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Lessons learned from developing the worldwide IEQ guidelines database

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ABSTRACT

Indoor environmental quality (IEQ) guidelines and standards aim to ensure consistent, safe and healthy indoor spaces by providing clear benchmarks for air quality, lighting, thermal comfort and acoustics. Many countries and organizations have established their own IEQ regulations and standards or guidelines, but discrepancies in parameters, definitions, methods, and updating frequency often cause them to lag behind the latest scientific and technological advancements, potentially limiting their effectiveness. Researchers and practitioners advocate for the simplification and unification of IEQ guidelines, though risking overlooking geographical and cultural specificities. To address these challenges, and to help preserve and use current knowledge, an open database compiling worldwide IEQ guidelines was developed, ensuring equitable access to up-to-date information. The database covers four key IEQ domains, indoor air quality (IAQ), thermal comfort, acoustics, and lighting, as well as two related domains: ventilation and outdoor air quality (OAQ). Ventilation is a critical factor influencing most of the other IEQ domains, while OAQ guidelines are sometimes used in the absence of indoor-specific guidelines. Each of the six resulting tables includes both mandatory governmental regulations and voluntary guidelines, along with internationally recognized standards for broader relevance. This paper summarizes key lessons learned from database development and data collection efforts over the past five years. Practical IEQ guidelines and standards balance health and wellbeing outcomes with environmental, economic, and comfort considerations. Guidelines and standards can work best when science-based, adaptable to regional contexts, and structured with clear, measurable parameters, such as exposure limits, timeframes, and validated measurement methods. Collaboration between scientific research, technological advancements, and policy development can ensure regulations remain effective and up to date. To increase compliance and raise public awareness, the database consolidates and shares existing international guidelines and standards, supporting global alignment with best practices while accommodating resource constraints and regional specificities.

1. Introduction

Indoor environmental quality (IEQ) includes four main domains: indoor air quality (IAQ), thermal comfort, acoustics and lighting. The importance of IEQ on enhancing health, wellbeing and productivity, and promoting sustainability is not a new concept and has been recognized

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since ancient times.

The ancient Romans and Greeks recognized the benefits of airflow for expelling pollutants, demonstrating early awareness of indoor air's impact on health [1]. However, the Industrial Revolution marked a turning point, as urbanisation and coal use significantly deteriorated indoor air quality (IAQ) [2]. This decline had health implications as a result of being in indoor spaces, with hygiene pioneers such as Max von Pettenkofer in Germany and Elias Heyman in Sweden leading epidemiological studies in homes, schools, and workplaces, to identify causes of morbidity, and measured CO_2 as a proxy indicator for ventilation [3]. In 1853, Pettenkofer identified CO_2 as an indicator of occupant-produced noxious substances, proposing thresholds for comfort and wellbeing: 700 ppm for optimal air quality and 1000 ppm for comfort, laying early foundations for IAQ guidelines [4]. An early milestone in the field of ventilation was the formation in the U.S. of the American Society of Ventilation Engineers (now ASHRAE) and one of the ASVE's first orders of business in 1895 was to recommend a ventilation rate of 30 cfm (14 L/s) per person to control infections such as tuberculosis [5].

The 20th Century marked a turning point for IAQ, mainly driven by mine workers' occupational health. After the 1896 Tylorstown Colliery explosion, John Scott Haldane identified carbon monoxide (CO) buildup as the cause and suggested using birds or mice to detect exposure. Canaries became a lifesaving tool in UK mines by 1911, later adopted by the US and Canada, until their use was discontinued in the UK in 1986 [6]. Early concerns about indoor air focused on tuberculosis [7], until the 1952 London smog shifted attention to outdoor air. Some attention was refocused on indoor spaces after the 1973 oil embargo. To save energy, natural ventilation was reduced but led to the deterioration of IAQ. Modern indoor air science began with questions about indoor versus outdoor air hazards, with research carried out in Scandinavia before spreading to Europe, USA and globally [8,9].

In the 1980s–1990s, indoor air regulation lagged behind outdoor air regulation, which was based on monitoring, as the home environment was considered a private matter. The US Environmental Protection Agency (EPA) launched its first IAQ program in the 1980s, setting a precedent for guidelines and recommendations [10]. During the same period, global initiatives have advanced knowledge on IEQ. The European Collaborative Action (ECA) for 25 years fostered scientific collaboration, aiming to create healthy, sustainable buildings, by addressing not only indoor air pollution and biological contamination, but also energy use, ventilation and thermal comfort [11].

The COVID-19 pandemic recently highlighted the role of IAQ and environmental factors in disease transmission. However, mandatory IAQ standards (i.e., numerical limit values established and enforced by regulatory authorities to protect occupants' health and comfort) remain absent in many countries [12,13]. The lack of global consensus led to variations in national standards and guidelines, creating inconsistencies in air pollutants regulation and recommendations [14,15]. The WHO tried to address the gap by developing IAQ guidelines in 2010 [16], updated in 2021 [17]. The WHO provides health-based guideline values, supported by epidemiological and toxicological evidence for outdoor air pollutants, with the recommendation that they can be applied to indoor air pollutants. Outdoor air regulations influence indoor environments, often supporting WHO's air quality guidelines for both settings.

Ventilation remains crucial for maintaining good IAQ by removing and diluting indoor pollutants [18], with some of the first recommendations on building ventilation rates published in the 19th century [19]. Older buildings rely on natural ventilation through open windows or structural gaps. Based on the stack effect with vertical channels, indoor spaces can also be ventilated. However, newer construction technologies with energy-efficient, airtight designs usually require mechanical ventilation, which also provide more controlled intake of outdoor air, with the possibility to filter outdoor air pollutants before introducing air to indoor spaces.

Thermal comfort in indoor environments has long been acknowledged as crucial for human well-being. In 1970, Fanger introduced quantitative methods to assess thermal comfort, developing the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) metrics [20]. These metrics evaluate thermal environments using six factors: air temperature, radiant temperature, humidity, air velocity, clothing insulation, and metabolic rate. These metrics became cornerstone standards globally, offering a way to predict thermal sensation on a seven-point scale and estimate the percentage of people likely to experience discomfort in given conditions.

Thermal comfort standards nowadays include adaptive models recognising occupants' ability to acclimate to different thermal conditions, especially in naturally ventilated buildings. This evolution reflects growing understanding that comfort perceptions are dynamic and influenced by factors such as outdoor climate, seasonal expectations, and individual control over the environment. Current guidelines distinguish between heating and cooling seasons, usually recommending winter temperatures of 20–22 °C and summer temperatures of 23–26 °C. Building-specific guidelines can be applied to diverse populations, often advising higher temperatures for vulnerable groups, like the elderly and children.

Acoustic quality also plays a vital role in IEQ, influencing concentration, communication, and overall well-being. Ancient Greeks and Romans pioneered architectural acoustics, with open amphitheatres being the earliest testaments of design of effective communication in public buildings [21]. Modern acoustics emerged in 1929 with the foundation of the Acoustical Society of America (ASA) [22], with key advancements including the Journal of the Acoustical Society of America. A committee on Acoustical Standardization was appointed in December 1929. First standards for acoustical terminology and noise measurements were approved in 1936. Throughout the years, the ASA has played a crucial role in advancing the knowledge of acoustics. The International Organization for Standardization (ISO), established in 1947, plays an important role in global standard harmonization. A notable contribution to acoustics is the ISO 1996 series, guiding environmental noise description, measurement, and assessment. Subsequent standards were developed, covering areas such as building acoustics and noise control.

