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Indoor environmental quality to ensure the health and wellbeing of vulnerable people in residential buildings: a systematic review

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Indoor environmental quality (IEQ) is an essential topic nowadays due to its direct impact on occupant health and wellbeing. Most research, however, has focused on commercial and workspace typologies, leaving residential buildings underexplored. Importantly, the effects of IEQ are not experienced uniformly across all populations. Age-related changes and cognitive function, in particular, significantly influence how occupants experience indoor environments. This makes infants and older adults and/or with disabilities especially vulnerable. Understanding these parameters is crucial to designing comfortable, healthy, and inclusive buildings for all user profiles. This review aimed to document research on IEQ, particularly concerning vulnerable populations in residential building typologies. The findings revealed how different vulnerable groups (children, elderly people, pregnant women, and people with disabilities) are affected by the main IEQ domains (thermal, air quality, lighting, acoustics). On the one hand, this relationship is essential for adopting healthy habits when using buildings as users, and on the other, for methods, factors, and strategies to consider and apply when designing healthy and inclusive buildings as architects, designers, and engineers. The quality of the indoor environment must be considered throughout the entire life cycle of a building, from decisions in the initial design stages to its maintenance.

KEYWORDS

indoor environmental quality, vulnerable people, healthy architecture, inclusive housing, elderly people, healthy buildings

1 Introduction

According to recent studies, most people spend approximately 80%–90% of their time indoors (Al Horr et al., 2016), so the quality of the interior environment is a topic that has drawn extensive scholarly attention. Recent research aimed at enhancing Indoor Environmental Quality (IEQ) is closely associated with the increasing demand for building rehabilitation across Europe and the imperative to decrease energy consumption while promoting sustainability and efficiency (Anderson et al., 2015). The confluence of these factors highlights the critical need for ongoing investigation

into the optimization of indoor environments to meet contemporary ecological and health standards (Soares et al., 2017; Ortiz et al., 2017). However, most studies and research focus on commercial typologies and workspaces, leaving the IEQ in residential buildings understudied (Al horr et al., 2016; Carton et al., 2022). The Association for Media Research (AIMC) estimates that the time spent in houses is around 65% in Spain. This percentage increases to 85% for individuals over 65 and up to 95% for those over 85 (Hughes et al., 2019).

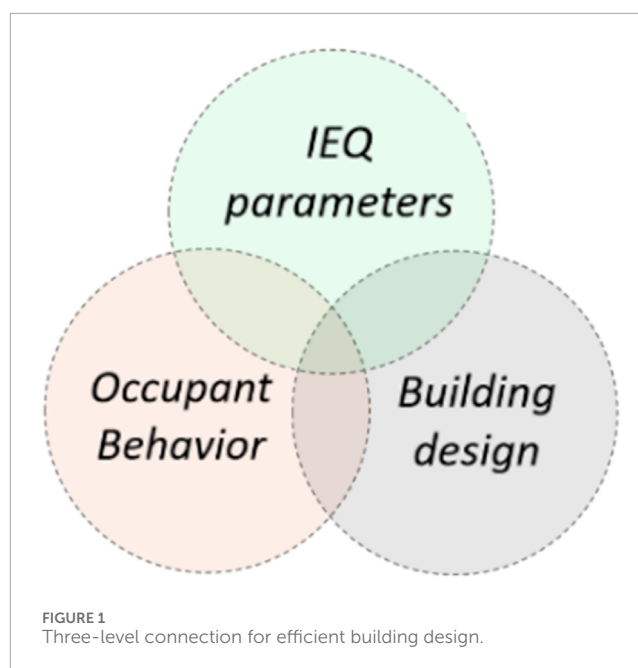
Previous research indicates that the quality of interior environments—including thermal, acoustic, visual, humidity, air quality, odors, and vibrations—significantly impacts the comfort and health of building occupants (Apte, 2000; Wolkoff, 2018; Wu et al., 2023a). Furthermore, the relationship between the occupants' wellbeing and satisfaction and the interior environmental quality is based on complex parameters. This complexity presents challenges in measurement and can lead to discrepancies affected by contextual factors such as local climate, building typology, and the interior layout of the structures. Additionally, the interplay between occupant wellbeing and satisfaction and the interior environment's quality is influenced by many parameters, which can be both diverse and complex. While these contextual elements may not be explicitly categorized as determinants of interior environmental quality, they directly influence user comfort, perceptions, and how individuals inhabit and utilize the spaces within buildings (Al horr et al., 2016; Carton et al., 2022).

The quality of the interior environment affects diverse population groups in different ways. Age-related variations are particularly notable, as seen in infants and elderly individuals (Putri et al., 2023). The World Health Organization also identifies other vulnerable groups including people with reduced mobility or disabilities, as well as pregnant women. These considerations highlight how interior environments interact uniquely with the specific needs and conditions of each group.

Allab et al. (2017), Dias Pereira et al. (2017), and Zuhair et al. (2018) addressed IEQ issues related to building energy efficiency or performance, user needs, and design strategies (Šujanová et al., 2019). Usually, only one of the aspects or parameters defining the quality of the interior environment is analyzed (Ortiz et al., 2017; Bluyssen, 2010). Understanding these parameters is essential to designing comfortable, healthy, and inclusive buildings for all user profiles. In addition, according to the WHO, healthy buildings must adapt to the future and, therefore, be protected under the now more latent criteria of sustainability, efficiency, and low consumption and cost without damaging the surrounding environment (Šujanová et al., 2019; Bluyssen, 2010).

However, the behavior of the occupants inside these buildings sometimes conflicts with the strategies designed for low energy consumption. To effectively adapt to future requirements, people's needs must be balanced with IEQ parameters (general comfort, energy efficiency, building design, and climate control), also called quality of life indicators (Bluyssen, 2010). Thus, a three-level connection is related, as Figure 1 shows (Šujanová et al., 2019).

Besides IEQ domains, psychological and physiological aspects related to the wellbeing of occupants influence the overall perception of comfort. All of these domains must be considered to achieve the right quality of the interior environment (Bluyssen, 2010). As relevant studies show, physiological and psychological domains,



such as the intrinsic characteristics of each occupant, the age range (Zalejska-Jonsson and Wilhelmsson, 2013; Frontczak et al., 2012; Chiang et al., 2001), sociocultural conditions, and the type of space (Frontczak et al., 2012; Heinzerling et al., 2013) (19) are important when evaluating IEQ and its impact. However, defining these domains can be difficult, as specific criteria for different user profiles may not always be known or considered (Bluyssen, 2010). Recent studies highlight the importance of adopting multi-domains approaches, as comfort cannot be fully understood by isolating individual parameters and factors. Instead, the interactions between IEQ domains (thermal, visual, acoustic and air quality), combined with psychological and physiological dimensions, provide a more comprehensive framework for assessing occupant wellbeing (Schweiker et al., 2020).

It is essential to consider not only all factors, but also the capacity for adaptation to change, and above all, the time frame in which it occurs, as this will be decisive. Even if actions with less impact and lower energy consumption are implemented, occupants' behaviour and their adaptation will be uncertain, influenced by actions such as (Šujanová et al., 2019; Coccolo et al., 2016; Gunay et al., 2013):

- behavioural adjustments (change in habits or tolerance limits).
- physical responses (level of activity, clothing use and environmental conditions)
- psychological adaptations, shaped by individual sensations and perceptions.

These actions may occur consciously, in the first case; subconsciously, in the second case, or automatically by the peripheral nervous system, in the last case.

The number of occupants in a space is another aspect to consider when measuring the IEQ. A higher occupancy can lead to increased indoor air pollution. Additionally, the interior air quality can be affected by the construction materials used and the types of

equipment present within the building (Al horr et al., 2016; Bakó-Biró et al., 2004). It is, therefore, essential to accurately assess both space occupation and interior pollutants. Numerous researchers studied various types of public buildings, such as offices (Kong et al., 2022), schools (Wu et al., 2023b; Tao et al., 2022), shopping centers (Deng et al., 2022), hotels (Xu et al., 2022a; Xu et al., 2022b) and nursing homes (Wang et al., 2022). These studies have used a variety of methods, including field measurements, simulations, behavioral observations, questionnaires, and interviews, as well as tools such as virtual reality (VR) and electroencephalography (EEG) (Wu et al., 2023a). However, the relationship between the objective aspects and the perception of the environment remains unclear and undefined. There is often a discrepancy between actual conditions and how user profiles respond to or evaluate their environment (Bluyssen, 2010).

The WHO confirms that approximately a quarter of the diseases around the world are due to modifiable environmental factors (Šujanová et al., 2019). Many studies have confirmed that the quality of the interior environment is correlated with diseases, such as cardiovascular, respiratory, and reproductive conditions, which are visible both in the short and long term (Al horr et al., 2016; Wu et al., 2023a; Bluyssen, 2010; Houtman et al., 2008; Fisk et al., 2007). Assessing diseases and discomfort among different populations, particularly vulnerable individuals, is crucial for understanding their relationship with IEQ domains (Bluyssen, 2010). Air pollution occurs due to factors such as the presence of mold, dust, mites, allergens, indoor aldehydes, volatile organic compounds (VOC), airborne fungi, pesticides, tobacco smoke, lighting, air exchange or circulation rates, carbon monoxide, carbon dioxide. These elements can lead to respiratory health issues (Al horr et al., 2016; Takigawa et al., 2009). Mechanical ventilation, as opposed to natural ventilation in buildings, may increase the incidence of diseases by 30%–200%, resulting in more hospital visits, particularly among women (Al horr et al., 2016; Preziosi et al., 2004).

