

Acute exposure to the CO at concentrations above 200 ppm can cause hypoxia, confusion, and, in severe cases, death due to suffocation, while chronic exposure contributes to cardiovascular risks and reduced oxygen transport in the blood. Similarly, prolonged exposure to the CO_2 at concentrations above 1,500 ppm has been associated with fatigue, impaired memory, and reduced productivity, particularly in workplaces with poor air circulation. Indoor air quality (IAQ) is a critical factor in maintaining a healthy indoor environment, particularly in confined spaces such as heritage buildings. Unlike modern structures, heritage buildings often experience higher levels of indoor pollutants due to aging materials, restricted ventilation, and structural limitations [49].

These factors contribute to the accumulation of airborne contaminants, including VOCs and CO_2, thereby posing significant health risks to occupants. Furthermore, preservation regulations in heritage buildings often limit the extent of ventilation improvements, necessitating alternative IAQ management strategies. Therefore, regular air quality monitoring and adaptive ventilation techniques are essential in balancing historical preservation with occupant health and safety. Given these risks, mitigation strategies should prioritize enhanced ventilation, the adoption of low-emission building materials, and real-time air quality monitoring systems to detect and control gas levels.

Despite the severity of these pollutants, current indoor air quality (IAQ) guidelines, including ICOP 2010 and WHO standards, lack comprehensive measures for managing VOCs and CO_2 in heritage buildings and enclosed spaces. Stricter enforcement of IAQ regulations, combined with increased awareness and the implementation of effective filtration technologies, is essential to safeguard public health in indoor environments.

3.6. Microplastic inhalation: An emerging IAQ concern

Microplastics, defined as plastic particles smaller than 5 mm, have become a critical concern in indoor air quality (IAQ) research, particularly in heritage buildings and confined spaces. These particles originate from various sources, including synthetic textiles, degraded plastic materials, paint coatings, and consumer products [14]. In poorly ventilated heritage sites, microplastics can accumulate due to the degradation of construction materials and frequent human activities such as cleaning and restoration. Research indicates that indoor microplastic concentrations are often higher than outdoor levels. For instance, a study by Vianello *et al.* [15] revealed indoor concentrations ranging from 1 to 15 fibres/m^3, depending on ventilation efficiency and human activity. In industrial workplaces, such as textile factories, concentrations have been found to exceed 40 fibres/m³, leading to higher exposure risks for workers [30].

Exposure to airborne microplastics has significant health implications. Inhalation of these particles can cause pulmonary inflammation, airway obstruction, and chronic respiratory conditions such as bronchitis [65]. Occupational exposure in environments with high microplastic levels, such as museums and restoration sites, has been linked to an increased incidence of interstitial lung disease and other respiratory disorders. Beyond respiratory effects, microplastics are often coated with harmful additives like phthalates and bisphenol A (BPA), which are known to disrupt endocrine functions and cause systemic inflammation [14]. Emerging studies suggest that nano-sized microplastics can enter the bloodstream, leading to cardiovascular issues and potential bioaccumulation of toxic chemicals [33]. Epidemiological studies suggest that individuals in polluted indoor environments may inhale substantial amounts of airborne microplastics annually, with occupational workers facing higher exposure risks. For example, workers in garment factories have been reported to inhale over 300 microplastic fibres daily, primarily originating from synthetic fabrics [30].

Despite ICOP 2010 enforcing strict IAQ monitoring requirements, there are currently no regulatory guidelines addressing airborne microplastics, suggesting a gap in existing air quality policies [1].

However, several studies have operationally defined high concentrations as exceeding 5,000 to 10,000 particles per cubic meter (particles/m³), particularly in enclosed areas with synthetic furnishings and poor ventilation. These levels are commonly observed in residential and office spaces where sources such as textile fibres, plastic coatings, and cleaning activities dominate. Although there is currently no official threshold for airborne microplastic exposure, high concentrations are typically associated with increased inhalation risks due to particle sizes smaller than 10 µm, which enable deep penetration into the respiratory tract. Further research is required to establish standardized units, consistent sampling protocols, and exposure-response relationships to define what constitutes hazardous microplastic levels in indoor environments.