Finally, lighting is another critical domain. Humans have long relied on indoor artificial light sources for extended daylight and security, with evidence of use dating back 70,000 years. Innovations over the past two centuries (gas lamps, low-pressure sodium lamps, high-pressure mercury lamps, and LED lamps), enhanced lighting efficiency, extended service life while reducing thermal power consumption. Early indoor lighting regulations for commercial buildings emerged in the 1930s, as manufacturer recommendations tied to office functions. Post-World War II advancements, like fluorescent lamps, significantly raised lighting levels (Illuminating Engineering Society, 1942, 1947). Low electricity prices in the late 1950s increased recommended levels further, reversed only in the 1980s due to the oil crisis [23].

National and international societies, institutions, associations and national committees on illumination shaped foundational indoor lighting standards. The International Commission on Illumination (founded in 1913) publishes technical reports and notes, and international standards later adopted by ISO and the International Electrotechnical Commission (IEC) [24]. Current standards and guidelines for interior lighting in most countries are linked to construction law and electrical installation requirements, with widely applied provisions like CEN - EN 12464–1, specifying minimum lighting parameters (e.g., illumination, unified glare ratio, and colour rendering index) for various indoor workplaces (e.g., hotels, schools, hospitals).

History has demonstrated that developing IEQ guidelines is important for protecting human health and well-being. These guidelines provide actionable frameworks for designing, operating, and controlling systems to create safe, healthy, comfortable, and productive indoor environments. They address challenges ranging from ventilation and indoor air pollution control to thermal, acoustic, and visual comfort. By establishing these standards, occupants' health and wellbeing can be protected, while also promoting energy efficiency and sustainability.

However, guidelines and standards are often scattered or inaccessible. Because regulations are typically written in the national language (s) of each country, accessing the information can be difficult. Besides, older documents might not be digitalized yet or are available only in scanned format making the indexation of the content harder. Without clear, up-to-date references, researchers, policymakers, and designers can struggle to choose and apply best practices effectively.

To address those challenges, the International Society of Indoor Air Quality and Climate (ISIAQ) Scientific and Technical Committee (STC) 34 has been developing, since 2020, an open database (https://ieqguidelines.org/) gathering worldwide IEQ guidelines and standards [14]. This initiative reviews numerical guidelines, shares insights, and offers recommendations. The development of the IEQ guidelines database was considered a critical step in advancing IEQ policy, overcoming language barriers, and addressing outdated information and regional disparities. The aim of this paper is to summarize key lessons learned from the development of the IEQ guidelines database and data collection efforts over the past five years. The ultimate goals are to assess existing information, identify knowledge gaps, and provide recommendations for future improvements in IEQ guidelines.

2. IEQ guidelines database content

2.1. Database overview

ISIAQ IEQ guidelines database [25] is divided into six distinct tables containing guidelines and standards for six domains: IAQ, outdoor air quality, thermal comfort, acoustics, ventilation and lighting. The structure of each table, i.e. the number of fields or columns, varies, depending on necessity to describe the guidelines. Overall, a guideline can be defined by:

- A domain: indoor air quality, outdoor air quality, thermal comfort, acoustics, lighting or ventilation. Each domain is represented by a separate table.
- A parameter: it can be directly measurable, e.g. temperature, or it can be a composite measure of multiple other parameters, e.g. PMV.
- A rule: e.g. inferior, superior or equal to a value, in between two values.
- An exposure time, e.g. 1 h, 24 h, or a year.
- A source of exposure, e.g. environmental noise.
- An applicable population, e.g. elderly people.
- An applicable environment, e.g. school building.
- An applicable period, e.g. during summer.

The compiled database includes guideline values from 48 countries and 4 international organisations, mostly from Europe and Asia (Fig. 1). Among the six domains in the database, IAQ is the most developed, featuring data from 40 countries (Fig. 2), followed by acoustics and thermal comfort, which have data from over 20 and 17 countries respectively.

From the total of 283 parameters included in the database, the majority are related to indoor air quality, followed by outdoor air and acoustics. (Fig. 2).

The focus was on collecting the latest available and applicable guidelines, although updates have occurred during the development of the database. A specific column for each table allows for distinguishing between current and historical guidelines. More than 40 % of the reference materials have been published between 2010 and 2025 (Fig. 3).

Guidelines and standards documents are classified into four distinct categories:

- Government Regulation: established by a government authority, enforced through various means (e.g. inspections, licensing, penalties for non-compliance, …)
- Government Guideline/Standard: non-binding recommendations or advisory documents issued by a government authority to provide guidance on best practices, standards, or procedures
- Non-governmental Guideline/Standard: developed and maintained by organizations or entities outside of governmental authorities (e.g. industry associations, professional bodies, or independent standard-setting organizations)
- International Guideline/Standard: globally recognized guidelines and specifications developed to ensure safe indoor environments across different regions and countries (e.g. World Health Organization)

The authors acknowledge that International Standards could be further divided into commercial and non-commercial standards. Building certification organizations and companies are usually creating their own set of guidelines built on existing national or international standards. They tend to use different levels, classes, or tiers covering basic health considerations but pushing toward stricter guidelines to ensure occupants' comfort and productivity. The current database focuses on non-commercial standards. Guidelines are often separated into categories such as residential, non-residential, and occupational settings. Occupational exposure limits (OELs) are set at higher concentrations and are not suitable for the general population. These limits are out of scope of the IEQ guidelines database. A detailed description and key takeaways of the data for each domain are provided in the following sections.

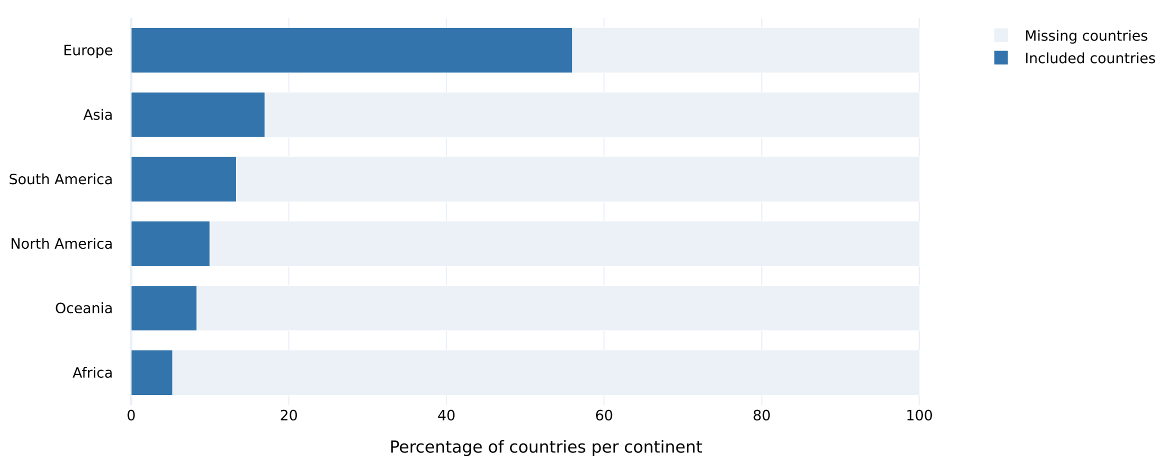

Fig. 1. Percentage of countries per continent represented in the IEQ guidelines database.

