Review

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Beyond the outdoors: indoor air quality guidelines and standards – challenges, inequalities, and the path forward

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Abstract: In the last few decades, indoor air quality (IAQ) has become a major threat to public health. It is the fifth leading cause of premature death globally. It has been estimated that people spend ~90 % of their time in an indoor environment. Consequently, IAQ has significant health effects. Although IAQ-related standards and guidelines, policies, and monitoring plans have been developed in a few countries, there remain several global inequalities and challenges. This review paper aims to comprehensively synthesize the current status of widely accepted IAQ guidelines and standards. It analyzes their global implementation and effectiveness to offer insights into challenges and disparities in IAQ policies and practices. However, the complexity of domestic environments and the diversity of international standards impede effective implementation. This manuscript evaluates international, national, and regional IAQ guidelines, emphasizing similarities and differences. In addition, it highlights knowledge gaps and challenges, urging the international scientific community, policymakers, and stakeholders to collaborate to advance IAQ standards and guidelines. The analysis evaluates the efficacy of guidelines, identifies deficiencies, and offers recommendations for the future of domestic air quality standards.

Keywords: indoor air quality (IAQ); global health; IAQ guidelines; implementation challenges; WHO

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Introduction

Air pollution is the most significant health risk worldwide. Population-based research has found acute and chronic health consequences from modest physiologic abnormalities and mental health to mortality from cardiopulmonary diseases and cancer from short-term air pollution exposure. According to a recent World Health Organization [1] and Health Effects Institute [2] report, air pollution is the world's fifth leading cause of premature death, causing 3.2 million indoor and 4.2 million outdoor deaths and 147 million healthy life-years lost. Almost all of the global population (99 %) breathes air that exceeds WHO health-based guidelines [3]. IARC [4] has classified outdoor air pollution as harmful to humans (Group 1). Group 1 carcinogens include outdoor air pollution's PM.

Indoor air pollution can originate from various sources, including combustion processes, building materials and furnishings emissions, and household cleaning products. Additionally, heating and cooling systems can contribute to indoor pollution by circulating and potentially distributing airborne contaminants, while moisture-related activities and occupants' behaviour also play significant roles. Outdoor sources, such as vehicle emissions and industrial activity, further infiltrate and impact indoor air quality. Some common indoor air pollutants that threaten IAQ include gases (i.e., carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), formaldehyde, benzene, radon), volatile organic compounds (VOCs), asbestos, fibres, particulate matter (PM), lead, and biological particles (dust mites, bacteria, fungi, pollen). Studies have shown that susceptible populations (e.g., children, elderly, women expecting babies, and low socioeconomic) may be disproportionately impacted by indoor asthma triggers, secondhand smoke, mould, Radon and other indoor pollutants [5, 6].

Inadequate IAQ is known to be a significant contributing factor to the development of Multiple Chemical Sensitivity (MCS), Sick Building Syndrome (SBS), and building-related illnesses (BRI). Furthermore, prolonged exposure to inadequate IAQ has been associated with the onset of asthma, cardiovascular diseases, and cancer, as reported by the World Health Organization in 2018[7]. According to Allen et al. [8], there is evidence to suggest that improved IAQ can positively impact cognitive performance and productivity. Nevertheless, diverse contaminants, including biological agents, building materials, and external pollutants, pose challenges to enhancing indoor air quality [9]. The foregoing intricacy highlights the necessity of implementing comprehensive IAQ regulations.

Standards and guidelines improve IAQ by recommending pollutant's guidelines and reference values for building design and operation and guiding monitoring and remediation [10]. They also shape environmental and public health policies to include IAQ [11]. IAQ guidelines and standards creation and implementation face many obstacles. Indoor spaces differ in structure, occupancy, and ventilation systems, making setting universal guidelines challenging. Establishing IAQ guide or reference values is complex due to indoor environments' varied interactions and health impacts. Pollutant sources, ventilation, building materials, and occupant behaviour interact in indoor environments. Despite guidelines and regulations, lack of understanding, financial restrictions, and opposition to change can make implementation and compliance difficult [9–12].

This review is dedicated to compiling and analyzing globally accepted guidelines and standards on IAQ. We compare and contrast these standards to identify commonalities, differences, and improvement areas in the global IAQ management approach. It provides an overview of the current international IAQ situation and addresses the numerous international, national, and regional IAQ guidelines and standards. The analysis assesses the efficiency of these guidelines and standards, identifies any shortcomings, and draws conclusions on the way forward for IAQ norms. This critique can be used as a springboard for additional reading and debate.

Current status of global IAQ

It is not easy to generalize about the status of IAQ worldwide because such a large variety of indoor habitats and components affect the air quality. It is not uncommon for the levels of pollution found indoors to be significantly higher than those found outside. According to the data compiled by the World Health Organization [7], the pollution levels within buildings can be up to several-fold higher than those outside. Such disparities in pollution levels necessitate immediate attention and action. According to the Global Burden of Disease Study [13], IAQ contributed to the mortality of approximately 2.3 million people worldwide in 2019.

Numerous studies have found that indoor air pollutants are 2–5 times, and often 100 times, higher than outdoor levels due to restricted dilution, low wind speed, and intense sources and biological pollutants [14, 15]. The types and concentration levels of pollutants can vary depending on time, location, geography, construction materials, and human activities [16]. The wide range of laws enforced in different countries adds another layer of complexity to the already challenging work of addressing IAQ guidelines and recommendations. Some communities have created IAQ standards to fit local situations, economic capacities, and political systems.

Improving the overall IAQ across the globe requires overcoming challenges. There is a lack of understanding about the difficulties associated with IAQ, insufficient research on the health consequences of various contaminants, uneven IAQ standards, and challenges in implementing rules [16]. Increasing awareness, carrying out research, defining IAQ standards that are both uniform and effective, and devising effective means for their application are all critical to overcoming these obstacles. It is necessary to find solutions to problems to protect public health and make indoor settings healthier globally.

Pollutants of concerns

Human health and well-being depend on the effective management of IAQ to improve the IAQ and lessen the likelihood of respiratory illnesses and other health problems. Monitoring and controlling pollutants such as CO, carbon dioxide (CO_2), indoor temperature, relative humidity, NO_2, O_3, formaldehyde, benzene, Radon, VOCs, asbestos, $PM_{2.5}$, lead, and bioaerosols, including moulds is critically essential [17, 18]. The concentration levels of pollutants can change depending on airflow, the amount of pollution outside, the building materials, and the activities done inside. Improving the air quality entails keeping track of pollutants, which is essential for a healthy and relaxed indoor environment. A brief description of the health-significant parameters commonly encountered in indoor environments is as follows.

Carbon monoxide (CO) is an odourless and tasteless gas primarily generated by the incomplete combustion of fossil fuels [12, 19]. CO binds to hemoglobin when inhaled and reduces the oxygen-carrying capacity of red blood cells, carboxyhemoglobin (COHb), which can cause various health problems. In high concentrations, symptoms can range from mild nausea and fatigue (20–30 % COHb) to severe asphyxiation and mortality (>70 % COHb). CO has been identified as a significant predictor of congestive heart failure hospitalization in elderly patients [20]. Carbon dioxide excessive levels may indicate inadequate ventilation and high occupant density. Monitoring CO_2 levels is essential because it aids in determining the efficacy of ventilation systems and the need for fresh air intake to maintain optimal IAQ and occupant comfort [21, 22]. Exposure to CO_2 can produce a variety of health effects, including headaches, dizziness, difficulty breathing, increased heart rate, elevated blood pressure, and coma.