Sick Building Syndrome (SBS) comprises a group of health issues caused by the indoor environment of a building (Al horr et al., 2016; Takigawa et al., 2009; De Dear and Brager, 2002). Various factors contribute to SBS, including temperature, humidity, chemical and biological contamination, and physical condition and psychosocial status of the occupants (Simonson et al., 2002; Wang et al., 2007; Wolkoff and Kjærgaard, 2007; Stolwijk, 1991). People experiencing SBS can suffer eye, nose, and throat irritation, headache, cough, wheezing, cognitive disorders, depression, sensitivity to light, gastrointestinal upset, fatigue, and similar to those of the flu (Šujanová et al., 2019; WHO, 1983; Mendell and Smith, 1990).

High exposure to poorly ventilated interior spaces or areas with airborne pollutants, such as soil fungal concentrations due to high humidity (Redd, 2002) or dust in chairs, is often associated with allergies, irritation of lung functions, asthma, and pneumonitis (Al horr et al., 2016; Redd, 2002; Fisk et al., 2007). These health issues, along with poisoning, are closely linked to indoor air quality, which is one of the leading contributors to health-related deaths (Šujanová et al., 2019; Franchi et al., 2006; WHO, 2017). The severity of these diseases depends on the intensity, duration, and source of harmful exposure (Šujanová et al., 2019). Prolonged exposure to

poor Indoor Air Quality (IAQ) can lead to serious illnesses like legionellosis and CO poisoning. Although symptoms like asthma, cough, and pulmonary infiltration may appear after brief exposure, they can become chronic and acute respiratory diseases. Many of these conditions can be avoided with proper indoor air quality management (Franchi et al., 2006).

Beyond air quality, other environmental domains also have measurable health impacts. High noise levels can cause cardiovascular risks and hypertension (Šujanová et al., 2019). In addition, heart rate variability has been related to indoor air temperature and may be a predictor of mortality (Bluyssen, 2010). Thermal comfort, air quality, and noise collectively influence not only health but also concentration, and motivation (Šujanová et al., 2019; Kallio et al., 2020). For example, increased temperatures can elevate the concentration of harmful substances in the air from the devices, relating temperature dependence to indoor air quality or ventilation (Šujanová et al., 2019). On the other hand, poor ventilation or fungal concentration can also cause fatigue (Šujanová et al., 2019; Redd, 2002). High humidity worsens the quality of sleep (Wolkoff, 2018).

Lighting conditions are equally critical. Inadequate lighting disrupts sleep quality and circadian rhythms, causing discomfort throughout the day (Šujanová et al., 2019; Chang and Chen, 2005). The effects of poor lighting can vary based on gender, age, and the time of year (Serghides et al., 2015). Similarly, poor acoustic environments are associated with insomnia and alter sleep patterns (Šujanová et al., 2019), particularly among the elderly (Putri et al., 2023). High noise levels, their frequency, and sound pressure differences cause discomfort in people (Landström et al., 1995). A deficit in the optimization of indoor acoustics not only affects cognitive decline in hearing but also causes distractions, irritability, stress, discomfort, and fatigue (Al horr et al., 2016; Šujanová et al., 2019; Passero and Zannin, 2012). It can even affect the development of learning disorders, such as dyslexia or voice problems (Bottalico and Astolfi, 2012).

This systematic review aims to identify key factors affecting building environmental quality in residential buildings and their impact on different vulnerability groups. The study also examines how sensory perception, cognitive function, and building design and operation interact with building environmental quality in vulnerable people.

This review addresses vulnerable groups from an age-related perspective, considering the elderly and children as classifications recognised by the World Health Organisation. However, other vulnerable groups, such as pregnant women and people with disabilities, are also mentioned. This classification is not addressed from a socio-economic perspective or based on housing characteristics, which could be another way of classifying vulnerable groups.

2 Methodology

This literature review aimed to document the key research and theories linking IEQ to design, focusing on the most vulnerable occupants in residential building typologies.

2.1 Initial literature search

This research began with an initial bibliographic search. Since the main objective of the study was to analyse the impact of IEQ on the health and wellbeing of vulnerable occupants in residential buildings, the keywords used for the search were related to this, in addition to wellbeing buildings.

The following multiple chains were used, taking into account both IEQ in residential buildings in general and in vulnerable groups:

(“Indoor Environmental Quality” OR IEQ);
 (“Indoor Environmental Quality” OR IEQ) AND (residen*);
 (“Indoor Environmental Quality” OR IEQ) AND (pregnan* OR baby OR babies OR child* OR infant);
 (“Indoor Environmental Quality” OR IEQ) AND (elder*);
 (“Indoor Environmental Quality” OR IEQ) AND (vulnerab*);
 (“Indoor Environmental Quality” OR IEQ) AND (disab*);
 (Acoustic) AND (indoor) AND (residen*);
 (IAQ) AND (residen*);
 (“thermal comfort”) AND (indoor) AND (residen*);
 (“visual comfort”) AND (indoor) AND (residen*)

Thus, an initial and rapid analysis using the Scopus search engine revealed the main trends and gaps, as well as areas that have been little explored.

It is important to recognize that the preliminary analysis has certain limitations, as the database used was not subjected to a rigorous selection process. Furthermore, the large volume of contributions prevented a thorough verification of the consistency of the dataset with the established search criteria.

The bibliography was then analysed using this data, revealing the results shown in the following figures:

Figure 2 illustrates the literature gap over time between the frequency with which the term IEQ is used in all articles *versus* its use alongside other terms intended for vulnerable groups, such as the elderly. Another important aspect is the comparison between all articles on IEQ and those that focus only in residential buildings. **Figure 3** shows that, in the residential sector, publications with a separate domains predominate rather than considering IEQ as a whole. It can also be seen that the frequency of publications increased after the pandemic.

All this information is important for future research to take into account.

Next, **Figure 4** shows that when the articles are broken down by domains, the frequency of articles in their entirety (yellow) is compared to existing research on vulnerable groups by domains and on IEQ as a single concept, which is minimal. Zooming in reveals that the effect of each domain is studied more in isolation than as a whole in terms of IEQ.

Geographically, the highest scientific output for both IEQ and each domain is concentrated in countries such as the US and China. In contrast, European countries have experienced more limited development in these areas and have tended to study the domains more separately, as illustrated in **Figure 5**.

Finally, as illustrated in **Figure 6**, the five most influential authors per topic were identified in this initial search, many of whom are referenced in the bibliography.

2.2 In-depth literature search and classification

Following the initial phase, the methodological structure of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram was adopted to systematically address, in a deeper way, this literature, identifying, evaluating and synthesising the available scientific evidence on the topic addressed in this review.

To this end, the Scopus and Web of Science scientific databases were consulted within the time range of 2000–2025.

In the context of this review, combinations of controlled terms were used alongside Boolean operators and search methods such as (*) to obtain additional words from semantic roots.

The relevant records were exported to an Excel spreadsheet for screening, in order to identify the most relevant publications.

The following inclusion and exclusion criteria were applied:

The inclusion criteria were: that there should be at least one IEQ domain—or IEQ as an overall concept—in addition to taking vulnerable groups into account, and even that it should be indoors or in a residential environment.

The following procedure was used to search for keywords in both databases, as we did in the initial search, using the same strings expressed in [section 2.1](#).

However, this time, the exclusion criteria were: a language other than English, full text not available, main focus on medical aspects not related to IEQ (transplants, molecular studies, pharmacology, *etc.*) (not medicine, not transplantation, not molecules, not paceut*not surgery not biology not cell not molecular not protein not physical not chemical), research related to an activity such as in hospitals, schools or offices, when the objective was to evaluate the functioning of the facility and not the impact on the health or wellbeing of the occupants. Also, studies that were not relevant or did not explicitly evaluate these issues.

Although this review primarily focuses on housing, it also includes articles related to schools, care facilities and offices, in order to determine symptoms and conditions, as well as important thresholds for different vulnerable groups.

Finally, the most impactful and frequently cited articles from high-quality, high-impact journals were read and included.