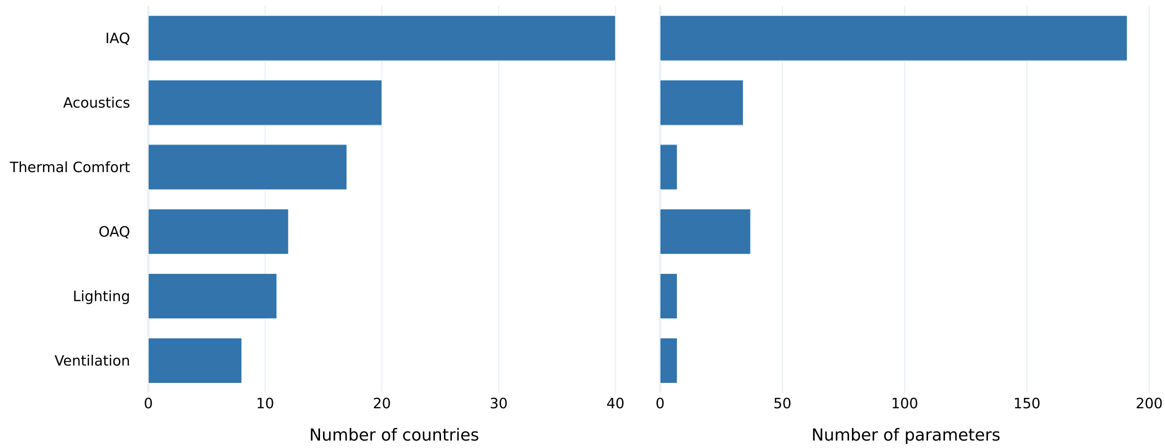

Fig. 2. Distribution of countries and parameters per domain.

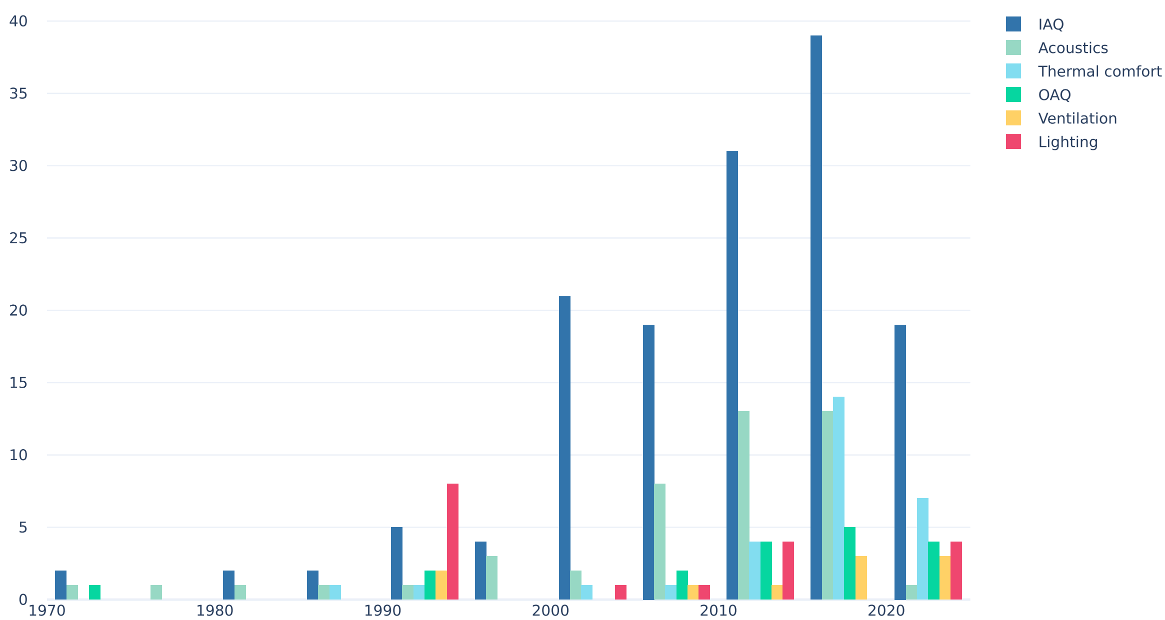

Fig. 3. Number of guideline documents published over time.

2.2. Indoor air quality

IAQ is affected by emissions from various sources that can have an impact on occupants' physical and mental health and wellbeing. Some national IAQ guidelines and standards refer to health relevant air pollutants emitted from indoor sources. These include carbon monoxide (CO), nitrogen dioxide (NO_2) and particulate matter (PM) from fuel combustion for cooking or heating, formaldehyde (HCHO) from building and construction materials as well as furnishing, radon (Rn) from ground sources, and carbon dioxide (CO_2) from human respiration as an indicator of ventilation.

The WHO (2010) set health-based guidelines for indoor air pollutants that are commonly found in indoor spaces around the world, such as CO, NO_2, Rn, HCHO, and benzene (C6H6), but few countries have adopted them. In 2021, WHO recommended aligning indoor and outdoor air regulations, though this remains largely unimplemented [17]. The WHO (2021) guidelines cover only CO, NO_2, O_3, PM_{10}, $PM_{2.5}$, and sulphur dioxide (SO_2), but WHO (2010) guidelines for other chemicals and radon remain valid and should still be considered. It is worth noting that there are existing national guidelines or standards for pollutants, which are not included in the WHO guidelines.

The WHO also published guidelines on dampness and mould, recognising microbial contamination as a significant aspect of indoor air pollution, with adverse impact on respiratory and mental health [26]. This arises from bacteria and fungi, particularly mould, thriving in damp indoor conditions. The WHO outlines conditions favouring mould growth and strategies to prevent the growth on internal surfaces and building structures indoors. A comprehensive guidance on understanding and addressing the health risks of damp and mould in the home was recently published in England, following the tragic death of a 2-year-old boy from prolonged exposure to mould in his home [27]. This guidance is primarily aimed at social and private rented housing providers and their workforce [27].

Some countries have adopted the health-based guideline values proposed by health organisations, including WHO, which were derived from toxicological and epidemiological evidence on the health effects associated with exposure to air pollutants indoors, while others have non-health-based guidelines that consider practical aspects such as energy efficiency. Some countries also specify limit values for short-term exposure (e.g., 15 min, 1 h), while others focus on long-term exposure (e.g., 24 h, 1 year).

In some countries, IAQ guidelines are enforced by law, making them mandatory. For example, Taiwan has implemented the Indoor Air Quality Act, making IAQ guidelines enforceable. In others, guidelines are voluntary and serve as recommendations. Based on the authors' current understanding, not all countries have updated their guidelines or standards regularly [14,18].

Proposals have been made to standardize and harmonize IAQ guidelines globally, particularly in public buildings [13]. However, these guidelines may be more effective if adapted to local factors such as climate, risk acceptability, available technologies, and economic considerations. These factors contribute to the complexity and diversity of IAQ regulations and guidelines worldwide.

2.3. Outdoor air quality

Outdoor air influences indoor pollutant levels, especially in buildings with natural ventilation systems, where pollutants can directly enter through openings such as windows and doors. This effect is also observed in buildings with mechanical heating, ventilation, and air conditioning (HVAC) systems. Although HVAC systems use filters to reduce pollutant entry, their effectiveness depends on the filter type, maintenance, and the overall design of the system. As a result, many researchers studying IAQ compare indoor pollutant concentrations with outdoor levels or calculate the indoor-to-outdoor (I/O) ratio [28,29]. This approach helps quantify the influence of outdoor air and assess the effectiveness of filtration or mitigation strategies, but it has not been commonly used in the guidelines or standards.