Maintaining a suitable temperature indoors is essential for thermal comfort and productivity. Extreme temperatures can cause discomfort and stress, negatively impacting the health of occupants. Sick Building Syndrome (SBS) symptoms have also been more prevalent in buildings with higher interior temperatures [23, 24]. Indoor relative humidity levels also affect the comfort of the occupants and the proliferation of bioaerosols, such as moulds and bacteria. Low relative humidity can accelerate the release of spores into the air and cause dry eyes and nasal passages, whereas high relative humidity can promote the growth of allergens and fungi, aggravating respiratory problems [25, 26].

NO_2 is a hazardous gas commonly found indoors due to outdoor air, kerosene and gas space heaters, wood and gas stoves, and tobacco smoke. Short-term exposure to NO_2 was linked with increases in all-cause, cardiovascular mortality, and hospital admissions for CVD, and short-term increases in NO_2 increased the risk of hospitalization from CVD [20]. Exposure to NO_2 can aggravate lung diseases, leading to respiratory symptoms, hospital admission, and increased susceptibility to respiratory infection. Husainy [27] and Vardoulakis et al. [28] have reported that long-term exposure to NO_2 can trigger asthma and other respiratory diseases. Ozone is typically formed by the chemical reaction of VOCs and NO_x in sunlight. It decreases lung function, causes respiratory symptoms, and aggravates asthma and other lung diseases. O_3 has been designated a carcinogen due to its ability to generate free radicals within the body. Chest pain, shortness of breath, and irritation of the pharynx are common symptoms of ozone exposure [19].

Important indoor PM sources are outdoor air, vacuuming/cleaning, cooking, wood and gas fireplaces, heaters, candles, incense, and smoking. Epidemiological studies provide evidence that short-term exposure to $PM_{2.5}$ is associated with numerous effects on human health, such as cardiopulmonary diseases, cancer, diabetes, tuberculosis, neurodegenerative (dementia, Alzheimer's and Parkinson's), mental health, pregnancy losses, reduced birthweight, and life expectancy [29–34]. Lead-based paint, dust, old furniture, dishware, and cosmetics are the most common sources of Pb in an indoor environment. It is a toxic heavy metal which damages the developing nervous system, resulting in IQ loss and impacting children's learning, memory, and behaviour [35]. In addition, cardiovascular and renal effects in adults and early effects related to anemia.

TVOC (Total Volatile Organic Compounds) concentration is a widely recognized indicator of indoor VOC levels, reflecting a range of compounds from various indoor sources such as air fresheners, solvents, building materials, and tobacco smoke. While TVOC is primarily used as a management tool to assess overall VOC presence, its relevance extends beyond mere quantification. Short-term exposure to high levels of VOCs, as indicated by elevated TVOC, can cause immediate discomfort, including eye and throat irritation, headaches, and nausea. These acute symptoms can significantly affect occupant comfort and well-being. Moreover, prolonged exposure to certain VOCs, which contribute to the TVOC metric, has been linked to more severe health outcomes, including respiratory issues, allergies, and, in some cases, chronic diseases like cancer [22].

Formaldehyde is a water-soluble gas. The primary indoor sources of formaldehyde are particleboard, insulation, furnishings, plywood, carpets, ceiling tile, and tobacco smoke. Exposure to formaldehyde can irritate the skin, throat, lungs, and eyes. Long-term exposure to formaldehyde can lead to cancer. Benzene in indoor air can originate from outdoor and indoor sources, such as glues, adhesives, paints, furniture wax, detergents, and tobacco smoke. Short-term inhalation of benzene can cause headaches, dizziness, and death (at very high levels). Compared to other gases, Radon (^{222}Rn) spreads into buildings from the soil, masonry and underground water. ^{222}Rn is not harmful, but its progeny polonium-218 (^{218}Po) and lead-214 (^{214}Pb) enter the lung directly and are believed to be highly carcinogenic. It is the second-leading cause of lung cancer after smoking. Radon-induced lung cancer kills thousands globally [22, 36]. Asbestos is a class of natural impure hydrated silicate minerals that may be separated into fibres. It is chemically inert. The primary health effects of asbestos exposure are lung cancer, mesothelioma, and asbestosis.

Aerosol particles that are either living or the products of living things make up bioaerosols. They include microorganisms (e.g., bacteria, fungi, viruses), cells and fragments of plants and animals, spores, fragments of excreta, animal dander and secretions. Bioaerosols probably produce more human death and discomfort than any other air pollutant. They cause respiratory problems and allergies, making them hazardous to human health. Inhaling bioaerosol particles can cause respiratory problems and allergic reactions in susceptible individuals [36, 37]. Common symptoms include coughing, wheezing, throat distress, nasal congestion, and rashes. Mold spores may exacerbate or induce asthma. Airborne transmission of bioaerosols is a mode of infection of some of the most common and deadly diseases [37, 38].

Global and regional IAQ guidelines and standards

Guidelines and standards for IAQ serve as benchmarks for permissible levels of indoor contaminants that have the potential to harm human health and well-being. Various organizations and regulatory authorities formulate and publish these rules and standards globally.

The World Health Organization (WHO) has issued guidelines for acceptable levels of pollutants in the indoor environment [5]. These guidelines protect public health worldwide in various economic and social settings. The WHO's recommendations cover IAQ issues like PM, CO, formaldehyde, Radon, and VOCs. The World Health Organization suggests that $PM_{2.5}$ levels for any exposure setting, other than the occupational settings, be maintained at or below 5 $\mu g/m^3$ annually and 15 $\mu g/m^3$ on a 24 h basis to reduce health risks [3]. The World Health Organization (WHO) suggests an 8-h average limit of 10 mg/m^3 to minimize CO-related harm [5].

In the US, the Occupational Safety and Health Administration (OSHA) set the standards for pollutant concentrations in indoor workplaces. They get the recommendations for standards from the National Institute for Occupational Safety and Health (NIOSH). NIOSH recommends permissible exposure limits (PELs), short-term exposure limits (STELs) and ceiling concentrations. CO and ozone indoor 8-h PEL are 35 and 0.1 ppmv, respectively. The Environmental Protection Agency (EPA) of the United States publishes guidelines and tools for various indoor settings but does not mandate minimum IAQ standards. For instance, the IAQ Tools for Schools Action Kit provides institutions with access to materials, guidelines, and examples of policies intended to improve IAQ [39]. These IAQ kit tests are for VOCs, PM, CO, and allergies [16]. Public and industrial buildings can use the EPA's Building Air Quality Guide. This document is helpful for facility managers in avoiding, detecting, and resolving IAQ problems. Solutions for VOCs, PM, CO, mould, and Radon are included [40]. The EPA offers guidance on dealing with Radon, a radioactive gas that can seep through the earth and into buildings, and access to testing and mitigation tools.

The European Union (EU) has no comprehensive regulation for IAQ. Instead, it utilizes a combination of guidelines from the WHO, standards established by the European Committee for Standardization (CEN), directives issued by the European Union (EU), and legislation enacted at the national level [41]. Energy Performance of Buildings Directive (EPBD) regulations for ventilation systems and IAQ are encouraged to improve the energy performance of buildings. The Construction Products Regulation (CPR) creates standardized guidelines for marketing construction products in the European Union (EU), including regulations on the release and emission of hazardous substances from building materials [42, 43].