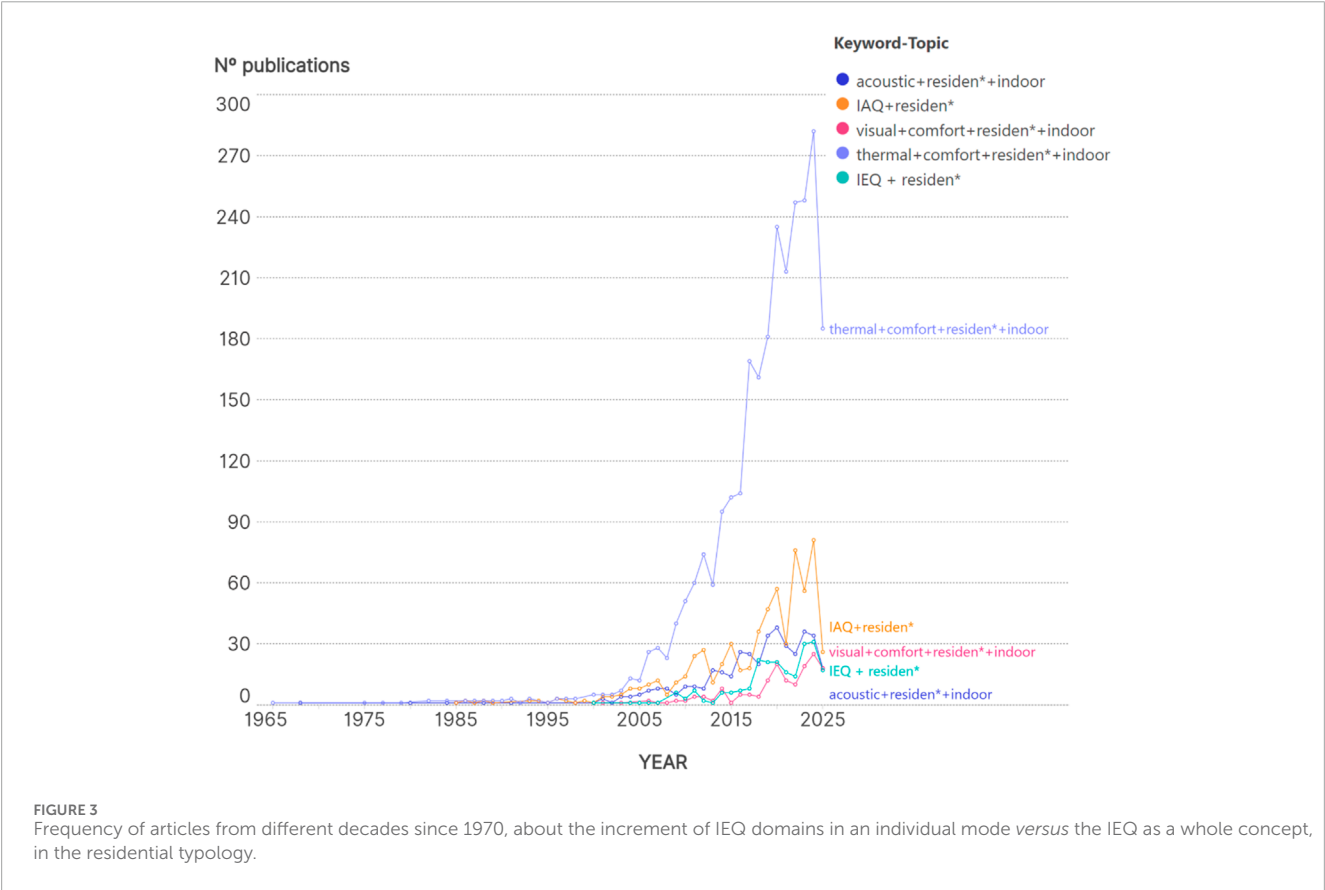
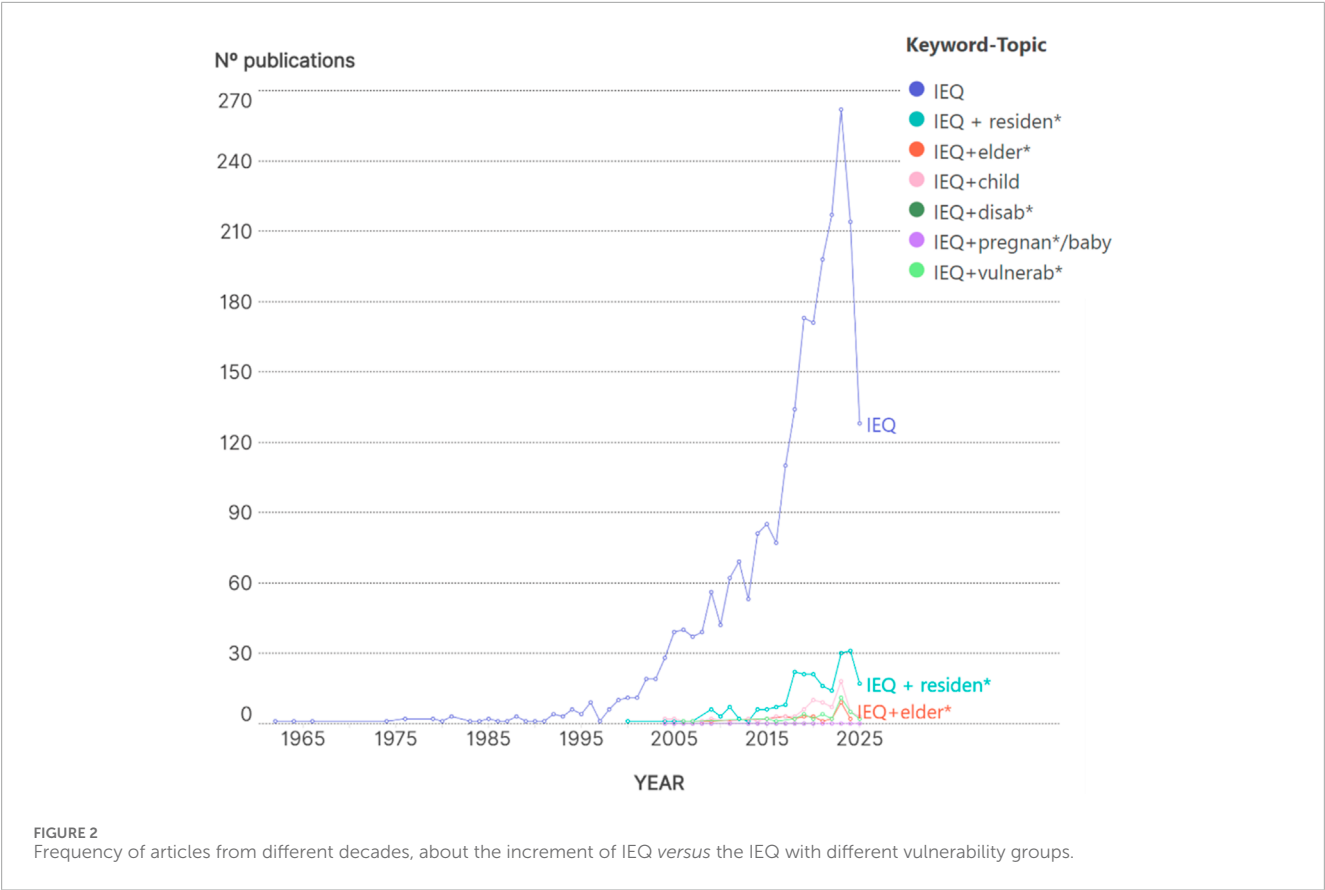
This review includes 138 references divided into database and grey literature.

The entire process is documented using the PRISMA diagram shown in **Figure 7**.

The final step of the process was the analysis of the downloaded papers, which allowed us to categorize the findings into specific thematic areas such as IEQ in the residential sector, air quality in the residential sector, indoor visual comfort in the residential sector, thermal comfort in the residential sector and acoustics in the residential sector.

Following the presentation of these sections, the authors address the main issues that can affect building design. Given the recent proliferation of healthy building design initiatives and the use of healthy building guidelines around the world, the discussion helps readers to establish a link between health and wellness parameters and the domains included in healthy building guidelines.

This systematisation made it possible to identify patterns, trends and areas that have been little explored in the literature, providing a solid basis for discussion and justification of the research.



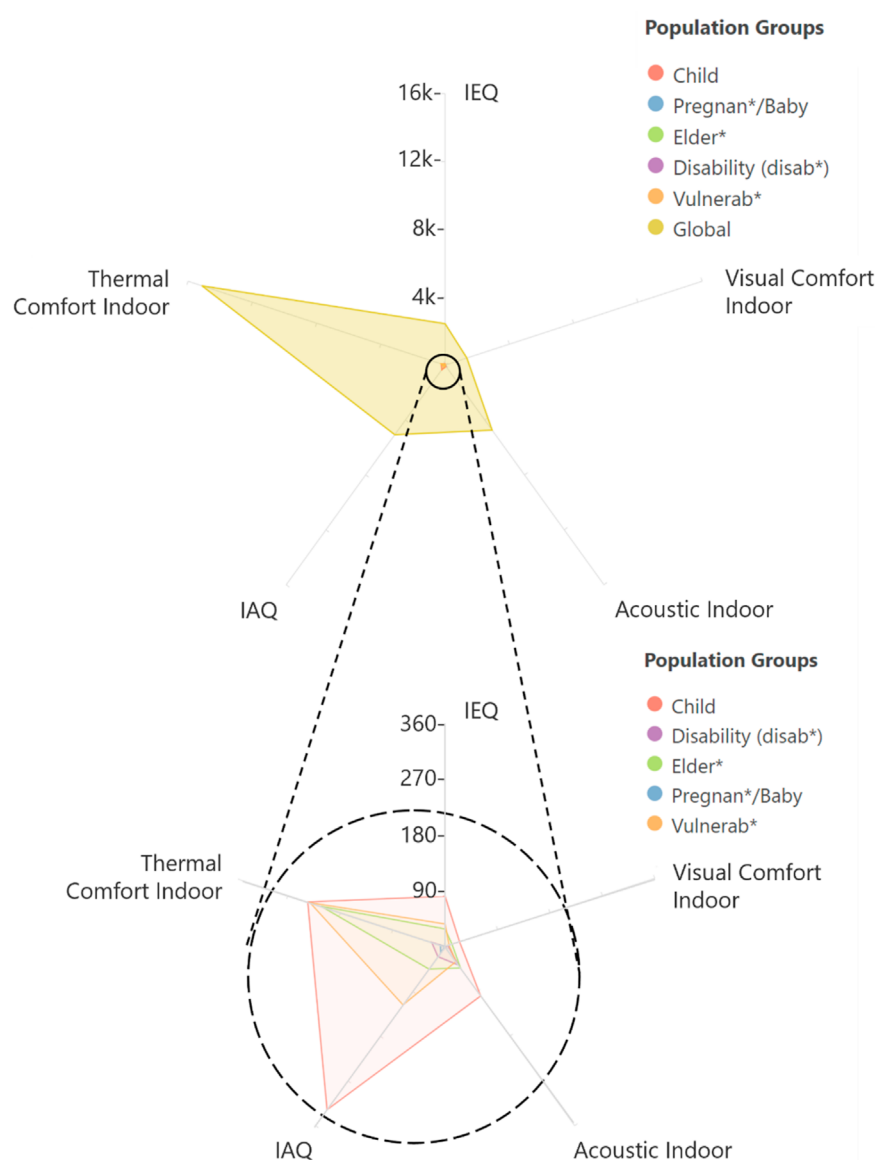


FIGURE 4

The overall impact of the IEQ issue is depicted, with the vulnerable groups barely visible. The frequency of items per IEQ domain is shown for each vulnerability group.