The WHO (2021) guidelines reflect updated health impact considerations, also providing interim targets and timelines for achieving the target levels. Compared to the previous 2005 WHO guidelines, the annual average guideline for $PM_{2.5}$ has been reduced from 10 µg/m^3 to 5 µg/m^3, while the 24-hour average has been reduced from 25 µg/m^3 to 15 µg/m^3. Similarly, for PM_{10}, the annual average has been reduced

Table 1
Regulations for pollutants recommended by WHO in indoor and outdoor air in selected countries [25].

Country	NO_2		Ozone		CO		SO_2	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Brazil		320 µg/m^3 (1 h) 100 µg/m^3 (1 y)		160 µg/m^3 (1 h)		40,000 µg/m^3 (1 h) 10,000 µg/m^3 (8 h)		365 µg/m^3 (24 h) 80 µg/m^3 (Primary) (1 y)
Canada	11 ppb (24 h) 90 ppb (1 h)		40 µg/m^3 (8 h)		10 ppm (24 h) 25 ppm (1 h)			67 ppb (10 min) 5 ppb (1 year) 70 ppb (1 h)
Finland		40 µg/m^3 (1 y) 200 µg/m^3 (1 h)		120 µg/m^3 (8 h)	7 mg/m^3 (24 h)			20 µg/m^3 (1 y) 125 µg/m^3 (24 h) 350 µg/m^3 (1 h)
Ghana		150 µg/m^3 (24 h) 250 µg/m^3 (1 h)						50 µg/m^3 (24 h) 520 µg/m^3 (1 h)
India		80 µg/m^3 (24 h) 40 µg/m^3 (1 y)		180 µg/m^3 (1 h) 100 µg/m^3 (1 y)		4 mg/m^3 (1 h) 5 mg/m^3 (8 h)		80 µg/m^3 (24 h) 50 µg/m^3 (1 y)
Italy						10 mg/m^3 (8 h)		350 µg/m3 (1 h) 125 µg/m3 (24 h)
Poland		40 µg/m^3 (1 y) 200 µg/m^3 (1 h)	100 µg/m^3 (8 h)		3 mg/m^3 (24 h) 10 mg/m^3 (30 min)			20 µg/m^3 (24 h) 125 µg/m^3 (24 h) 350 µg/m^3 (1 h)
South Africa	40 µg/m^3 (1 y) 200 µg/m^3 (1 h)			120 µg/m^3 (8 h)	7 mg/m^3 (24 h) 10 mg/m^3 (8 h) 35 mg/m^3 (1 h) 100 mg/m^3 (15 min)		20 µg/m^3 (24 h) 500 µg/m^3 (10 min)	
Sweden	0.5 ppm [Non-residential]		200 µg/m^3 (0.1 ppm) [Non-residential]			10 mg/m^3 (8 h)		200 µg/m^3 (1 h) 100 µg/m^3 (24 h)
UK	40 µg/m^3 (1 y) 200 µg/m^3 (1 h) [NTE 18]			100 µg/m^3 (8 h) [NTE 10]	10 mg/m^3 (8 h) 30 mg/m^3 (1 h) 60 mg/m^3 (30 min) 100 mg/m^3 (15 min)			20 µg/m^3 (winter) 20 µg/m^3 (1 y) 125 µg/m^3 (24 h) [NTE 3] 350 µg/m^3 (1 h) [NTE 24] 266 µg/m^3 (15 min) [NTE 35]
WHO guidelines	40 µg/m^3 (1 y) 200 µg/m^3 (1 h)	200 µg/m^3 (1 h) 25 µg/m^3 (24 h) 10 µg/m^3 (1 y)		100 µg/m^3 (8 h) 60 µg/m^3 (Peak season)	7 mg/m^3 (24 h) 10 mg/m^3 (8 h) 35 mg/m^3 (1 h) 100 mg/m^3 (15 min)	100 mg/m^3 (15 min) 35 mg/m^3 (1 h) 10 mg/m^3 (8 h) 4 mg/m^3 (24 h)		500 µg/m^3 (10 min) 40 µg/m^3 (24 h)

[NTE X] = Not to be exceeded more than X times a year from 20 μg/m³ to 15 μg/m³, and the 24-hour average from 50 μg/m³ to 45 μg/m³. For O_3, the 8-hour average during peak seasons has been reduced from 100 μg/m³ to 60 μg/m³. For NO_2, the annual average has been significantly reduced from 40 μg/m³ to 10 μg/m³ , while the 1-hour average remained unchanged at 200 μg/m³. For SO_2, the 24-hour average has been revised from 20 μg/m³ to 40 μg/m³, and for CO, the 24-hour average is now set at 4 mg/m³. More stringent guidelines are reflecting growing evidence of the health risks associated with air pollution.

Currently, the database has data for outdoor air pollutant levels from 12 countries, including regional guidelines: the United Kingdom (UK) has additional information specific to Wales, England, Scotland and Northern Ireland (as of early 2025). The regulations for the UK, Scotland, England, Wales, and Northern Ireland were set when the UK was still part of the EU, so all levels and regulations comply with EU law.

EU regulations are intended to apply to all 26 Member States; however, the database currently contains confirmed data from only four EU countries—Finland, Italy, Poland, and Sweden. EU regulates the levels of CO, NO_2, O_3, PM_{10}, $PM_{2.5}$, and SO_2, all of which are also covered in WHO guidelines. However, the specific pollutant limits in some countries differ from current WHO guidelines, primarily because certain national regulations were established years ago and have not yet been updated. Table 1 presents national guidelines for these pollutants in both indoor and outdoor environments for selected countries.

The pollutants listed in Table 1 are regulated outdoors in most countries present in the database. However, not all of them are regulated indoors. For example, SO_2 is regulated in indoor air only in South Africa, where there is no recommended level for this pollutant in outdoor air. A similar situation exists with ozone: it is regulated outdoors in Brazil, for instance, but not indoors, whereas in Canada it is regulated indoors but not outdoors. An additional challenge when comparing data is the difference in averaging times, which vary. They may be based on one year, one hour, 24 h, or even 8 h. For example, ozone in outdoor air in Finland is regulated based on an 8-hour average. These different approaches benefit from special attention and may be more effective if unified based on health impacts and exposure time.

Both PM_{10} and $PM_{2.5}$ guidelines are recommended by WHO, and they are usually regulated in all countries included in the database. Specifically, PM_{10} is regulated in outdoor air in Finland, Ghana, India, Nigeria, Poland, Sweden, Thailand, Scotland, South Africa and the UK. $PM_{2.5}$ is regulated in the same countries except South Africa.

Considering the current knowledge about impact of particles, especially ultrafine particles, the regulations of $PM_{2.5}$ in both indoor and outdoor air are crucial. Some countries have listed more pollutants, which is the result of country regulations before they joined the EU, or because of particular interests in certain pollutants, e.g., lead, cadmium, nickel, arsenic, or benzene.

The data for non-European countries contains, apart from UK and UK members, information for Brazil, Canada, Ghana, Nigeria, South Africa, India, and Thailand. Countries outside Europe often regulate many more substances, e.g. Thailand regulates the substances in outdoor air, which are typically regulated in indoor air, such as trichloroethylene, dichloromethane, tetrachloroethylene, 1,3-butadiene, and vinyl chloride. In turn, Nigeria regulates both indoor and outdoor formaldehyde, which is a typical pollutant indoors.