The European Union has established threshold limits for specific indoor air contaminants in buildings, including benzene and carbon monoxide (CO). Very Volatile Organic Compounds (VVOCs) are a significant category of indoor air pollutants. Among these, formaldehyde is the most common VVOC [41, 44]; the EU recommends keeping its concentration below 0.1 parts per million (ppm) in consumer goods, furniture, and building materials. Benzene, a known carcinogen, has a recommended limit of 5 $\mu g/m^3$. Also, the European Union has capped the home's safe level of CO. The European Committee for Standardization (CEN) has created numerous domestic air quality standards [45, 46]. The guidelines for thermal environment, indoor air quality, illumination, and acoustics in buildings have been updated to conform to EN 16798-1:2019, which supersedes the decommissioned EN 15251. This advisory standard, part of the EN 16798 series that focuses on energy-efficient ventilation, can potentially influence national building regulations within the European Union [47]. In 2017, the EN 13779:2007 standard, previously applicable to ventilation in non-residential structures, was discontinued. However, its essential elements have been integrated into the EN 16798 series.

The International Organization for Standardization (ISO) provides a framework for assessing and bettering IAQ in buildings, ISO 16814:2008, that addresses multiple factors that can affect the health and well-being of building occupants. It does not specify precise pollutant limits but provides guidelines for measuring IAQ variables [48]. The criteria for evaluating IAQ include ventilation, sources of indoor pollution, and other factors. Professionals in the construction industry can help improve IAQ by implementing the guidelines in ISO 16814:2008.

The challenge of managing IAQ is compounded by the lack of standardized guideline values, especially considering the diverse sources of indoor contaminants and their varying health impacts. Given the evolving nature of IAQ research and the influence of regional conditions, establishing universal global guidelines remains complex. The World Health Organization (WHO) provides guideline values for indoor air pollutants derived from extensive scientific research, while the European Union (EU) recommends parameters for maintaining IAQ, although it does not enforce specific limits. While organizations like USEPA and ASHRAE develop voluntary standards for managing Indoor Air Quality (IAQ), they do not establish specific pollutant thresholds. In contrast, bodies like ISO primarily focus on providing a general framework for IAQ standards [49]. Health-based IAQ recommendations and regulations are critical in places with severe conditions like the Middle East, where people spend a disproportionate amount of time indoors. International organizations frequently prioritize IAQ management, and recommendations for improving IAQ through ventilation, pollutant source control, and building design are commonly provided. Promoting healthy indoor environments can be significantly aided by developing region-specific IAQ thresholds following these principles and keeping current with research findings.

National IAQ standards and guidelines

In recent decades, IAQ has become a significant public health concern. Many countries worldwide have adopted or are developing IAQ recommendations and standards in response to this concern. In the United States, the Occupational Safety and Health Administration (OSHA) has established stringent IAQ requirements in response to incidents such as “Sick Building Syndrome” [50]. The European Union has also created recommendations for many indoor pollutants to reduce the health burden associated with non-communicable diseases. Countries undergoing rapid industrialization, such as China and South Korea, have acknowledged IAQ’s importance and established the IAQ standard. The following section briefly discusses the national IAQ guidelines and standards from selected countries worldwide. Figures 1 and 2 and Tables A-1 and A-2 depict the IAQ guidelines or standards for the most prevalent physicochemical, biological, and VOC parameters established by various nations.

To protect public health and promote a secure indoor environment, the German Federal Environment Agency (UBA) has established criteria for IAQ [45, 51]. The French National Agency for Health and Safety (ANSES) has outlined recommendations regarding IAQ to protect public health and promote a secure indoor environment, establishing limits for several pollutants, including formaldehyde, benzene, and CO [52]. Formaldehyde should not exceed 100 μg/m^3 in interior air, according to the ANSES. The recommended exposure limit for benzene, a carcinogenic compound typically emitted by tobacco smoke, vehicle exhaust, and industrial processes, is 30 μg/m^3 for short-term exposure (1–14 days). ANSES also suggested that concentrations of NO_2, individual VOCs, and CO in indoor air should be monitored. These regulations aim to regulate indoor air pollutants and protect public health.

UK has no IAQ standards or legislation on a national scale. Instead, government agencies and organizations issue IAQ guidelines to address specific pollutants and their health risks [4, 53]. In the UK, Public Health England, the Education & Skills Funding Agency, and the Department of Environment, Food, and Rural Affairs (DEFRA) have set IAQ thresholds with updated recommendations for different contaminants in buildings. Public Health England has set limit values for certain VOCs based on their dangerous and common characteristics [53, 54]. Benzene and Trichloroethylene do not have safe exposure amounts. The restrictions the Education and Skills Funding Agency put in place align with what the WHO and Public Health England suggest. The Air Quality Expert Group of DEFRA recommends measuring indoor emissions and making activity-based inventories to improve IAQ modelling and interventions for UK homes to improve IAQ and public health.

The USEPA does not regulate IAQ in the United States because of its complexity and fluctuation. Instead, it provides guidelines and tools [46, 55]. The building materials, indoor activities, and resident habits complicate IAQ. States have enacted regulations to improve IAQ to address this critical issue. There are often more stringent state regulations regarding Radon, mould, ventilation, and indoor air pollution than federal ones. Standards vary from state to state based on the requirements of the local people. For example, the Texas Department of State Health Services developed the statewide voluntary IAQ Guidelines [56]. These guidelines for improving the quality of air within government buildings are comprehensive, but they are not binding. Building envelope, HVAC, thermal comfort, relative humidity, and low-emitting materials are all discussed. California’s Department of Public Health also runs a strict program to improve IAQ [57]. This program offers detailed recommendations for indoor air pollution, conducts extensive studies, and supplies households with tools. Due to the rising importance of comprehensive air quality solutions, the Environmental Health Laboratory merged its IAQ and ambient air quality sections in 2021 to become the Air Quality Section (AQS). Mould must be assessed and removed under New York State regulations, which in turn necessitate the use of trained professionals. Radon testing and abatement tools are also available in New York [58]. New York City officials are examining potential IAQ rules. The law will force the Department of Health and Mental Hygiene (DOHMH) to create standards for indoor air quality (IAQ) in municipal facilities and to conduct education and outreach efforts addressing IAQ [59].