In addition to taking into account the high impact of the journals analysed, the origin of the references used was also considered, which analyses the geographical framework of the research used. This distribution is shown in Figure 8, where the United States, China, and central European countries predominate.

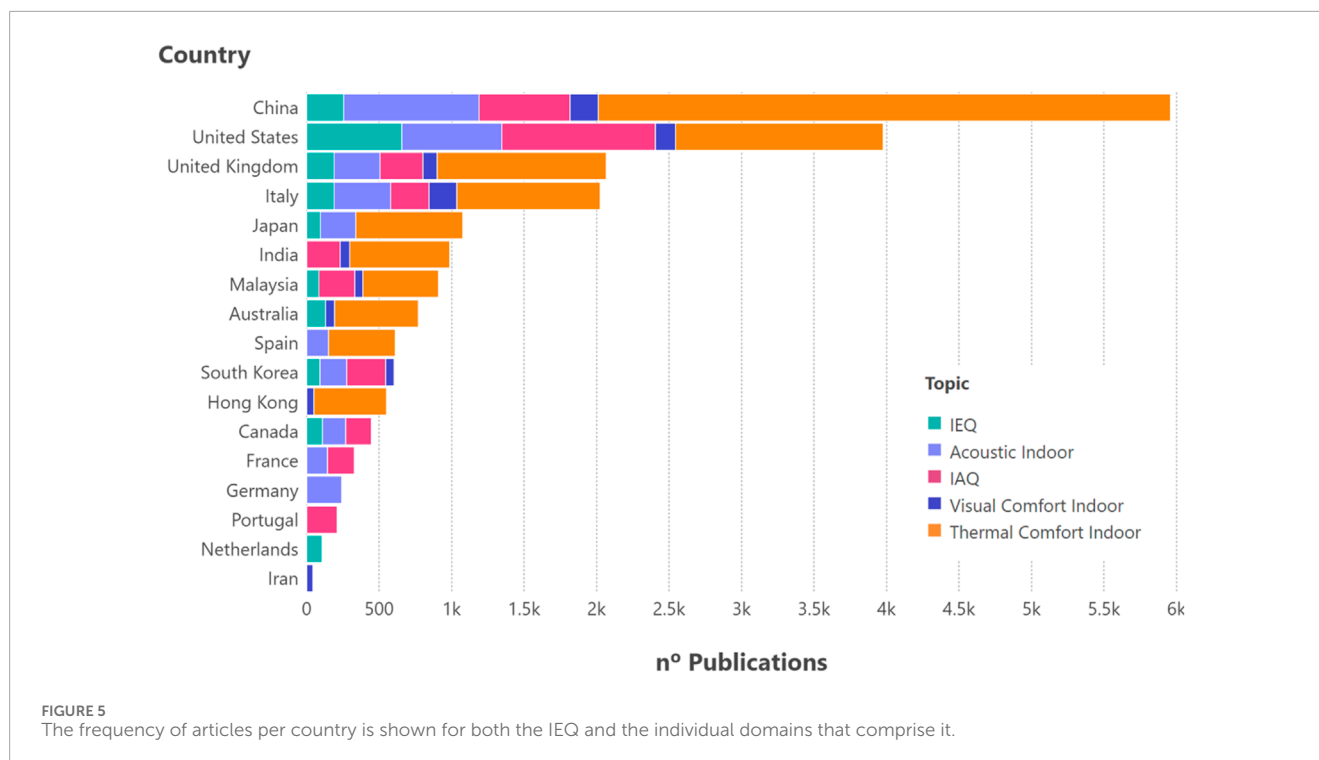
3 State of the art of the research on thermal comfort

Thermal comfort directly impacts buildings' energy consumption. Over 60% of a building's energy consumption is used for heating and cooling a space (Šujanová et al., 2019).

Even a slight feeling of discomfort can lead users to adjust the controls to suboptimal levels (Al horr et al., 2016; Catalina and Iordache, 2012; Corgnati et al., 2009).

3.1 Thermal comfort and people's wellbeing: sensitivity to thermal conditions, preferred temperatures, adaptability and perception of thermal comfort

Thermal comfort can be defined depending on more specific patterns known as climate, geographic location, the design typology of the building, and the time of year, which are determined using air



temperature, radiant temperature, relative humidity, and the speed of the air (Al horr et al., 2016; Šujanová et al., 2019; Frontczak and Wargocki, 2011). Beyond these parameters, the most important and variable element is personal thermal adaptation theory, which relies on behavioral, psychological, and physiological aspects (Zhou et al., 2023). The assessment of those parameters includes habits and behaviors, as well as intrinsic characteristics of the individual, such as gender, race, and age (Al horr et al., 2016; Quang et al., 2014), along with metabolic rates (activity levels) and insulation provided by clothing (Clo value) (Šujanová et al., 2019; Katafygiotou and Serghides, 2015). Four environmental variables are also assessed: air temperature, air speed, humidity, and radiant temperature. The most recurring method for measuring thermal comfort is Fanger's PMV-PPD model, using metrics either by expected average vote (PMV) or by the expected percentage of dissatisfaction (PPD), which depends on user responses (Hughes et al., 2019; Zhou et al., 2023; Ole Fanger and Toftum, 2002; Papadopoulos et al., 2008).

Physiologically, temperature perception is detected by cutaneous sensory fibers, which respond to cold and heat. Cold perception is felt at temperatures ranging from 17 °C to 34 °C, whereas heat receptors are activated from 33 °C to 46 °C. The point that is considered neutral is a temperature of 32 °C. Temperatures below 17 °C and above 46 °C are considered harmful if there is a long time exposure. The maximum sun exposure is 3,500 W/m² (Šujanová et al., 2019).

Regarding body temperature, human bodies stay around 37 °C through the heat exchange from the human body and the environment through radiation, convection, and evaporation, as explained in ASHRAE 55. These regulations, together with ISO 7730 (1994) and ISO 17772-1, define thermal comfort and serve as a reference for the design of buildings worldwide (Al horr et al., 2016) (Šujanová et al., 2019). If body temperature exceeds 40 °C,

there would be a risk of heart attack, and below 35 °C, there would be a risk of hypothermia (Šujanová et al., 2019; Noonan et al., 2012). Adjustments to thermal factors generally produce slow physiological responses, and their effects tend to manifest over the long term (Šujanová et al., 2019).

3.2 Effect of hygrothermal variables on age, gender and disability

Hygrometric variables are among the key factors that influence user perceptions based on gender and age (Smolander, 2002; Nicol and Humphreys, 2002). As the body undergoes physiological changes over the years, it adapts to different thermal conditions. A weak self-regulation of thermal comfort (thermoregulation) is observed, resulting in less precision in assessing comfort levels. Consequently, older adults tend to have a broader range of comfort temperatures than young adults. Studies indicate that older individuals demonstrate lower thermal sensitivity, especially in cold environments. A primary factor driving these age-related differences is the metabolic rate, typically 5%–30% slower in older adults than in sedentary young adults (40.6–55.1 W/m²) due to loss of muscle tissue and neurological changes. Besides, older adults commonly experience a decrease in body temperature and an increase in body fat and overall weight, which enhances the body's thermal insulation.

As a consequence, the elderly produce less metabolic heat, resulting in a lower heart rate and cardiac output—between 3.4% and 40% less than that in young adults and, therefore, a slower response to cold. The thresholds for the start of vasodilation and sweating are also different, as they approach 0.5 °C and 0.21 °C, respectively. Due to these differences, sweating begins at higher temperatures due to reduced sweat secretion rate, and tremors or chills occur at