2.4. Thermal comfort

Thermal comfort represents one of the fundamental aspects of IEQ, directly influencing occupant health, wellbeing, productivity, and overall satisfaction within the built environments [30]. Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [31] highlighting its subjective nature that encompasses both physiological responses and psychological perceptions. The database currently includes 17 countries, primarily from Europe. Analysis reveals several key patterns regarding 1) parameters and measurement approaches, 2) seasonal variations and building types, 3) adaptation and acceptability, 4) regulatory strength, 5) regional variations, and 6) health-based vs. comfort-based approaches.

Most thermal comfort guidelines use operative temperature as the primary parameter, with some incorporating air temperature as the main metric. Additional parameters used include relative humidity, air velocity, and radiant temperature asymmetry, which contribute to a more comprehensive assessment of thermal comfort. Most of countries distinguish between a winter heating season and a summer cooling season, with recommended indoor temperatures typically ranging from 20 to 22°C and 23–26°C, respectively. The data shows differentiation by building type, with specific guidelines for various building categories reflecting different thermal needs.

The concepts of PMV and PPD, developed by P.O. Fanger, have become cornerstone metrics for evaluating thermal comfort standards globally. These metrics provide a quantitative approach to assessing thermal comfort that considers six critical factors: air temperature, mean radiant temperature, humidity, air velocity, clothing insulation, and metabolic rate [20]. The PMV model predicts the mean thermal sensation vote on a seven-point scale from -3 (cold) to + 3 (hot), with 0 being neutral. The PPD estimates the percentage of people likely to feel thermally uncomfortable. Multiple countries have incorporated the PMV and PPD indices, demonstrating the international adoption of these research-based thermal comfort models.

An emerging trend is the incorporation of adaptive comfort models, which account for occupants' adaptability to different thermal conditions based on outdoor temperatures, particularly in naturally ventilated buildings. The ASHRAE Standard 55, UK Building Bulletin 101, and National Building Code of India, include adaptive models that allow for wider temperature ranges when occupants have control over their environment. A majority of the countries include specific ranges for either wider temperature bounds acceptable to 80 % of occupants or narrower temperature bounds acceptable to 90 % of occupants. This approach recognizes the impossibility of satisfying all occupants with a single temperature setting and provides flexibility while ensuring reasonable comfort for the majority. The database also reveals a distinction between health-based approaches, which prevent adverse effects through narrower acceptable ranges, and comfort-based approaches, which prioritize occupant satisfaction with greater flexibility.

Implementation strength varies significantly between countries, with Northern European nations generally having more stringent and legally binding thermal comfort requirements. Regional variations reflect climatic differences—northern countries emphasize minimum temperatures while warmer regions focus on maximum temperatures and cooling strategies. The database also reveals a distinction between health-based approaches, which prevent adverse effects through narrower acceptable ranges, and comfort-based approaches, which prioritize occupant satisfaction with greater flexibility. Challenges in standardization include diverse measurement methodologies and seasonal definitions. A notable limitation is the insufficient integration with other IEQ factors despite growing evidence of interactive effects between thermal conditions and air quality, acoustics, and lighting.

To summarize, thermal comfort regulations and guidelines or standards represent a complex balance between physiological needs, psychological preferences, energy efficiency considerations, and practical implementation challenges. The database reveals both commonalities and significant variations in approaches across different countries and regions, highlighting the need for continued refinement that can address climate diversity, occupant adaptability, and integration with other IEQ factors for a more holistic approach to building design and operation.

2.5. Acoustics and noise

Environmental noise is among the top environmental risks to health [32]. The WHO has published several documents recommending noise limits to safeguard human health. These documents and their associated limit values are summarized in Table S1.

Acoustic comfort, in terms of indoor spaces, is affected by the way sound behaves within and travels between those spaces. Metrics used to assess this behaviour of sound include reverberation time, sound insulation performance specifications, values for speech privacy and speech intelligibility, and levels of perceptible vibration. This wider assessment of acoustic comfort is currently out of the scope of the IEQ database, which instead focuses on limits for noise levels inside or just outside buildings. These limits have been defined as a result of exposure studies and to protect human health.

Noise limits for 21 countries, 19 of which are European, are included in the database (Fig. 4). Among those, seventeen countries have governmental regulations, five have governmental guidelines, and seven have non-governmental guidelines or standards regarding noise level. The database consists of 20 countries with residences as the applicable environment and twelve countries with values for public environments (offices, schools, health care, and industrial facilities). Environmental noise (from transportation or industry) is considered in all 21 countries and building service noise in four countries. Ten countries give penalties for specific noise characteristics. In the database, 21 countries consider external noise levels, with ten countries providing values for noise levels indoors. The table consists of a total of 465 regulations or guideline values. The work is ongoing and there are potentially other countries which have noise regulations or guidelines but are not yet included in the database.

Of the 21 countries included in the database, 13 have one or more values that are in line with WHO noise guidelines [32–34]. There are many additional parameters, such as road traffic noise during daytime, which are difficult to directly compare to the WHO Lden values averaged over the day, evening, and night. It has previously been assumed in many country-specific guidance documents that the indoor noise limits would be achieved by designing the building envelope to mitigate external noise at any level. In naturally ventilated buildings this usually assumes that sound coming through an open window would be attenuated by approximately 15 dB, however this can be an oversimplification which leads to excessive noise levels indoors. The most recent guidelines published by the WHO (2018) specify only outdoor noise limits, indicating a move towards more control of noise at source.

The focus of this database has been to collect prescribed or recommended limits for sound level across different countries. Future work could include recording other acoustic comfort-related metrics, as well as investigating how acoustic comfort is defined and assessed in IEQ studies. Sound level, however, though it is easy to measure, and it is the most common acoustic metric assessed in IEQ studies, is not the only metric relevant to acoustic comfort, productivity, or to health. In addition to vibration, building and room acoustics' metrics are highly relevant, and these include reverberation time, noise specifically from building services (quantified in terms of Noise Rating level), sound insulation of the building envelope or of separating internal partitions, speech privacy factor (SPF) or speech privacy potential (SPP), speech transmission index (STI) for speech intelligibility, and distraction distance.

2.6. Lighting

Spaces in residential buildings and workplaces are provided with internal lighting from two sources or their combination, i.e. daylight and artificial (electric) light. Designing electric lighting must often assume its use as the only source of light indoors. This is often due to shorter days in winter and limited access to daylight in most interiors in buildings. Lighting in buildings can fulfil several functional and decorative/aesthetic tasks: it ensures proper perception of the surroundings (visual comfort), affects the mental and physical state as well as health of users, and regulates the circadian rhythm. The guidelines and standards in the database only focus on visual comfort, omitting other aspects.

The database currently includes lighting guidelines and standards for 11 countries. Lighting, as an IEQ parameter, is most often regulated in the form of national standards, government regulations (national building code, labour law, decrees) and recommendations of international lighting associations and organisations, e.g. ICE. The recommended or required values of individual lighting parameters are given as minimum. They are intended to protect eyesight and provide an appropriate work area. However, in most countries, standards are not mandatory, and their use is a voluntary practice among designers. The regulations are common to both newly designed, modernized, and existing buildings.