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) created the rules and criteria for IAQ. ASHRAE Standard 62.1 outlines the

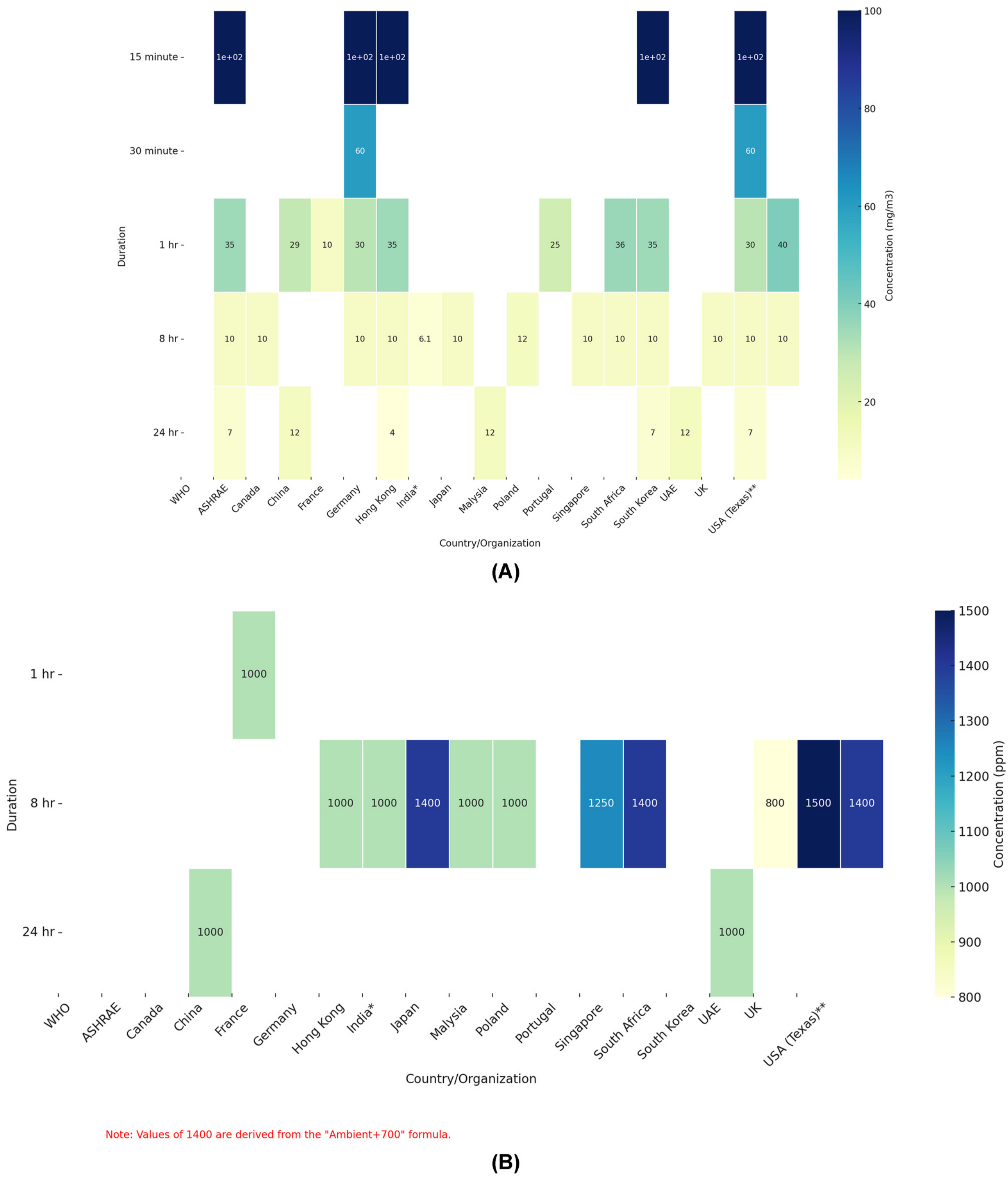
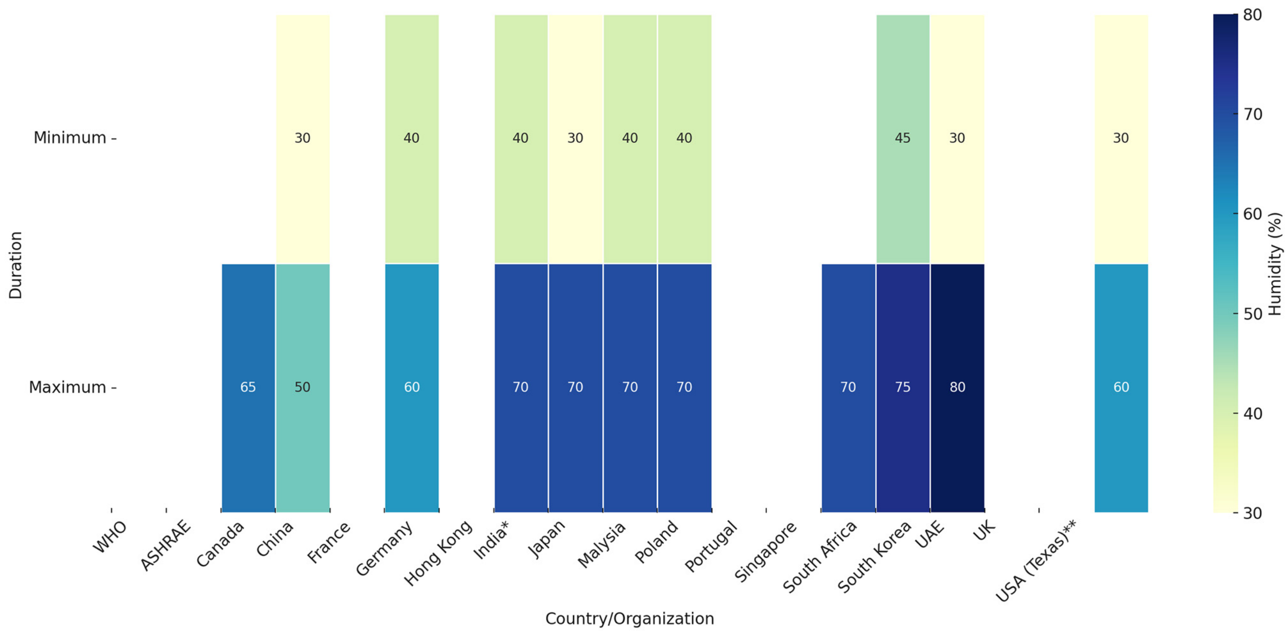


Figure 1: Recommended levels of (A) CO (ppm) (B) CO_2 (ppm) (C) %RH and (D) Temp. (°C) across various exposure duration.

minimum ventilation rates for commercial and institutional buildings, while ASHRAE Standard 62.2 covers residential structures. Commissioning and air change efficiency are addressed in ASHRAE Guidelines 0-2019 and 1.4-2019, respectively. IAQ is encouraged in low-rise residential structures per ASHRAE Guideline 24-2015 [60]. The ASHRAE standard 241B was recently introduced to address the problem of bioaerosols. This guideline assists building owners and managers in reducing exposure to infectious agents such as the SARS-COV-2 virus, which causes COVID-19