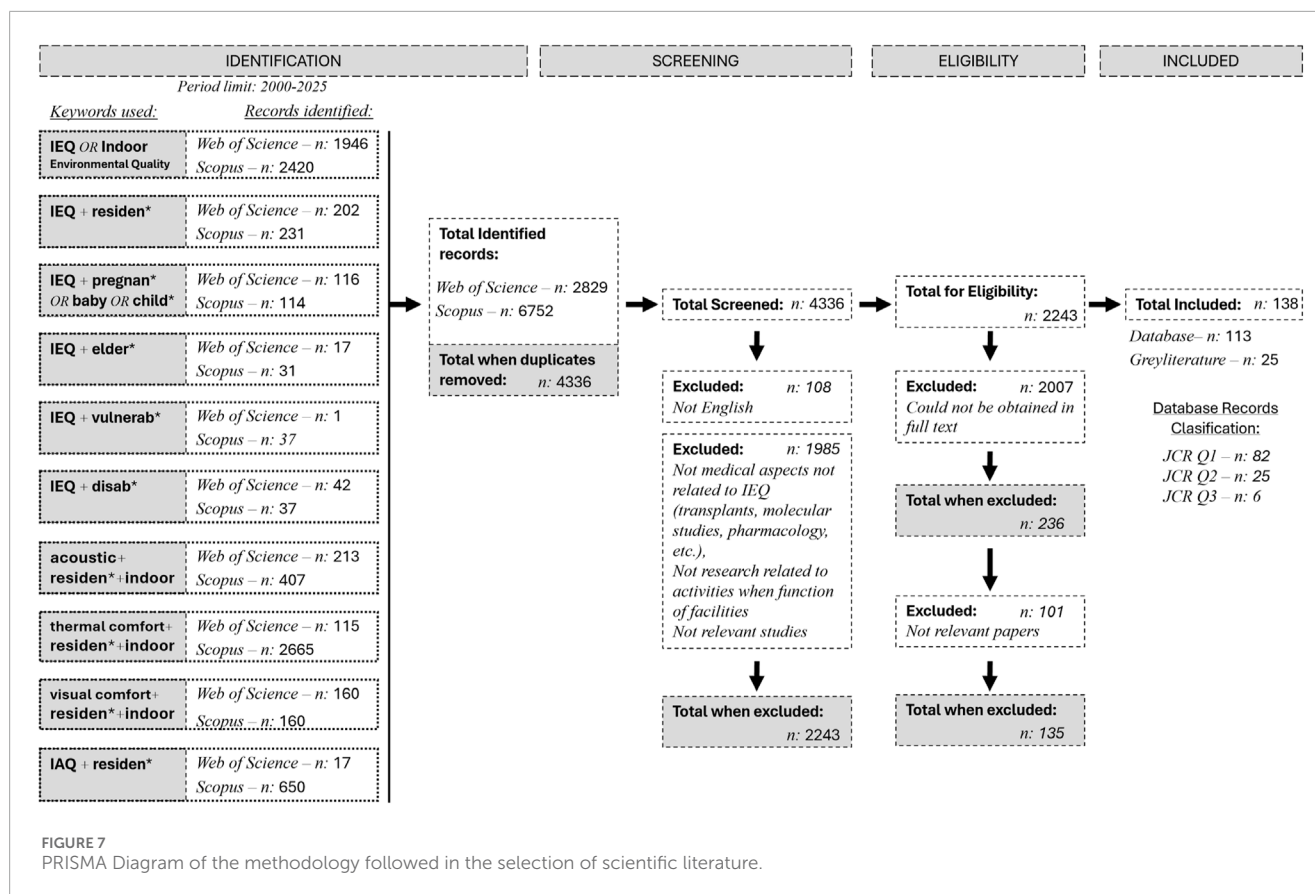
FIGURE 6
Authors with the most publications on IEQ in the residential sector by IEQ domain.

lower temperatures due to less effective peripheral vasoconstriction. When evaluating this parameter, other behavioral and psychological aspects must be considered (Zhou et al., 2023).

These age-related changes in thermal perception have significant health implications. Older adults may not adequately adapt to their environment, increasing their vulnerability to cold and related health risks, such as arthritis, respiratory conditions as lung diseases, and even higher mortality rates. The WHO recommends a temperature of 18 °C in rooms. However, if the occupants are older, the recommended temperature rises to 20 °C–21 °C (Hughes et al., 2019). In the case of infants, there is a lack of emphasis on thermal comfort, so the space is adapted for the comfort of a young adult. On the other hand, infants spend their time at a lower height and are more vulnerable to diseases like influenza because their immune system is not fully developed. The space temperature

must be set at 26 °C–28 °C in summer and 20 °C–23 °C in winter, with a humidity of 60% for optimal health outcomes for this demographic (Genjo, 2022).

In the thermal comfort domain, as shown in Table 1, the literature focus on established metrics and standards, such as ASHRAE 55, and on reviewing approaches to energy efficiency and wellbeing. Though energy consumption and sustainability have been linked to thermal comfort through a multitude of studies, still remains a normative and generalist view that address contextual variations or the specific needs of different environments and housing types. Moreover, although advances have been made in incorporating psychological and social aspects, studies remain fragmented and limited in terms of the diversity of populations analysed, especially vulnerable groups such as children and older adults. It is evident that there is a clear need for more research should



connect standardised metrics with physiological and psychological parameters that have yet to be fully explored.

4 State of the art of the research on indoor air quality

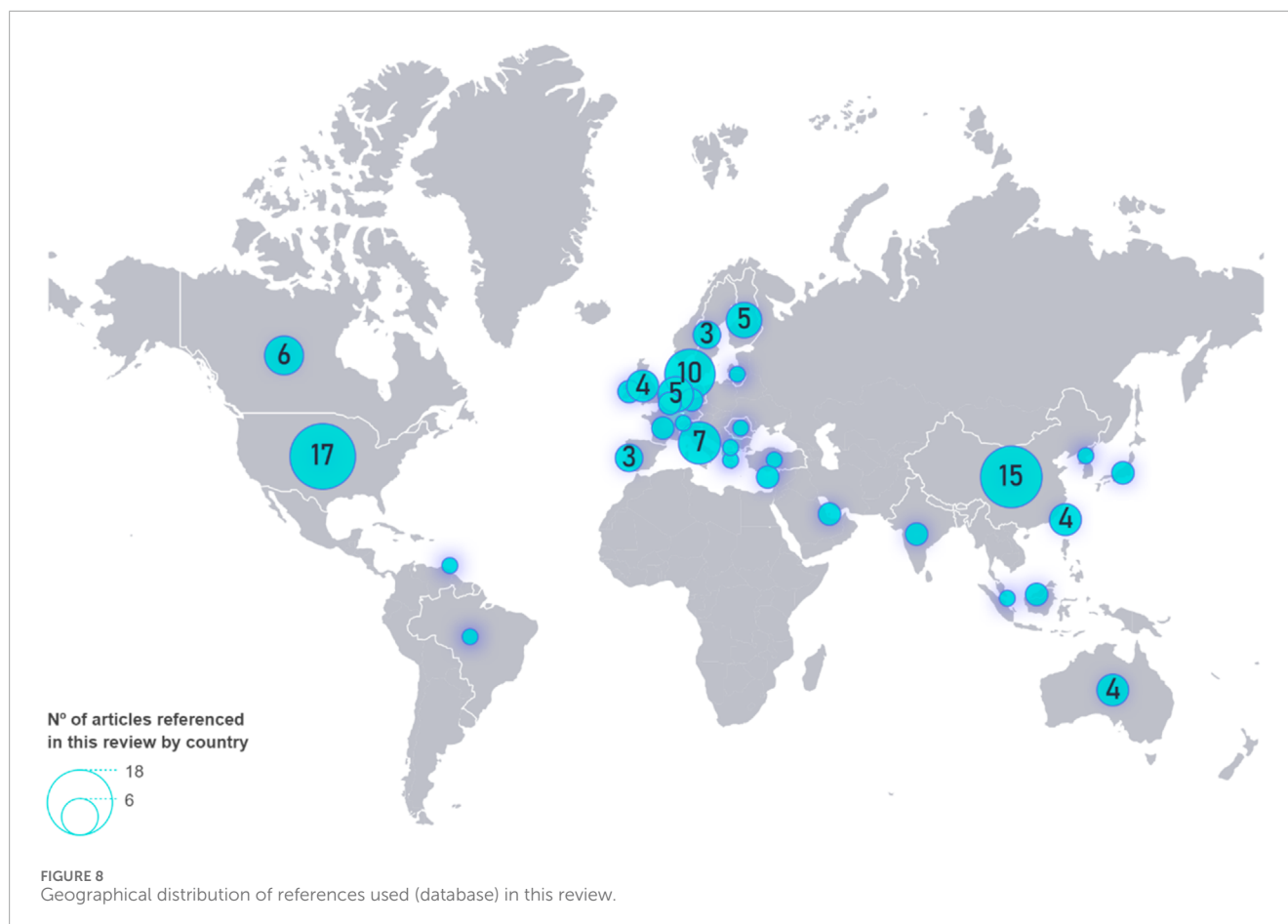
Indoor air quality (IAQ) impacts the health of the building occupants in the short and long term (Simonson et al., 2002; Wargocki et al., 2002). Addressing IAQ comprises three critical factors: external weather conditions, air renewal rates, which directly affect the consumption of HVAC systems (Mancini et al., 2020) and a comprehensive assessment of various air quality parameters. The complexity of pollutant selection goes beyond simple measurements of air temperature and relative humidity, which are typically reported. The wide range of pollutants found in indoor environments complicates the identification of any single pollutant as a sole indicator of IAQ (Ortiz et al., 2017; Wong et al., 2016).

The scientific literature shows that the most prevalent indoor air pollutants include volatile organic compounds (VOC), detected in 84% of cases; carbon dioxide (CO₂), present in 65%; asbestos in 45%; particulate matter (PM10 or PM2.5) in 16% (Karami et al., 2018). Other studies consider the former factors and add environmental parameters such as temperature (T) and relative humidity (RH) (Vilčeková et al., 2017), highlighting the close relationship between environmental conditions and thermal comfort (Šujanová et al., 2019). In addition to the pollutants already mentioned, several other airborne particles adversely affect

occupant health. Tobacco smoke, mites, pet allergens, cockroaches, mold, pollen, nitrogen oxide, formaldehyde, radon, and mineral fibers must be mitigated by adequate ventilation and air quality management strategies (Franchi et al., 2006).

These parameters are classified into intervals by classes, depending on the different contaminants obtained from the EN 13779: 2007 standard and their relationship to temperature and relative humidity. Table 2 illustrates the relationship of these parameters.

An acceptable concentration of CO₂ indoors is usually up to 1,000 ppm (Lai et al., 2009). However, the concentration levels of pollutants usually differ in summer and winter and in different rooms (Zhang et al., 2022). Under external weather conditions, the interior air relative humidity usually goes unnoticed. Not only does relative humidity affect thermal comfort, but it also affects IAQ and the occupants' health (Simonson et al., 2002). Previous research states that high relative humidity implies a higher formaldehyde concentration. Some material finishes of walls and floors can also produce volatile organic compounds (VOCs) emissions, contributing to unpleasant odors and the perception of stale air (Wolkoff and Kjærgaard, 2007). It is also important to consider air filtration systems, heat gains, airflow patterns, and pressure ratios (Šujanová et al., 2019). The tightness of the building and the use of synthetic construction or furniture materials also impact air quality (Lai et al., 2009). Occupants' habits and ventilation methods can also be relevant in maintaining good IAQ. Poor ventilation is a significant issue that typically leads to unhealthy indoor air conditions (Zhang et al., 2022).