The basic design parameters defining the lighting environment in the regulations include illuminance, luminance distribution, glare, light direction, colour rendering, light colour appearance, and flicker. The only parameter that is present in the guidelines and standards of all countries in the database is the illuminance, measured as Lux (lx). Moreover, the recommended values are similar and range from 100 lx to 1000 lx, with an average of 300 lx – 500 lx. Another photometric parameter in regulations is the colour rendering index (CRI, sometimes referred to as Ra) with a maximum value of 100. For lighting interiors in

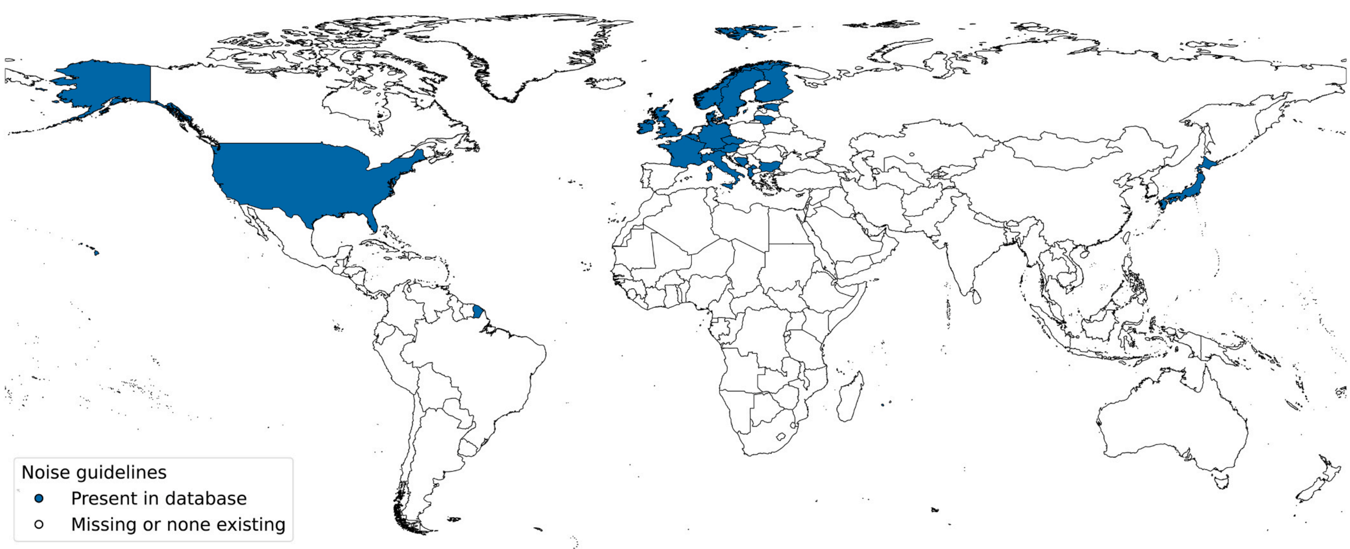

Fig. 4. Countries with noise guidelines present in the database.

which people spend all their time at work, light sources that ensure natural and faithful rendering of the colours of objects and human skin, i.e. with a CRI of no less than 80, should be used. Lighting uniformity in the visual task area should be as good as possible, but not less than 0.7. However, the uniformity of illumination in the immediate surroundings cannot be lower than 0.5. Typical values of this factor in the regulations available in the database are in the range of 0.4–0.7. The limitation of unpleasant glare is sufficiently effective by limiting the value of the unified glare index (UGR) which takes variable values from 16 to 28.

There are different approaches to specifying recommended values for indoor lighting conditions around the world. In European countries, Japan, China, Brazil, India, Panama, and Russian Federation they are assigned to categories of industrial and non-industrial rooms, such as offices, preschools, educational buildings, hospitals, airports, means of transport, and theatres. In other countries (Bolivia, Mexico), the type of work and the visual requirements determine the illuminance conditions.

In most European countries, including all European Union members, the harmonized provisions of the EN 12464–1 are used. Its main objective is to standardize the requirements that affect visual comfort and efficiency, and thus the quality of working conditions. If the work performed is short-term or the work items are large, the designer has the right to reduce the lighting requirements. The designer may also increase these requirements if the visual work performed is extremely difficult, the employees' vision is worse than normal, or the visual work items are exceptionally small or have a low contrast value.

The current guidelines and standards on interior lighting lack a special approach to the lighting of workplaces and places where elderly people spend their time. In developed countries, the percentage of elderly people in society is increasing, while life expectancy and the active participation of elderly people in the labour market are simultaneously increasing. With age, the visual organ loses its elasticity, and its structures become more susceptible to various types of diseases, which consequently leads to a deterioration in the quality of vision. The elasticity of the lens is lost, which causes difficulties with close-up vision; contrast is reduced: colours become less distinct and the contours of objects less sharp. Elderly people also have a reduced ability to adapt to changing lighting conditions and, as a result, seeing in the dark or bright light becomes more difficult [35].

Another issue for lighting indoor spaces is the global demand for energy savings that tend to reduce indoor lighting levels. Interior lighting accounts for 30 % of electricity consumption in buildings. This demand for energy savings creates conditions that do not fully support human well-being [36]. The issue of using blue light sources indoors in terms of their impact on human circadian rhythm also requires more detailed regulation [37]. Additionally, there are still no more precise guidelines for greater use of daylight in buildings when local conditions allow it [38]. There also may be value in considering similar guidelines and standards for single-family and multi-family residential buildings, especially for spaces where residents spend the most time.

2.7. Ventilation

To maintain good IAQ in buildings, pollutants need to be diluted by supplying outdoor air. Pollutants may consist of human bio-effluents, emissions from building materials, furniture, and occupants' activities such as cooking and burning candles. In total 164 ventilation parameters for 8 countries are currently included in the database. Additionally, ASHRAE 62.1 guidelines provide ventilation standards applicable in various indoor spaces, of which 15 are currently included in the database. The work of collecting worldwide ventilation guidelines is ongoing and there may be other countries with ventilation guidelines that have not yet been included in the database.

Regarding ventilation measures, different units are being used, which makes it difficult to compare ventilation standards between countries. The most used unit is the (minimum) ventilation flow with outdoor air. Part of Singapore's governmental standard for ventilation is expressed in air changes per hour (ACH), which is defined by the total airflow divided by the volume of the space. These requirements are for mechanical ventilation in non-air-conditioned buildings in Singapore and range from 6 ACH for offices up to 20 ACH for commercial kitchens. Most standards specify ventilation rates in terms of flow rate per person. However, a small portion of these standards is expressed as flow rate per unit of floor area. Two countries, the Netherlands and Belgium, have established fixed ventilation values for wet rooms such as toilets, bathrooms, and kitchens. In the Netherlands and Belgium, there are specific requirements for the minimum percentage of outdoor air and the maximum percentage of overflow from areas like bedrooms. Additionally, in some countries, such as Lithuania, Hong Kong, and the Netherlands, there are requirements for the maximum air velocity due to ventilation. Typically, air movement may not exceed 0.2 m/s.

When emissions other than human bio-effluents are minimal and the indoor air meets the WHO air quality guidelines [16], the EU HealthVent project [39] recommends a base ventilation rate of 4 L/s per person. In the context of COVID-19, the WHO has published a minimum ventilation recommendation for both residential and utility buildings of 10 L/s per person [40]. Morawska and colleagues proposed 14 L/s per person as a minimum for public buildings [13].

The ventilation rate per person in the database ranges from 2.5 L/s per person (Thailand) up to 13.2 L/s per person (Singapore). Most of the entries are around 7 L/s per person. Among the entries in the database, only specific rooms with high intensity activities, such as gyms and dance halls, or those with indoor pollution sources, such as beauty salons, have ventilation requirements higher than 10 L/s per person. In Belgium, office spaces are legally required to comply with a flow rate higher than the WHO 2021 recommendation. Currently, none of the database entries meet the Morawska et al. (2024) recommendation of 14 L/s per person.