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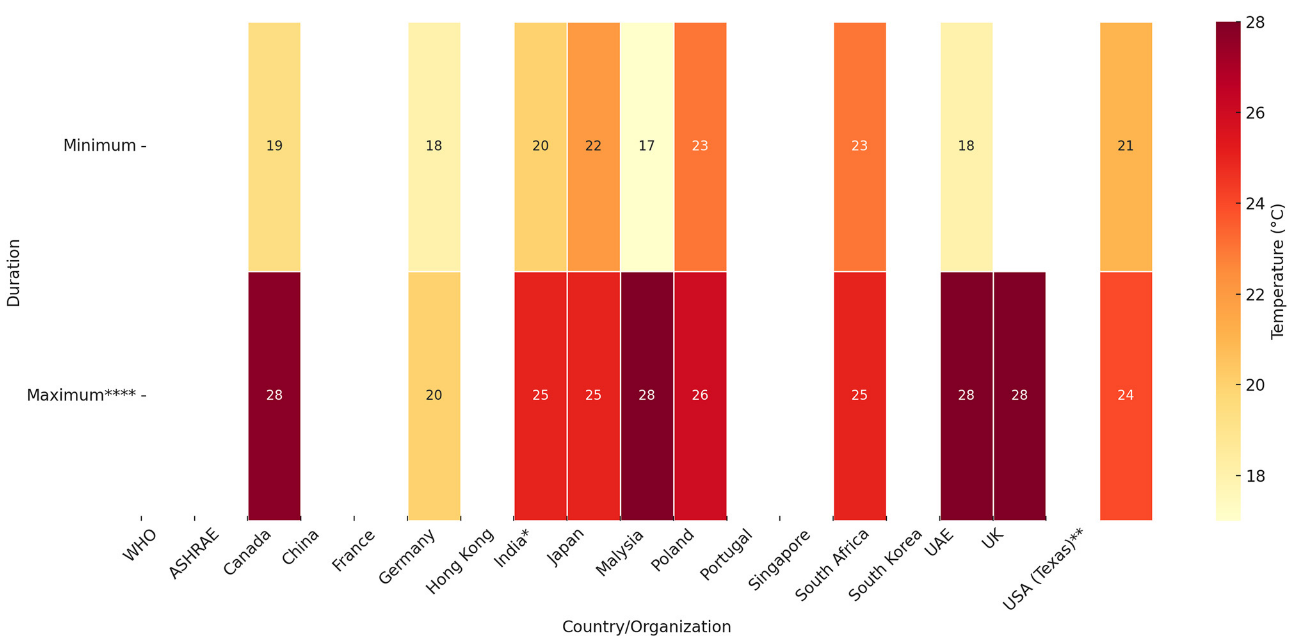

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and influenza. ASHRAE Standard 241 requires infection risk management mode (IRMM) standards during high disease transmission risk periods. Resilience allows IAQ control design and operation. The standard also requires an equal clean airflow rate, which is pathogen-free air entering occupied areas, using technologies like filtration and germicidal UV light. This flexible approach lets users choose technology that meets their energy and economic needs. The standard also promotes filtration and air cleaning technology to maintain interior air quality without energy-intensive exterior air ventilation. It also assesses, plans, and commissions systems, including a building preparedness plan, to ensure proper installation and operation. ASHRAE Standard 241 protects indoor settings against infectious aerosols, improving public health and decreasing disease-related economic harm [61].

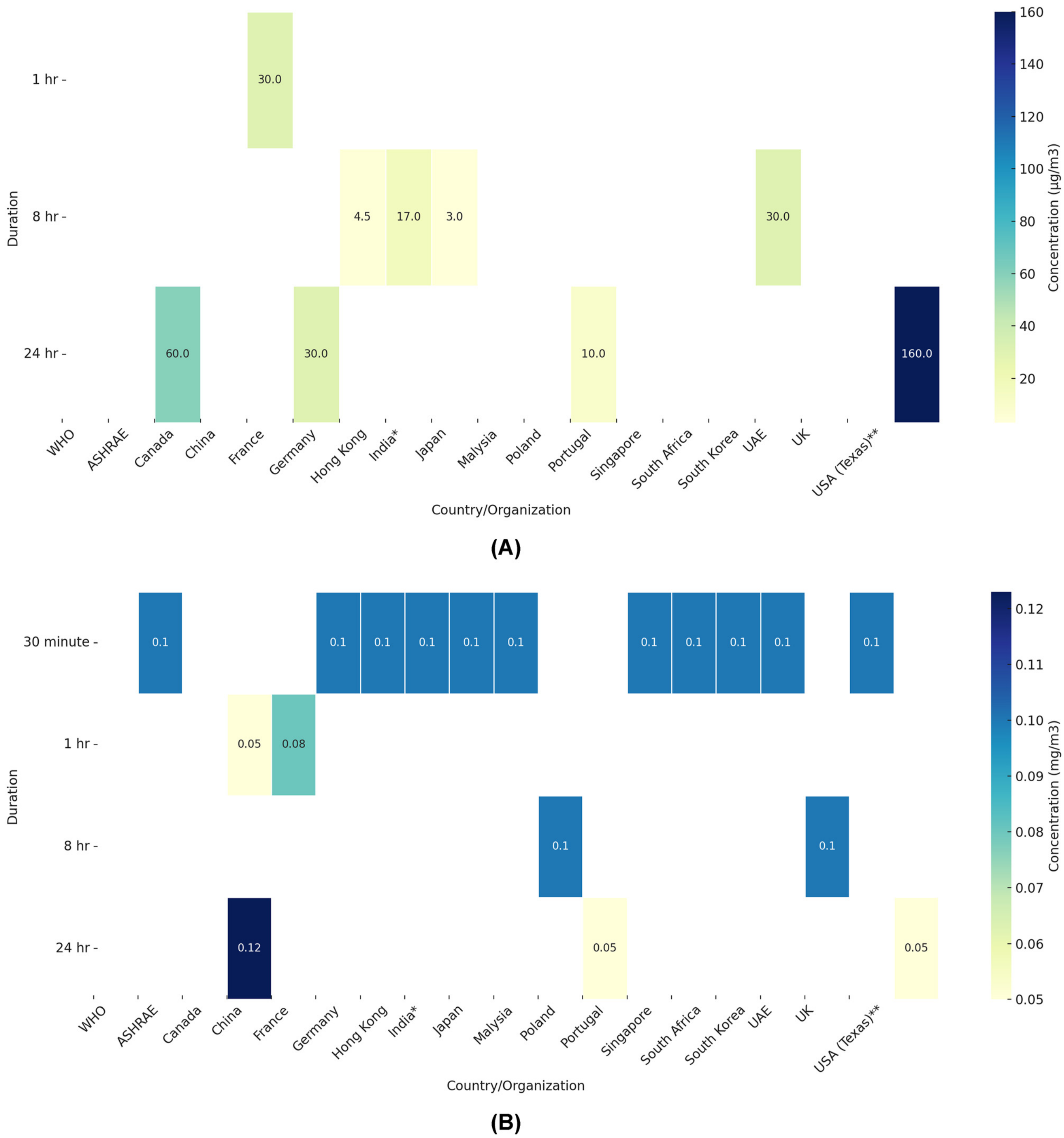
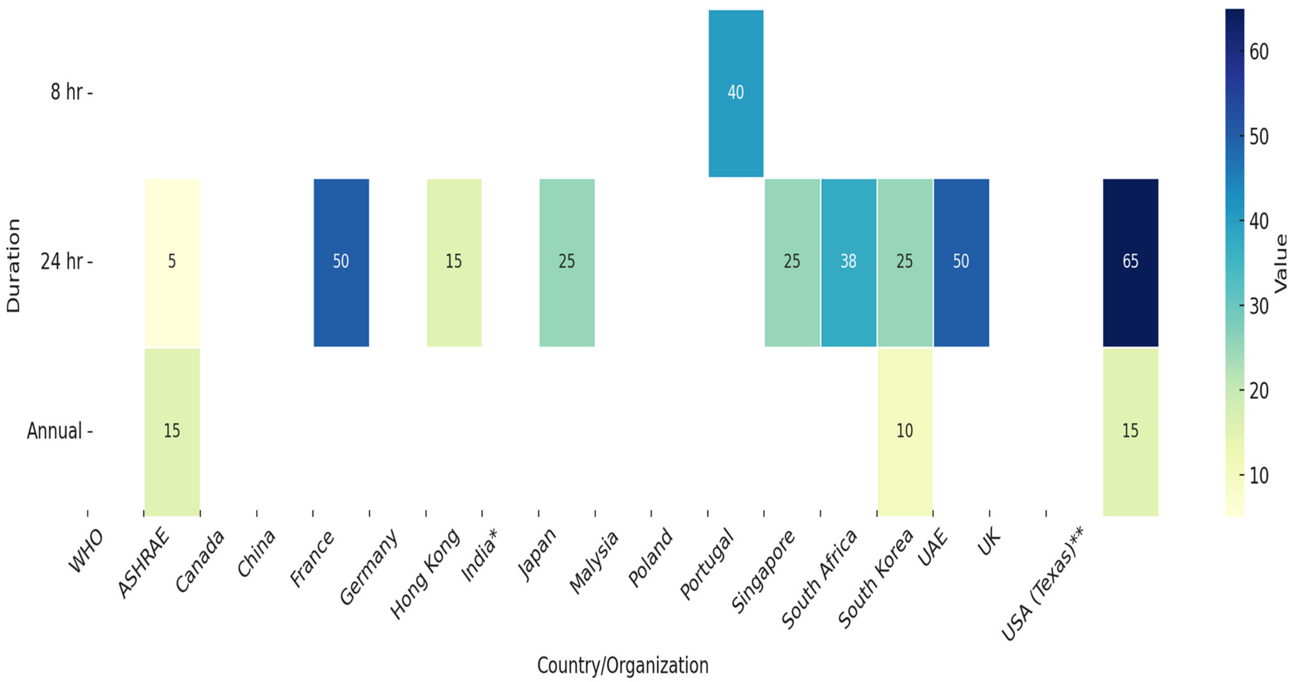