Recommended values for IAQ can be found in standard EN 16798-3 for non-residential buildings, ASHRAE 62.1 and 62.2, and CR 1752. These standards outline ventilation requirements and offer guidance for designing buildings with adaptable IAQ. IAQ control can be achieved through natural ventilation or mechanical systems for air renewal (Šujanová et al., 2019).

4.1 Initiative indoor air quality and people's wellbeing: vulnerability in children, respiratory health in adults, sensitivity in the elderly, and cognitive function

Bluyssen et al. (2011b) and Bluyssen et al. (2011a) state that it is necessary to study the psychological and physiological state of the occupants and its impact on the way the human body reacts to IAQ. Consequently, it is essential to correlate the measurements of the IAQ factors with occupant satisfaction surveys (Andersen et al., 2009).

A perception of dryness, experienced through the mucosal surfaces of the eyes and nose, is exceptionally responsive to irritants and odors (Šujanová et al., 2019). This sensation mostly occurs due to a lack of relative or absolute humidity in indoor environments (Wolkoff, 2018; Wolkoff and Kjærgaard, 2007).

Moreover, a high accumulation of humidity due to a low ventilation rate can favor the transmission of viruses, lengthen their

lives, and worsen people's sleep quality (Wolkoff, 2018; Zhang et al., 2022). In addition, exposure to moisture can cause an increase of 30%–50% in respiratory problems, and, notably, respiratory distress and asthma usually occur slightly more in children than in young adults (Fisk et al., 2007). More aged people will be more sensitive to moisture levels, as there is less mucociliary activity, and they develop eye irritation more rapidly when relative humidity is low (Wolkoff and Kjærgaard, 2007).

Respiratory symptoms and other diseases have often appeared due to poor IAQ (Koponen et al., 2001). Numerous studies show that elevated carbon dioxide (CO₂) concentrations have been positively correlated with ocular and nasal symptoms and respiratory conditions such as cough, asthma, fatigue, and headache. Furthermore, these symptoms were most evident when mechanical ventilation or air conditioning was used, compared to natural ventilation (Apte, 2000). These effects are especially harmful among vulnerable populations, including pregnant women and children (Zhang et al., 2022).

Prolonged exposure to indoor air with CO₂ concentrations ranging from 1,000 to 2,000 parts per million (ppm) has been associated with drowsiness, while short-term exposure to concentrations around 10,000 ppm can induce respiratory toxicity in adults (Zhang et al., 2022). The high concentrations of PM_{2.5} and PM₁₀ cause arterial problems and a reduction in life expectancy by 8.6 months (Zhang et al., 2022). Other particles, such as VOCs, can become carcinogenic (Wang et al., 2007). Acknowledging the

TABLE 1 Critical synthesis across studies in thermal comfort domain. Main advances in research, common themes, differences and areas where further research is needed.

Thermal confort domain				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Coccolo et al. (2016)	JCR Q1 - 324 Cit.	Thermal comfort metrics are reviewed.	De Dear and Brager (2002) review the ASHRAE 55 standard, and Coccolo et al. (2016) review standards from the perspective of outdoor comfort and thermal stress. While Nicol and Humphreys (2002) formulate sustainable standards for an adaptive model of thermal comfort, Nikolopoulou and Steemers (2003) do so from a link with psychology for the urban environment.	Despite the significant influence of regulations, more evidence is needed, taking into account other contexts and other indoor and outdoor environments.
De Dear and Brager (2002)	JCR Q1 - 1204 Cit.			
Nicol and Humphreys (2002), Nicol et al. (2008)	JCR Q1 - 1484 Cit.			
Nikolopoulou and Steemers (2003)	JCR Q1 - 725 Cit.			
Allab et al. (2017)	JCR Q1 - 113 Cit.	Relationship between energy use, thermal comfort and sustainability.	Most studies are based on the relationship between energy, consumption and sustainability. From a more theoretical point of view, Manfren et al. (2019) and Ortiz et al. (2017) link comfort with energy consumption and wellbeing; and from a more experimental perspective, universities [Allab et al. (2017)], offices [Jazizadeh et al. (2014)], passive houses [Elsarrag and Alhorr (2012)] or, in general, [Papadopoulos et al., 2008] are taken into account. [Jazizadeh et al. (2014)].	As the balance between energy efficiency and comfort is a key issue, greater consensus on common metrics and more longitudinal studies are important.
Elsarrag and Alhorr (2012)	SJR Q2 - 33 Cit.			
Jazizadeh et al. (2014)	JCR Q1 - 190 Cit.			
Manfren et al. (2019)	Congress - 30 Cit.			
Ortiz et al. (2017)	JCR Q1 - 152 Cit.			
Papadopoulos et al. (2008)	JCR Q1 - 64 Cit.			
Corgnati et al. (2009)	JCR Q1 - 154 Cit.	Analysis of thermal perceptions based on age and gender.	Thermal comfort is studied in different age groups. On the one hand, Zhou et al. (2023) and Hughes et al. (2019) study comfort in the elderly, while on the other, Genjo (2022) studies it in babies and Corgnati et al. (2009) in schoolchildren in classrooms.	It would be interesting to see more studies on other vulnerable groups. There is a lack of housing typologies. There is a shortage of integration of these perceptions with other psychological and physiological parameters.
Genjo (2022)	JCR Q2 - 4 Cit.			
Hughes et al. (2019)	JCR Q1 - 55 Cit.			
Indraganti et al. (2014)	JCR Q1 - 244 Cit.			
Zhou et al. (2023)	JCR Q1 - 41 Cit.			

TABLE 2 Saad et al., 2017; Mancini et al., 2020.

IAQI classes	IAQI index	CO ₂ [ppm]	TVOC [ppm]	PM10 [μg/m ³]	Temperature [°C]	Relative humidity [%]
Hazardous	0–25	1501–5,000	0.431–3,000	141–750	39.1–45.0	90.1–100
Unhealthy	26–51	1001–1,500	0.262–0.430	91–140	29.1–39.1	80.1–90
Moderate	52–75	601–1,000	0.088–0.261	31–90	26.1–29.0	70.1–80
Good	76–100	340–600	0.000–0.087	0–30	20.0–26.0	40–70

external pollutants transported indoors, which must be filtered, is also crucial (Koponen et al., 2001). A controlled ventilation rate is essential in environments with children or babies, trying to reach less than 1,000 ppm (Genjo, 2022).

As shown in Table 3, related to the IAQ domain, most studies concentrate on the effects of ventilation and air pollution on health, with a particular emphasis on offices and institutional spaces. Although risks associated with chemical pollutants,

particulate matter and humidity are identified, the approaches remain partial and lack a more robust integration between chemical and biological pollutants, as well as psychosocial and behavioural parameters that condition the perception of air quality. Furthermore, there is a significant limitation in the differentiation of vulnerable populations, particularly women, children and the elderly, which reduces the applicability of the findings in more general housing scenarios. The lack of international comparisons

and methodological standardisation restricts the transferability of results to different contexts. To address this, studies need to connect scientific evidence with diverse realities and practical strategies for improving IAQ in residential and urban environments.

5 State of the art of the research on lighting and visual comfort

Good visual comfort is beneficial for users' wellbeing, who also achieve greater comfort (Serghides et al., 2015; Leech et al., 2002; Veitch, 2001). To ensure this wellbeing through visual comfort, it is crucial to consider the lighting conditions and views of the interior space. These aspects are likely to cause a significant therapeutic impact (Al horr et al., 2016; Aries, 2005; Aries et al., 2010).

5.1 Lighting conditions, glare, contrast and visual clarity, and visual comfort

Consequently, artificial and natural light, along with glare and visual comfort, must be analyzed together to achieve optimal lighting conditions (Al horr et al., 2016; Yun et al., 2012; Van Den Wymelenberg and Inanici, 2014; Huang et al., 2012). Attenuation controls could enhance visual comfort in users (Newsham et al., 2004). When evaluating lighting conditions, it is essential to analyze quantitative measurements of the light environment and qualitative aspects of vision. The former includes light flow, intensity, illuminance, luminance, availability of natural light, sunlight exposure, and glare. The latter comprise light uniformity, light sources, distribution, the intended use of interior spaces, chromatic reproduction, and the spectral composition of radiation (Putri et al., 2023; Šujanová et al., 2019).

For these measurements, we can rely on the EN 12665 standard. International standards are only based on the photopic sensitivity (diurnal) of the human eye, unknown scotopic vision (nighttime), and non-visual effects of light (Šujanová et al., 2019; Alrubaih et al., 2013). Melatonin segregation is important due to the influence of light since it invites us to sleep when it occurs. This hormone stops when humans are exposed to light, primarily to blue wavelengths, which also predominate at night (Bluyssen, 2010). Exposure to light or darkness influences sleep cycles, memory formation, immune response, and metabolic health due to its connection to circadian rhythms (Altomonte et al., 2020).

Improvements made to enhance visual comfort can produce rapid results (14). These improvements can positively affect occupants' wellbeing and reduce the total energy consumption of the building or house by up to 25% (Costa et al., 2013; Energy Efficiency, 2008; Von Neida et al., 2001).