These findings highlight the urgent need for improved IAQ management and targeted interventions in confined spaces. However, current IAQ guidelines, such as the ICOP 2010 and WHO standards, do not yet address microplastic contamination, leaving a significant regulatory gap. To mitigate exposure, heritage sites and industrial spaces should prioritize enhanced ventilation systems, implement HEPA filters capable of trapping microplastic particles, and adopt regular cleaning protocols to reduce airborne particle dispersion. Future research should focus on developing global standards for acceptable indoor microplastic concentrations and evaluating the long-term health effects of chronic exposure [14, 15, 33].

In response to regulatory gaps and pollutant exceedances identified in IAQ studies, this review further evaluates the effectiveness of indoor air pollution mitigation strategies reported in the literature. These include the implementation of mechanical ventilation systems, the use of high-efficiency particulate air (HEPA) filters, and periodic air monitoring using portable detection instruments. Studies have shown that installing localized exhaust ventilation and dehumidifiers significantly reduces PM and microbial concentrations in enclosed heritage spaces. In some cases, the introduction of air purification units equipped with activated carbon filters has helped to reduce VOC and CO levels, especially in underground galleries and archives. However, challenges remain in heritage buildings where structural limitations restrict mechanical upgrades, thus requiring passive strategies such as natural ventilation optimization, moisture control, and routine inspection of potential pollutant sources. The review highlights that while several interventions are promising, their effectiveness is often context-specific and influenced by site characteristics, usage patterns, and maintenance practices. To consolidate the findings, a conceptual framework was developed to visually represent the interrelationships between pollutant sources, exposure pathways, health effects, and mitigation measures in heritage buildings and confined spaces. This framework, as illustrated in Figure 1, aims to guide risk assessment and control planning in indoor environments with complex pollutant dynamics.

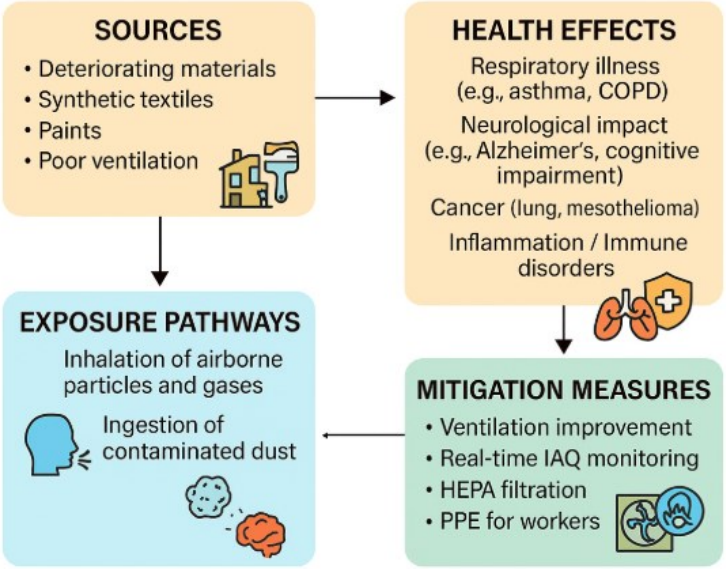

Figure 1. Conceptual framework of indoor air pollutants in confined and heritage buildings.

4. CONCLUSIONS

Indoor air quality (IAQ) in heritage buildings and confined spaces presents distinct challenges to occupational safety and health. These challenges arise from structural limitations, aged construction materials, and inadequate ventilation. This review has identified major indoor air pollutants such as particulate matter, heavy metals, silica dust, asbestos, microbial agents, and microplastics, many of which are frequently found at concentrations exceeding established safety thresholds in such environments. Although regulatory frameworks, including ICOP 2010, OSHA, and WHO, provide general guidance on exposure limits, there remains a notable lack of regulation for emerging pollutants such as microplastics. Furthermore, enforcement of existing standards is often limited, particularly in heritage contexts where compliance monitoring may be difficult due to preservation constraints. The review emphasises that effective IAQ improvement strategies must be customised according to the physical and functional characteristics of each site. These may include a combination of mechanical solutions, such as filtration and ventilation systems, and passive methods like moisture control and regular maintenance. However, the implementation of such measures is often constrained by the need to preserve the historical and architectural integrity of the buildings. Pollutant levels are also influenced by several variability factors, including the building's age, usage, material composition, and surrounding environmental conditions. Future research should therefore focus on developing context-sensitive IAQ assessment frameworks that integrate health protection with heritage conservation objectives. It is also essential to establish clear thresholds for emerging contaminants and to enhance the use of advanced air monitoring technologies to support more effective control of indoor pollutants in heritage and confined spaces.

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

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