Figure 2: Recommended levels of (A) benzene (µg/m^3); (B) formaldehyde (mg/m^3); (C) $PM_{2.5}$ (µg/m^3); (D) VOCs (µg/m^3) across various exposure duration.

China has recently substantially improved IAQ directives to protect public health and enacted stringent regulations that promote safer and healthier indoor environments. The most recent standard, GB/T 1883-2022, is an update to the preceding standard from 2020, which was last revised in 2002 [62]. Privacy concerns make it difficult to monitor IAQ on a large scale, but guidelines have been developed to assist individuals in maintaining healthful indoor environments [63]. New technologies, such as low-cost sensors and models, also contribute to evaluating environmental contamination. The GB/T 18883-2020 draft suggests reducing daily indoor PM2.5 concentrations to 50 µg/m^3. However, the WHO suggests a significantly lower 15 µg/m^3 value. China has also enacted regulations (GB 50736-2012) to enhance IAQ for building heating, ventilation, and air conditioning systems. Such legislative improvement demonstrates China's commitment to creating healthier indoor



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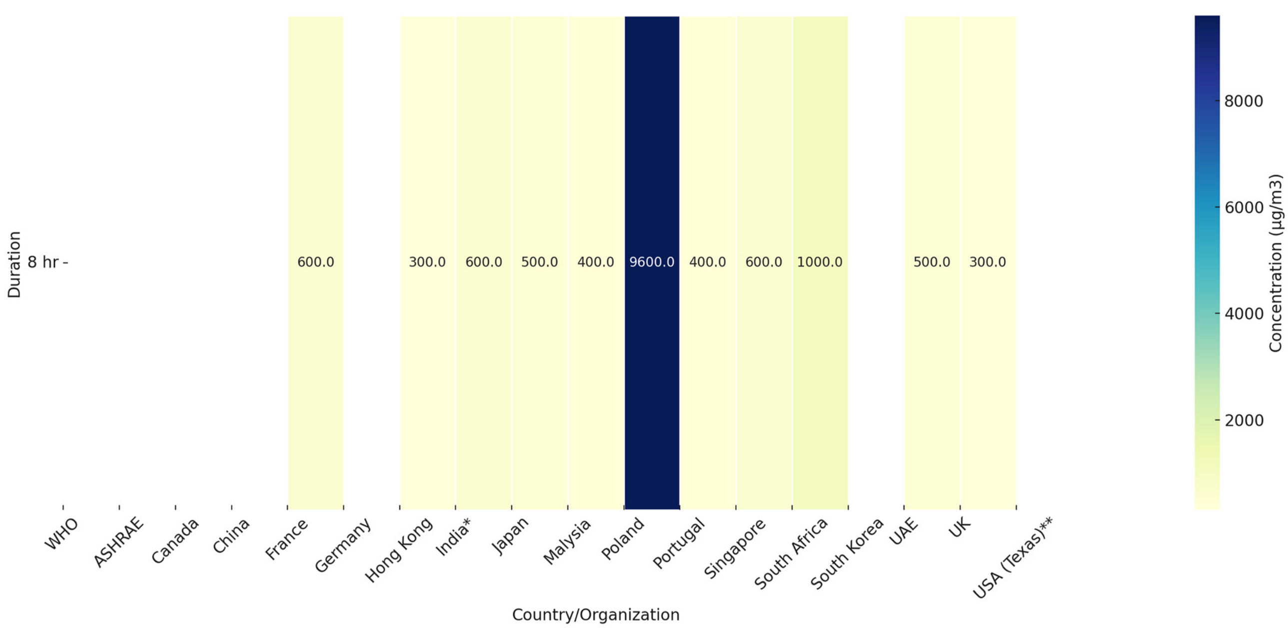

(D)

Figure 2: Continued.

environments and protecting human health. They serve as a model for those who seek to improve IAQ standards by implementing these measures.

The Environmental Protection Department (EPD) in Hong Kong ensures that indoor environments are healthy and safe for everyone. There is no IAQ law, although ventilation systems are regulated. They prefer self-regulation to handle IAQ issues' complexities and uncertainties. The EPD's IAQ Objectives define permissible indoor air contaminants. In 2019, the EPD amended the "Guidance Notes for the

Management of IAQ" in Offices and Public Places and developed a voluntary certification program for mechanical ventilation and air conditioning systems [64].

In India, there is a lack of IAQ-related federal and state laws. The Indian Society of Heating, Refrigerating, and Air Conditioning Engineers (ISHRAE) has provided a thorough guideline for indoor environmental quality. The ISHRAE Indoor Environmental Quality Standard (IEQ) for 2018–2019 governs IEQ management in Indian buildings [65]. The standard defines thermal comfort, IAQ, and visual and acoustic comfort as the four pillars of IEQ. IEQ threshold values designate each component as either Class A (Aspirational), Class B (Acceptable), or Class C (Just about acceptable). The typical is the same whether in a home without air conditioning or a large, air-conditioned building.

The global presence of IAQ regulations (voluntary or regulatory) from government and professional organizations, regardless of their legal or regulatory framework, such as in India, is depicted in Figure 3. Several countries, including but not limited to Australia, Belgium, Brazil, Bulgaria, the Czech Republic, Denmark, Estonia, Finland, Greece, Italy, Latvia, Lithuania, New Zealand, Norway, Russia, Slovenia, Spain, Sweden, Thailand, and the Netherlands (per IEQ Guidelines 2023) – primarily from the EU – have adopted guidelines that are either partial, specific to certain pollutants, or tailored to workplaces [66]. These regulations correspond to the similar IAQ pollutant and microenvironment earlier highlighted, and additional insights are not discussed.