5.2 Effect of lighting on older people and issues such as age, gender and disability

The human visual system is sensitive to wavelengths of visible radiation ranging from approximately 370 nm–730 nm, with peak sensitivity at around 555 nm. However, empirical evidence indicates that the optical performance of the human eye tends to diminish

with advancing age (Šujanová et al., 2019). Additionally, luminous flux and light intensity significantly affect sleep quality in older people (Putri et al., 2023). It is essential to consider major lighting components in relation to melatonin and serotonin production. Current estimates suggest that at least 2.2 billion people experience visual disabilities, which include 1.8 billion with presbyopia and 196 million with macular degeneration. These visual disorders have become a global health problem as the numbers grow gradually with aging (Wu et al., 2022a). The interior spaces must adapt to the deterioration of visual capacity suffered by the elderly (Fu et al., 2022). At earlier stages of life, good lighting or natural light positively affects visual capacity, immune system improvement, and comfort (Optimizing et al., 2022).

In Table 4 (visual comfort domain), we observe that research focuses on the influence of lighting and the visual environment on health, performance and psychological perception, as well as on the development of technological systems and metrics to evaluate this comfort. However, studies remain fragmented between technical (lighting systems, energy optimization) and perceptual approaches (influence of natural light, circadian rhythms, subjective perception), with little integration between the two. Also, there is a lack of validation in different building types and specific populations, such as people with visual impairments, which limits the applicability of the results. The absence of standardization in indicators, as well as the link between objective metrics and subjective perceptions, limits the findings' capacity to establish universal design criteria. It is therefore essential to adopt more robust comparative methodologies that can translate this evidence into practical guidelines that can be applied in a range of building contexts.

6 State of the art of the research on acoustic comfort

To maintain good quality of the indoor environment, it is essential to protect users from noise and provide a comfortable acoustic environment. Indoor spaces must be protected from outdoor noise and noise generated by neighboring equipment or facilities (Al horr et al., 2016). Sound perception depends not only on the intensity of the sound and its temporal and spectral characteristics but also on the individual's activities, psychological state, and a variety of other contextual factors (Šujanová et al., 2019).

6.1 Conditions for noise perception, acoustic comfort, and speech intelligibility

A high noise level, spectrum, and variation over time influence the level of disturbance and can be perceived as a lack of privacy in communication (Al horr et al., 2016). Continuous and regular sound patterns are less disruptive than noise emanating from various sources and irregular sounds (Veitch et al., 2002). Therefore, a thorough analysis of indoor acoustics must include indoor sound frequency and pressure, sound insulation, acoustic absorption, and reverberation time. In addition, the acoustic quality is multidimensional since it comprises three main variables: sound field, auditory evaluation, and auditory perception (Šujanová et al.,

TABLE 3 Critical synthesis across studies in IAQ domain. Main advances in research, common themes, differences and areas where further research is needed.

Indoor air quality domain				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Apte (2000)	JCR Q1 - 279 Cit.	Relationship between poor ventilation and its impact on health (SBS symptoms and illnesses, among others) depending on different sources of air pollution.	Most studies focus on the impact on health due to poor air quality in office buildings, except for Takigawa et al. (2009) , which focuses on homes, and Wargocki et al. (2002) , which focuses on non-industrial buildings in Europe. While some studies indicate that CO ₂ particles are the source of pollution [Apte (2000)], others point to other types generated by computers [Bakó-Biró et al. (2004)] or air conditioners [Mendell and Smith (1990)]; other types of ventilation systems [Seppänen and Fisk (2002) ; Wargocki (1999)]. Most focus on the symptoms of Sick Building Syndrome, while others delve into a wider range of health impacts in offices [Chao et al. (2003)] or symptoms due to outdoor pollution inside buildings [Koponen et al. (2001)].	It does not integrate most psychosocial and behavioural variables. It is very limited to office buildings. Nor does it differentiate between population groups, even by gender or age.
Bakó-Biró et al. (2004)	JCR Q1 - 179 Cit.			
Chao et al. (2003)	JCR Q1 - 102 Cit.			
Koponen et al. (2001)	JCR Q1 - 147 Cit.			
Mendell and Smith (1990)	JCR Q1 - 189 Cit.			
Seppänen and Fisk (2002)	JCR Q1 - 225 Cit.			
Stolwijk (1991)	JCR Q1 - 6 Cit.			
Takigawa et al. (2009)	JCR Q1 - 58 Cit.			
Wargocki (1999)	JCR Q1 - 410 Cit.			
Wargocki et al. (2002)	JCR Q1 - 366 Cit.			
Fisk et al. (2007)	JCR Q1 - 576 Cit.	Importance of relative humidity in health and comfort; if it is deficient, there is clear evidence of risks from mould and other contaminants, causing illness.	While most focus on the quality of air humidity, Fisk et al. (2007) and Franchi et al. (2006) apply it to homes, and Fisk et al. (2007) also describe effects and symptoms on the health of occupants. Simonson et al. (2002) explore the possibility of achieving greater comfort and a perception of better air quality based on indoor humidity.	There is a need for greater integration between chemical and biological contaminants.
Franchi et al. (2006)	JCR Q3 - 52 Cit.			
Simonson et al. (2002)	JCR Q1 - 155 Cit.			
Wang et al. (2007)	JCR Q1 - 632 Cit.			
Wolkoff (2018)	JCR Q1 - 540 Cit.			
Wolkoff and Kjærgaard (2007)	JCR Q1 - 201 Cit.			
Ben-David and Waring (2016)	JCR Q1 - 131 Cit.	Direct impact of ventilation on energy consumption and indoor air quality, seeking to improve quality while increasing energy efficiency.	The impact on consumption depending on the type of natural or mechanical ventilation is observed in offices by Ben-David and Waring (2016) . When compared to buildings without air conditioning: Ole Fanger and Toftum (2002) . The optimisation of consumption based on ventilation rates is observed in Mancini et al. (2020) , while Wang et al. (2016) analyses a way to conserve and recover heat in multi-family dwellings. Merema et al. (2018) show what has been learned from controlled ventilation in offices and also in schools. Zhang et al. (2022) conduct a study on a new type of ventilation system for homes in rural China with elderly people. In addition, efforts are being made to improve IAQ through ventilation and energy efficiency, as in Chenari et al. (2016) , and in schools: Daisey et al. (2003) .	While different types of buildings and different population groups such as children, adolescents and the elderly are assessed, the effect on pregnant women is not considered.
Chenari et al. (2016)	JCR Q1 - 408 Cit.			
Daisey et al. (2003)	JCR Q1 - 812 Cit.			
Mancini et al. (2020)	JCR Q1 - 33 Cit.			
Merema et al. (2018)	JCR Q1 - 82 Cit.			
Ole Fanger and Toftum (2002)	JCR Q1 - 712 Cit.			
Wang et al. (2016)	JCR Q1 - 38 Cit.			
Zhang et al. (2022)	JCR Q2 - 3 Cit.			

(Continued on the following page)

TABLE 3 (Continued) Critical synthesis across studies in IAQ domain. Main advances in research, common themes, differences and areas where further research is needed.

Indoor air quality domain				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Preziosi et al. (2004)	JCR Q1 - 25 Cit.	Methods and strategies for improving indoor air quality and, consequently, health.	On the one hand, Vilčeková et al. (2017) focus on housing in Macedonia, while Preziosi et al. (2004) efocus on women working in offices. Wong et al. (2016) conduct an assessment and seek strategies.	International standardisation or comparisons between countries would be interesting.
Vilčeková et al. (2017)	JCR Q2 - 48 Cit.			
Wong et al. (2016)	JCR Q2 - 14 Cit.			

TABLE 4 Critical synthesis across studies in Visual Comfort domain. Main advances in research, common themes, differences and areas where further research is needed.

Visual confort domain				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Aries (2005)	JCR Q2 - 116 Cit.	Influence of lighting and the visual environment on health (sleep, circadian rhythms, vision) and psychological perception.	The visual demands required by humans to be healthy are outlined in Aries (2005), and the characteristics for visual comfort in offices are discussed by Aries et al. (2010), while Fu et al. (2022) apply this to nursing homes. Putri et al. (2023) discuss the effect of light and sleep on older adults, Tao et al. (2022) discusses colour in classrooms, and Kong et al. (2022) discusses physiological responses to natural light. Chang and Chen (2005) write about the importance of nature (plants and outdoor views) at work in order to achieve visual comfort.	Shortages in different types of buildings and in other interesting groups, such as those with visual impairments.
Aries et al. (2010)	JCR Q2 - 424 Cit.			
Chang and Chen (2005)	JCR Q2 - 372 Cit.			
Fu et al. (2022)	JCR Q2 - 11 Cit.			
Kong et al. (2022)	JCR Q2 - 21 Cit.			
Putri et al. (2023)	SJR Q3 - - Cit.			
Tao et al. (2002)	JCR Q2 - 11 Cit.			
Budhiyanto and Chiou (2022)	JCR Q2 - 11 Cit.	Lighting control through systems and technologies.	While Budhiyanto and Chiou (2022) propose a lighting control system with HDR, Von Neida et al. (2001) proposes occupancy sensors for energy saving. On the other hand, Optimizing et al. (2022) explains how lighting in classrooms with atriums improves light performance, and Wu et al. (2022a) explains how to achieve light optimisation in heritage buildings.	Despite its importance in future smart buildings, further validation and more building typologies are needed.
Optimizing et al. (2022)	JCR Q2 - 15 Cit.			
Von Neida et al. (2001)	JCR Q4 - 105 Cit.			
Wu et al. (2022a)	JCR Q2 - 15 Cit.			
Xu et al. (2022a)	JCR Q2 - 16 Cit.			
Alrubaih et al. (2013)	JCR Q1 - 127 Cit.	Analysis of metrics that determine visual comfort and evaluation of designs and spaces to achieve visual comfort.	Van Den Wymelenberg and Inanici (2014) questions current lighting design metrics and indicators, while Veitch (2001) focuses on the psychology of perception and Alrubaih et al. (2013) on light dimming control. The effect of interior space design and window geometry is evaluated in schools [Jia et al. (2023)], hotels [Xu et al. (2022b)] and open-plan offices to determine visual and thermal comfort [Yun et al. (2012)].	In the metrics presented, there is little integration with physiological indicators and subjective perception, and standardisation, which is important for design standards.
Jia et al. (2023)	JCR Q2 - 12 Cit.			
Van Den Wymelenberg and Inanici (2014)	JCR Q2 - 175 Cit.			
Veitch (2001)	JCR Q4 - 153 Cit.			
Xu et al. (2022b)	JCR Q2 - 11 Cit.			
Yun et al. (2012)	JCR Q2 - 107 Cit.			