3. Discussion

The study reviewed IEQ guidelines across 48 countries, with significant geographical and population coverage. However, the varying publication years mean some nations' guidelines are based on potentially outdated information. Air quality guidelines both indoors and outdoors, are more prevalent than other guidelines such as those for biological safety. Diverse units, averaging times, and sampling methods complicate comparisons across countries. Additionally, the objectives of the guidelines, whether targeting health, comfort, or environmental concerns are frequently ambiguous.

Although the IEQ guidelines database includes data from over 40 countries, this remains a relatively small number compared to the total number of countries worldwide and is even more limited when considering those with specific IEQ legislation. For instance, the database currently represents only three countries from Africa and two countries from South America, as shown in Fig. 5. On the other hand, the geographical and population-based coverage appears to be higher as the database includes data from many large countries, as well as many European countries.

The database is continuously expanding through ongoing effort to source and incorporate guidelines or standards from countries not yet included. A key limitation of the current database is that it is unclear whether a country is absent because of missing data or because it has no established IEQ guidelines. To address this, future iterations of the database could explicitly mark countries that do not have any IEQ guidelines. This enhancement would help users easily identify regions where advocacy for IEQ standards is needed. As such, the database could help policymakers and researchers develop globally more harmonized guidelines. As scientific research advances, guideline values should be regularly updated and refined to reflect new knowledge.

The database has already been used by researchers for various purposes from developing guidelines for protecting occupants from wildfire smoke [14] to assessing specific guidelines [41]. However, users of the

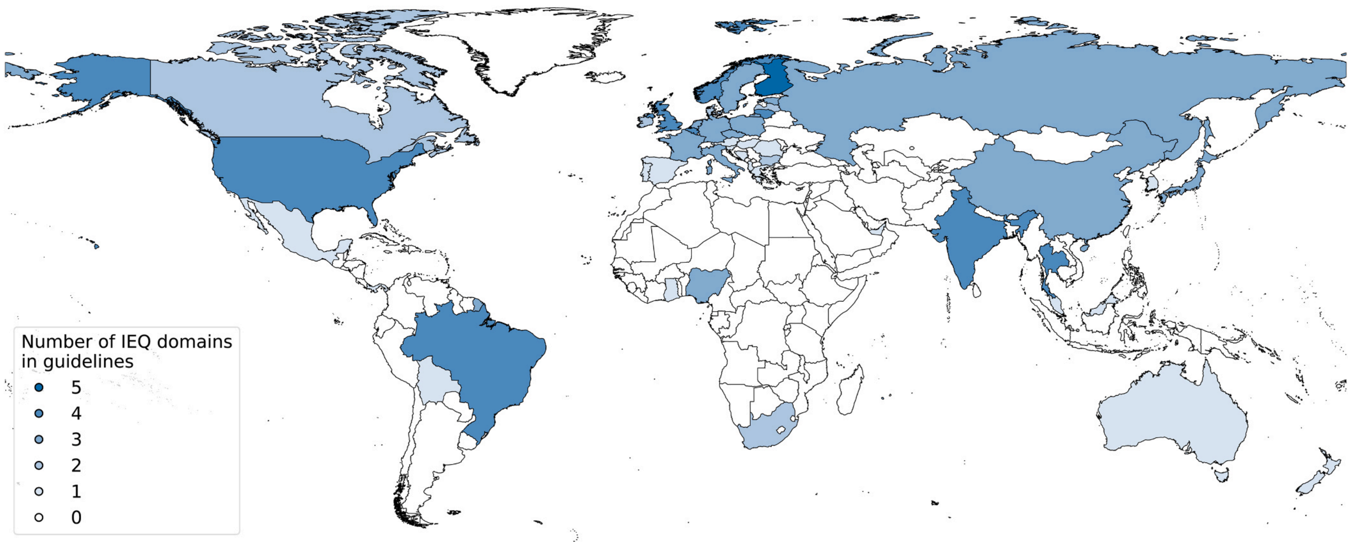

Fig. 5. Number of IEQ domains considered in each country guidelines.

database may encounter challenges in interpreting and utilizing some information. For instance, the database lacks criteria documents that justify or support numerical standards or guidelines. Application of the numerical guidelines or standards should be accompanied by standardized sampling and analytical methods, which are also not readily available. Future database development could address these two limitations by broadening the criteria defined in 2.1. Other challenges persist, particularly in overcoming language barriers and finding subject matter experts to translate native-language standards. Therefore, readers who can provide information on their country's guidelines or standards and wish to contribute to the database are encouraged to reach out to the database developers, such as through their website.

While the WHO has identified 13 priority indoor air pollutants, research suggests that even more may pose health risks. Ideally, comprehensive monitoring would cover all harmful pollutants, but practical constraints, such as cost, technical feasibility, and regulatory enforcement, make this unrealistic. A reasonable approach would be to determine a core set of pollutants that balances health protection with practical implementation.

The health effects of various indoor pollutants vary depending on the substance, exposure level, and duration. Some pollutants cause immediate symptoms, while others contribute to long-term health risks that may manifest only years later. This complexity is reflected in the different averaging times used. Additionally, citing guidelines or standards using different measurement units can create inconsistencies in interpretation and comparison. Nevertheless, IEQ guidelines or standards promote healthier indoor environments and improve the well-being of building occupants, as demonstrated in numerous studies. Systematic reviews also highlight their importance and impact on IEQ, emphasizing the need for standards to have statutory status [42,43].

Expanding and refining IEQ standards require balancing health-based thresholds with practical considerations such as economic constraints, energy consumption, and climate-related challenges. For example, consideration of CO_2 levels and ventilation rates could also acknowledge the associated energy demands and potential challenges for naturally ventilated buildings. However, these concerns could be better addressed separately through energy-efficient design, optimized building operations, or localized mitigation measures rather than compromising health-based standards. Achieving this balance requires a multidisciplinary approach that integrates IEQ standards with sustainable and region-specific solutions.

Many countries have mandatory or voluntary IEQ guidelines or standards [18]. However, a significant portion of building occupants remains dissatisfied with IEQ. Graham et al. (2021) analysed data spanning over two decades from 897 buildings and 84,366 respondents, finding that 25 % were dissatisfied with IAQ and 39 % with temperature [44]. Similarly, Radun and Hongisto (2023) examined occupant satisfaction across different office types using a global dataset of 82,315 respondents from 68 countries [45]. Their findings revealed that approximately 31 % of respondents were dissatisfied with thermal conditions, 28 % with noise levels, and 17 % with air quality.

The previous point highlights the inherently subjective nature of IEQ even though guidelines and standards have traditionally focused on measurable parameters. However, it is worth noting that IEQ can extend far beyond the indoor parameters used in the database. Less tangible aspects can significantly influence how occupants perceive and experience indoor spaces [46,47]. Psychological wellbeing, for instance is linked to perceived safety, visual aesthetics, and biophilic design, all of which can influence stress, cognitive performance, and overall occupant satisfaction. Comfort expectations are influenced by cultural and behavioural preference, which can differ significantly depending on regional norms, personal habits, or functional use of a building [48]. Additionally, social dynamics, such as workspace layout or accessibility, can affect how individuals interact with and perceive their environment [49]. Even factors like odour, perceived humidity, and personal control over environmental conditions (e.g. adjustable ventilation or lighting) contribute to IEQ in ways that are difficult to quantify but equally significant [50,51].