Commonalities and differences

The dynamic landscape of IAQ standards and guidelines reveals universal principles and national distinctions. A shared commitment to protecting human health bonds nations together, resulting in a convergence in identifying vital pollutants and the significance of ventilation. Despite this, the diversity of IAQ regulations reflects the influence of local and cultural contexts, resulting in differences in the pollutants targeted, the scope of regulations, and the nuances of approaches to indoor air management. In our collective pursuit of healthier indoor environments, this fabric depicts the complex interplay between global cooperation and regional particularities.

The differences in IAQ regulatory regimes result from a complex interplay of factors, some of which include regional concerns about air quality, economic inequities, and cultural norms. However, despite these differences, there is a common ground that nations have in the way that they manage and improve IAQ. This thread of common ground serves as the unifying thread that runs across these discrepancies.

On the other hand, the foremost of these shared characteristics is a commitment to protecting human health through health-based standards. Globally, IAQ guidelines and standards are fundamentally designed to protect individuals from the adverse effects of substandard IAQ conditions. Organizations such as the WHO, the EU and its member states, the USEPA, and China's Ministry of Health exemplify this commitment [5, 15, 62,

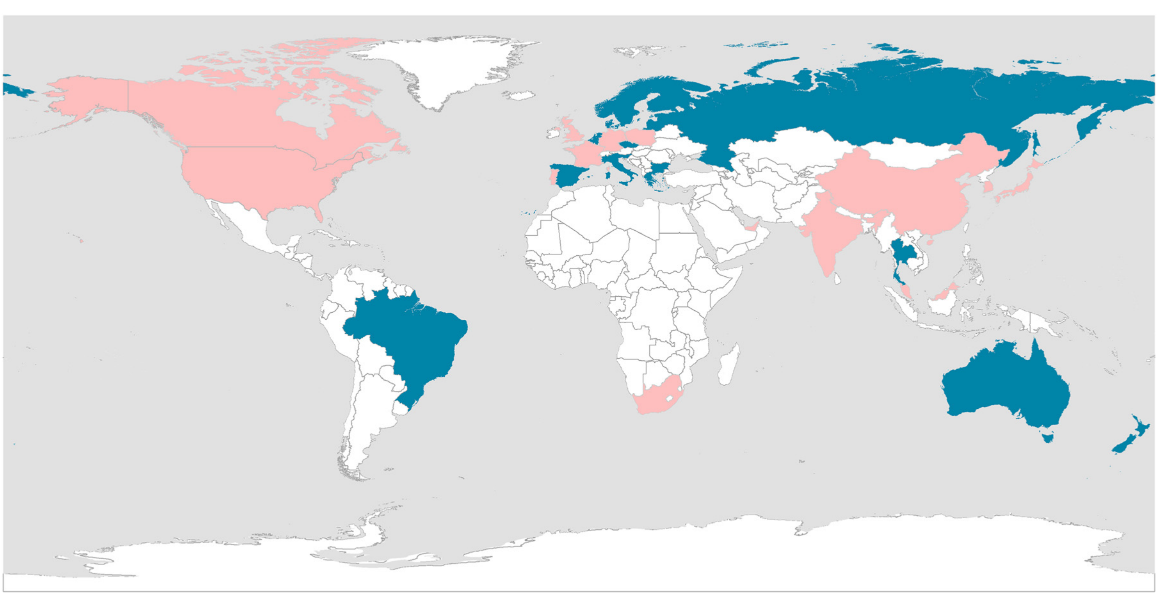

Figure 3: Map displaying countries with IAQ guidelines. Countries under the current study are highlighted in pink, while countries with at least one IAQ guideline are shown in blue.

67]. The global influence of significant pollutants on IAQ is widely recognized; this is especially true of particulate matter, volatile organic compounds, carbon monoxide, formaldehyde, and biological contaminants [19, 46]. Guidelines frequently specify minimal ventilation rates to minimize indoor pollutants, and ventilation is a well-known approach for regulating IAQ [10, 48, 49].

Divergence manifests itself in certain areas despite the harmony in pursuing IAQ development. Regional variation exists in the permissible levels of specific pollutants and their respective limits. For instance, China's IAQ standards include limits for Ammonia (NH_3), a substance not typically included in other nations' standards [62]. In addition, IAQ regulations differ in scope and enforceability. Certain nations, such as the United States, enforce stringent IAQ standards in the workplace through the Occupational Safety and Health Administration (OSHA), whereas others provide non-binding guidelines without legal enforcement. In addition, there are disparities in the emphasis placed on distinct indoor environments, with some nations placing a premium on schools or workplaces. The influence of cultural and geographic contexts is also indelibly marked on IAQ guidelines and standards. In climates characterized by colder temperatures, heating system concerns are prioritized, whereas air conditioning and humidity control concerns take precedence in hot-milder climates.

Gaps and challenges

While IAQ guidelines and standards have significantly improved indoor environments, this section will explore significant gaps and challenges worldwide.

The lack of comprehensive IAQ standards is a significant challenge in developing IAQ worldwide. Many countries only have standards for a few select pollutants or specific places, such as workplaces or schools. A limited approach can hinder efforts to address the various factors that affect IAQ and ensure healthy indoor environments for everyone [68]. It is essential to consider a broader range of pollutants, including biological contaminants, allergens, and environmental tobacco smoke (ETS). Additionally, IAQ standards should apply to different indoor settings, such as residential buildings, healthcare facilities, and public spaces, to protect people's health in various environments. Emerging challenges like energy-efficient buildings and new construction materials call for comprehensive standards adapting to indoor environments. Researchers, policymakers, and public health professionals should work to establish or update IAQ guidelines for various contaminants and environments to provide a healthy atmosphere for everyone [69].

The lack of standardized IAQ criteria significantly hinders IAQ advancement globally. This review explores the complexity and feasibility of achieving a more harmonized approach to IAQ regulations, considering the diverse legal, regulatory, and health implications across different regions. Without a universally accepted set of criteria, ensuring accurate and uniform global assessments of IAQ is challenging. Because of this, it may be more difficult to collaborate among nations and educate the public about the significance of IAQ. A global consensus on pollutant thresholds is necessary to overcome this impediment and create a minimum acceptable IAQ standard worldwide [70]. Harmonizing IAQ standards and providing comprehensive guidance for indoor contaminants and conditions requires international cooperation and organizations like the World Health Organization [5]. Countries may collaborate to research IAQ and create healthier indoor environments worldwide [71].

Multiple factors, such as limited resources, skilled personnel, insufficient institutional capacity and infrastructure, make enforcing and monitoring IAQ laws in developing countries challenging. Lack of public awareness of the significance of IAQ and its potential health effects is another factor that can impede compliance efforts. It is necessary to allocate sufficient resources, develop regulatory frameworks and institutional capacities, and devise strategies to enhance enforcement mechanisms. Education and outreach programs are essential to increase awareness of the significance of domestic air quality. These measures can ensure that all socio-economic groups have access to safe and healthful environments [5, 16].