Hence, IEQ can be shaped by both objective measurements and subjective perceptions. Combining objective measurements with user feedback can help understanding real-world perceptions, though intangible factors are frequently addressed as non-binding considerations. While health-based guidelines are essential for preventing adverse effects, comfort-based guidelines contribute to occupant satisfaction. Balancing both approaches can create indoor environments that are both healthy and comfortable.

The relationships between IEQ and occupant well-being are multifactorial, with complex interactions among various IEQ factors. One question is whether effective IEQ regulation should consider pollutant sources separately, distinguishing between outdoor air pollution, emissions from building materials and components, and occupant-related factors such as cooking and personal activities. Addressing each source individually could help develop more targeted and effective control strategies. An example could be to regulate pollutants relative to outdoor levels (e.g., based on I/O ratios or differences), where applicable.

Characterizing IAQ in buildings is especially difficult due to the presence of complex mixtures and incomplete understanding of the impacts on human health of exposures to such mixtures of indoor contaminants. Although accepted metrics for mixtures have not been developed, several metrics addressing multiple pollutants have been proposed. One early approach to addressing mixtures was the proposal by Mølhave (1991) to compare the total concentration of non-reactive volatile organic compounds (TVOC) in indoor air to an irritation and discomfort scale, where $< 0.20\ mg/m^3$ was identified as having "no effect" and $> 3\ mg/m^3$ as "expected discomfort" [52]. Issues identified with this approach have included the lack of a standard measurement method for TVOC and a built-in assumption that individual compounds have a similar and additive impact on health. Brinke et al. (1998) expanded the concept of a TVOC metric to six additional metrics incorporating multiple VOCs [53]. Several other metrics based on multiple pollutants have been proposed [54–56].

Regarding thermal comfort, some countries use individual metrics, while others have incorporated complex indices, such as PMV, PPD, into their standards. The methodological inconsistencies create barriers for international harmonization efforts and complicate the interpretation of standards for multinational organizations seeking to implement consistent comfort policies across global operations.

On the other hand, various indexes have been proposed with the primary goal to simplify the assessment of IEQ [57,58]. Typically, indexes combine multiple pollutants, such as PM ($PM_{2.5}$, PM_{10}), CO_2, VOCs, temperature, and relative humidity into a single score, resulting in a numerical value that could reflect the overall quality of an indoor environment. However, such indexes lack granularity to fully understand the severity of specific pollutants, and they can oversimplify the situation by not accounting for individuals' sensitivity to specific pollutants, or regional differences. To the authors' knowledge, indexes have not been included in the national regulations or guidelines, while some of them have been proposed by non-governmental organizations.

Developing health-based guidelines for individual pollutants—requiring the establishment of exposure-response relationships between pollutants and specific health endpoints—in real-world scenarios involving exposure to mixed chemical and biological agents is an extremely complex and time-consuming process [12,14]. On the other hand, incorporating these health-based numerical guidelines into mandatory standards through legislation and enforcement requires additional considerations, including socio-political and economic conditions, cost-benefit analysis, regional practices, culture, and climate [12,15].

In conclusion the IEQ guidelines database was developed in response to a core challenge: the need for a comprehensive, globally accessible overview of how IEQ is currently addressed and managed around the world. Its purpose is to make this knowledge widely accessible while serving as a foundation for the development and refinement of future guidelines and standards at both national and global levels. While the database still faces several limitations (uneven representation across countries, particularly distinguishing those missing and those lacking established IEQ guidelines; missing guideline definition criteria, such as sampling methodologies or the underlying research studies supporting the guidelines; maintaining timely updates in a dynamic, evolving worldwide legislation), it reveals that effective IEQ guidelines must balance health, environmental, economic, and comfort factors and be science-based, regionally adaptable, and measurable. The authors would like to propose, in the following section, a set of recommendations based on lessons learned over more than five years of developing the worldwide ISIAQ IEQ guidelines database.

4. Recommendations

1. IEQ regulations/guidelines/standards can be clearly differentiated based on their relevance to health, environmental, economic, productivity, and/or comfort outcomes.
2. Government agencies can consider prioritizing the development of IEQ standards that are based on robust scientific health and well-being evidence. For example, IAQ standards, which are based on outdoor standards, can be complemented with evidence coming from indoor epidemiological and toxicological studies.
3. As a minimum, regulatory standards can consider both acute and chronic health outcomes. Given that human well-being depends on the stability of the planet's ecosystems, including climate, biodiversity, water, and air quality, future standards may incorporate planetary health, which integrates public health, environmental science, economics, and social justice. Additional / voluntary guidelines may also consider comfort outcomes.
4. Health-based IEQ regulations/guidelines/standards can be structured to include for each parameter: clear exposure limit, exposure time, source of exposure, applicable environment, population and period. Defining the acceptable measurement method(s) can also facilitate better implementation.
5. IEQ standards benefit from being economically and regionally adaptable, acknowledging the cultural and societal specificities of the applicable environment and population. Regulatory standards that require disproportionate material or financial investments from communities with limited resources may lead to distrust and disengagement.
6. Development of IEQ regulations/guidelines/standards, scientific research, and technological advancements can be most effective when they complement one another. Selected outcomes can help drive the development of suitable measurement tools, while latest scientific knowledge and technological innovations may inform updates to regulations/guidelines/standards. For example, only a few current guidelines included in the database used continuous monitoring data, which could allow more accurate spatial and temporal characterization of exposure (providing that the reliability and accuracy of the measuring devices have been thoroughly validated).
7. IEQ regulations/guidelines/standards benefit from using clear, measurable parameters. Composite indices support for health assessment is limited in current scientific knowledge; more research is needed to better understand the effects of complex mixtures and interactions between IEQ factors. Besides, indices might require that each parameter used for calculation be measured, potentially limiting their applicability. On the other hand, indices can be useful in voluntary comfort and/or performance-based guidelines, rating systems, and to help disseminate results.
8. Openly available and easy-to-access IEQ regulations/guidelines/standards can help promote adherence among practitioners, policymakers, and the public, while supporting both research and policy. When they can be readily found and comprehended, they are more likely to be followed. However, keeping such information up to date requires ongoing effort and resources. A sustainable solution could include an automated and regularly maintained platform, such as the one developed by ISIAQ STC34. In addition, such a system can serve as a reference point for countries that have yet to develop their own IEQ regulations/guidelines/standards, helping them align with established best practices.

CRediT authorship contribution statement

Henna Maula: Writing – review & editing, Writing – original draft. **Ulla Haverinen-Shaughnessy:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. **Samy Clinchard:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Amelia Staszowska:** Writing – review & editing, Writing – original draft. **Piet Jacobs:** Writing – review & editing, Writing – original draft. **Marzenna Dudzinska:** Writing – review & editing, Writing – original draft. **Suchismita Bhattacharjee:** Writing – review & editing, Writing – original draft. **Christina Higgins:** Writing – review & editing, Writing – original draft.

Sani Dimitroulopoulou: Writing – review & editing, Writing – original draft. **Xiaojun Fan:** Writing – review & editing, Writing – original draft, Project administration. **Oluyemi Toyinbo:** Writing – review & editing, Writing – original draft. **Ju-Hyeong Park:** Writing – review & editing, Writing – original draft.

Disclaimer

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Declaration of Competing Interest

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indenv.2025.100124.

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