Understanding the toxicological effects of indoor contaminants underlies comprehensive IAQ guidelines. The lack of toxicological evidence for many indoor contaminants makes it difficult to determine safe exposure levels for use [72]. Toxicological studies determine dose descriptors, explaining a contaminant's effects and dose. Hazard categorization and risk assessment require descriptors like the no-observed-adverse-effect level (NOAEL) and the lowest-observed-adverse-effect level (LOAEL). The changing pollutant concentrations and sources in indoor environments make it challenging [73]. Real-time IAQ monitoring and modelling are essential to solving this problem, but they have limitations and uncertainties [27]. People's different reactions to contaminants also complicate IAQ rules. Children, the elderly, and individuals with health issues may be more susceptible to certain contaminants. This variability makes it hard to create a general rule [74]. The toxicological aspect of setting thresholds is still vague despite improvements. Bridging these gaps is vital for creating thorough and effective IAQ guidelines that protect public health globally [75].

The existence of emergent pollutants that existing guidelines and standards may not adequately cover is one of the obstacles associated with IAQ management. Emerging contaminants, such as VOCs and other chemicals, may threaten inhabitants' health. Continuous research is vital to identify and comprehend these contaminants' causes and health impacts [70]. IAQ regulations must be regularly updated to incorporate these new contaminants and set suitable limitations. Policymakers and researchers can ensure that IAQ standards safeguard public health by monitoring the evolving indoor pollution environment [16].

Numerous IAQ regulations concentrate on specific contaminants. There may be synergistic effects when these contaminants interact. Multiple pollutants may increase or change health risks. More research is required to comprehend the effects of pollutants on human health. These studies can evaluate synergistic effects and health consequences [70, 71]. Researchers, policymakers, and IAQ management organizations should collaborate to understand pollutant interactions. Knowledge sharing, multidisciplinary research, and platforms for exchanging information can assist stakeholders in designing recommendations for pollutant interactions and devising effective strategies.

Globally, climate change significantly threatens IAQ. IAQ can be adversely impacted by rising temperatures, increased frequency of wildfires, dust storms and other climate-related impacts. Existing IAQ guidelines may not adequately account for the effects of climate change, which could result in increased pollutant concentrations and a decline in IAQ. For instance, climate change can impact IAQ by increasing the demand for cooling, reducing ventilation rates and air circulation in buildings, and confining pollutants indoors. Climate change-related dust storms and wildfires can pollute indoor air. Comprehensive research and guidelines that account for climate change are needed to address IAQ risks. Climate change factors in IAQ guidelines safeguard public health and improve indoor resilience. Adapting building design, ventilation, and air filtration in changing climates may improve IAQ [7, 76].

Recent research underscores the vital link between indoor air quality (IAQ) and public health, emphasizing the urgency of enhancing IAQ monitoring and standardization. Effective surveillance can facilitate early detection of contaminants, aiding in prompt health interventions, while robust guidelines can guide effective remediation across various indoor settings. Addressing these challenges requires collaborative efforts among IAQ experts, climate researchers, policymakers, and health organizations [77].

Prospects for advancing IAQ guidelines and standards in the future

Several implications for the future of IAQ standards and guidelines can be drawn from the difficulties and knowledge gaps in the current section:

- *Harmonization of Regional/Global Standards:* IAQ management could vary due to global IAQ norms and standards. Harmonization of IAQ standards should be pursued to address this issue. This harmonization should start regionally, where shared issues can be addressed. This single set of IAQ guidelines can be expanded globally to provide a global IAQ standard. Harmonization could improve IAQ management procedures worldwide.
- *Comprehensive and Inclusive Standards:* Future IAQ guidelines and regulations should attempt to be more all-encompassing, addressing not only traditional but also future sources of pollution, such as those produced by new technologies or materials: offices, classrooms, private residences, public transportation, and other community gathering places.
- *Enforcement and Compliance:* Implementing and enforcing IAQ standards can be difficult, particularly in areas with limited resources. To enhance compliance, future strategies should explore avenues for improvement, including education and awareness initiatives, as well as the reinforcement of legal and regulatory frameworks.
- *Consideration of Pollutant Interactions:* Interactions between contaminants are rarely considered in current standards. People are rarely exposed to a single pollutant in the real world, but rather a cocktail of several whose effects can complement or counteract one another. Guidelines considering the health effects of pollutant combinations require more research in this area.
- *Incorporation of Toxicological Evidence*: Comprehensive knowledge of indoor contaminants' toxicological effects is required to develop effective IAQ guidelines. As a result of the scarcity of in-depth toxicological data for several pollutants, future IAQ standards must prioritize incorporating these studies. It is of the utmost importance to consider the varying responses of distinct population segments, including children and the elderly. Given the dynamic nature of indoor environments, the importance of IAQ monitoring in real-time intensifies. By addressing these toxicological aspects, we can develop IAQ regulations that are both comprehensive and protective.

- *Equity Considerations:* The disproportionate impact of poor IAQ on already vulnerable populations has led to the recognition of IAQ as an environmental justice issue. Future IAQ recommendations and standards should make narrowing these gaps and providing people of all socioeconomic backgrounds with access to high-quality air a top priority.
- *Adapting to Climate Change*: IAQ will unavoidably be affected by the ever-changing climate, with its rising temperatures, increased humidity, and increased frequency of dust storms and wildfires. In light of these impending obstacles, future IAQ standards must demonstrate adaptability and responsiveness to these dynamic conditions.

Collaboration among researchers, policymakers, and stakeholders is essential in promoting good change as we seek improvements in IAQ guidelines and standards. Addressing these ramifications may pave the way toward safer, more beneficial indoor environments for current and future generations. If we work together, we can make a world where everyone can access clean air.

Urging action: advancing research, collaboration, and implementation

IAQ is complicated and challenging to manage. There is a great need for a worldwide coordinated effort to promote comprehensive studies, cooperation, and enforcement of IAQ standards.

Additional research is required to comprehend the health effects, interactions, and emerging pollutants from novel technologies and materials. In addition, understanding how climate change affects IAQ and adapting regulations to these changes requires extensive research. Also, harmonizing IAQ standards and guidelines requires the collaboration of international organizations, governments, researchers, and industry stakeholders on a global scale. A global consensus on minimum IAQ standards can be reached by exchanging research findings, best practices, and strategies for IAQ enhancement.

Governments and related authorities can increase compliance with IAQ rules and promote a healthier indoor environment by strengthening legal frameworks, allocating sufficient resources for enforcement, and managing public awareness initiatives. Architects, engineers, and building operators should follow some attainable criteria to consider IAQ at every building design and operation stage. Guidelines for enhancing IAQ should be based on considerations for equity to ensure that they benefit people of all socioeconomic backgrounds and geographic locations. A concerted effort in study, cooperation, and application can create indoor environments that are good for people's health and happiness.

Conclusions

Given the increasing issues around IAQ, this review emphasizes the imperative requirement for developing globally standardized and comprehensive guidelines. It aims to comprehensively evaluate current recommendations, focusing on advocating for a progressive perspective considering the many cultural, socioeconomic, and environmental contexts. Existing guidelines have improved, but discrepancies in approach and coverage remain due to diverse cultural, socioeconomic, and environmental contexts. Emerging pollutants, complex contaminant interactions, and climate change impacts compound the challenge of harmonizing global standards. Implementation faces hurdles like lack of awareness, limited resources, and local requirements. A forward-thinking approach is needed, focusing on understanding pollutants' health effects, incorporating emerging pollutants and pollutant interactions, and adapting to changing climate conditions. Collaboration between researchers, policymakers, health organizations, and stakeholders is essential to advance understanding, overcome implementation challenges, and promote widespread adoption of IAQ standards.

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