2019). Some standards outlining measurement procedures and associated guidelines include ISO 10140, ISO 717, ISO 3382, and ISO 12354. The auditory system can perceive volume, 1300 tones, intervals, and timbre, as well as the spatial perception of the source in direction and distance (Zhong et al., 2014).

6.2 Effect on the wellbeing of elderly people who are exposed to loud noise. Impact of age, gender, and disability

Humans can perceive vibrations and resonances even in the fetal stage ranging from 10–5 Pa to 100 Pa (with 0 dB being the hearing threshold and 120 dB the pain threshold) and in a frequency spectrum from 20 Hz to 20 kHz. However, the upper-frequency limit is often reduced with age to 16 kHz (Šujanová et al., 2019). This age-related decline in the auditory range explains that satisfaction with the noise level is higher for elderly people (Zalejska-Jonsson and Wilhelmsson, 2013; Frontczak et al., 2012; Chiang et al., 2001). Nonetheless, the acoustic quality of the current environment is inappropriate for the elderly with hearing loss (Fu et al., 2022). In addition to auditory decline, other issues such as tinnitus, sleep disturbances, hypertension, and cardiovascular diseases may arise, and, in the case of children, cognitive decline (Altomonte et al., 2020). Therefore, ensuring an adequate acoustic environment is critical in the presence of children and babies engaged in crucial stages of speech intelligibility development. The World Health Organization (WHO) recommends that background noise levels should not exceed 35 dB to foster an optimal auditory environment (Genjo, 2022), in contrast to the higher tolerable noise level of up to 80 dB reported by young adults (Altomonte et al., 2020).

In the Acoustic domain, as shown in Table 5, research has been conducted on the impact of noise on health, productivity and cognitive function, with a particular focus on educational settings, offices and specialized residences. However, literature is limited in terms of replication and geographical scope, which weakens the robustness of the conclusions. Furthermore, although architectural and technological solutions for acoustic control are recognized, the studies lack comparative integration that would allow for an evaluation of the joint effectiveness of these strategies in different types of buildings. Another significant gap is the lack of attention to populations with specific vulnerabilities, including people with hearing loss. Therefore, there is a need to move towards interdisciplinary and comparative research that allows for an understanding of the acoustic impact in a greater diversity of contexts and users, contributing to more inclusive and applicable design guidelines.

7 Interaction between sensory perception, cognitive function and design and IEQ in vulnerable groups

Although there is still a limited understanding of human perception's neurological and biological mechanisms, it is necessary and beneficial to understand how humans perceive and what effects it brings to the environment. Researchers must address psychological and sociological methodologies (Wu et al., 2023a).

Indoor natural light landscapes can influence physiological indicators (Kong et al., 2022), while colors can affect emotional indicators (Tao et al., 2022). These findings provide supporting data for future developments in the therapeutic effects of indoor environments on health (Wu et al., 2023a). In addition, natural or biophilic elements, vegetation, and even artificial greenery are incorporated into buildings to improve mental health, help stress, and achieve cognitive recovery and mental fatigue. Being surrounded by plants causes positive stimulation that favors the recovery of diseases (Chang and Chen, 2005).

When analysing the four domains of environmental comfort (Tables 1, 3, 4, 5)—thermal, visual, acoustic and indoor air quality—together, it is evident that, although there is a solid base of studies addressing metrics, standards and effects on health and wellbeing, research remains fragmented and with significant gaps. Each domain focuses on a limited set of technical variables, leaving integration with the psychological, social and behavioural aspects that are essential to understanding the actual experience of occupants in the background. Furthermore, the diversity of contexts and populations is underrepresented: studies favour offices, schools or institutional environments, while vulnerable groups—such as children, older adults, or people with disabilities—receive little attention.

Even in Table 6 (Critical synthesis across studies in IEQ), research lacks of consensus and standardisation in metrics and indices across studies. This limits comparisons between building types, cultural contexts and population groups:

Lack of standardized metrics and methodologies, along with limited international comparability, restricts the application of results of practical design and regulatory criteria.

7.1 Thresholds for vulnerable population according to regulations

Reviewing different regulations enables us to identify certain reference thresholds applicable to groups not considered vulnerable. Therefore, the values for vulnerable groups in Table 7 are estimates, as they are not specifically defined and do not apply to each group. Further research is needed in this regard to determine whether the domains are relevant, or whether it would be more advisable to propose adjustments for a more accurate and consistent representation of vulnerability conditions based not only on global regulations and find standardised metrics applicable worldwide.

8 Design of healthy and inclusive buildings

The World Health Organization (WHO) defined healthy buildings in 1990. In many investigations, wellbeing is related to the design of buildings and quality standards. However, to achieve and seek objectives to improve the interior environment's quality, it is important to formulate pertinent inquiries that facilitate effective design strategies to promote wellbeing and accommodate forthcoming factors (Bluyssen, 2010; Altomonte et al., 2020). Attributes of the building, such as the construction materials, the climatic conditions, or those related to users (gender and age, needs

TABLE 5 Critical synthesis across studies in Acoustic domain. Main advances in research, common themes, differences, and areas where further research is needed.

Acoustic domain				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Anderson (2008)	JCR Q1 - 11 Cit.	Effect of noise on health and productivity, in cognitive aspects.	While Anderson (2008) and Bottalico and Astolfi (2012) focus on the school context and how acoustics affect the educational process and cognition in children and adolescents, Wu et al. (2022a) investigate sound perception in elderly and blind people in care homes. On the other hand, Landström et al. (1995) and Loewen and Suedfeld (1992) focus on the cognitive effects and exposure levels caused by noise in offices.	Few replicated studies, with no real evidence in different regions. Long-term work performance needs to be determined and other new working conditions such as teleworking need to be considered. Studies on hearing impairment would be interesting.
Bottalico and Astolfi (2012)	JCR Q1 - 103 Cit.			
Landström et al. (1995)	JCR Q1 - 124 Cit.			
Loewen and Suedfeld (1992)	JCR Q1 - 111 Cit.			
Wu et al. (2022a)	JCR Q2 - 3 Cit.			
Passero and Zannin (2012)	JCR Q2 - 37 Cit.	Acoustic control through design to improve noise levels in interior spaces.	Passero and Zannin (2012) use architecture and design as a solution to acoustic exposure; Veitch et al. (2002) explore the use of the concept of masking noise (simulated ventilation).	Lack of comparative studies seeking to integrate architectural and technological solutions.
Qu et al. (2022)	JCR Q2 - 7 Cit.			
Veitch et al. (2002)	Internal Report Canada			

and comfort) (95) must be considered at early design stages since they affect the quality of the interior environment (Frontczak et al., 2012). Additionally, economic factors—about financing and the final valuation—coupled with environmental considerations, such as resource utilization, sustainable management practices, and life cycle assessments, must also be incorporated (Bluyssen, 2010). These behavioral aspects remain absent in building certifications such as LEED, BREEAM, or CASBEE. The challenges in defining a healthy building may be due to the conflicting interests between sustainability and the quality of life of the occupants, among others (Bluyssen, 2010; Hua et al., 2014; Schiavon and Altomonte, 2014). This review observes a scarcity of literature that connects IEQ with energy efficiency (Manfredi et al., 2019; Lee and Guerin, 2010).

Renovation projects provide clear opportunities to improve building efficiency, including upgrades such as window replacement, roof and wall insulation, renewable energy integration, and the installation of adapted heating or indoor humidity control systems for enhanced thermal comfort (De Santoli et al., 2018; Mikučionienė et al., 2014). In contrast, in new buildings, there must also be a physical adaptation of the environment at the early stages of the design, avoiding the inefficiency and cost associated with renovations (Jazizadeh et al., 2014; Indraganti et al., 2014; Lozinsky et al., 2025). In this adaptation, it is important to consider the climate and the influence of culture (Lovins, 1992). For instance, mechanical cooling is necessary in the Middle East to maintain an optimal level of comfort for occupants (Nicol et al., 2008), whereas, in tropical climates, natural ventilation consumes significantly less energy and provides users with a closer connection to nature (Fisher, 2000).

Design strategies to achieve thermal comfort have evolved to adapt to environmental variability (Table 8). These strategies include

operable windows, blinds devices, or automated controls that change their settings in response to changing weather conditions. Among sustainable design strategies, natural ventilation and other passive climate approaches have proven to be the most effective (Deuble and de Dear, 2012). Other factors determining the occupant's final perception are behavior, physiological adaptation, and psychological expectation (Bluyssen, 2010; Nikolopoulou and Steemers, 2003). As a reference for the design, the ASHRAE 55 and the ISO 7730 standards (1994) define thermal comfort worldwide.

IAQ is a more complex problem because it depends on external weather conditions and air renewal rates, which directly affect the consumption of HVAC systems (Mancini et al., 2020). Energy-saving strategies must include building design, the implementation of demand-controlled ventilation (DCV) (Merema et al., 2018), or building automation and control systems (BACs). These systems optimize HVAC operation by regulating airflow rates and employing diverse ventilation methodologies (Chenari et al., 2016; Ben-David and Waring, 2016; Mancini et al., 2019; Aste et al., 2017). At the time of day, intelligent or Smart control systems control airflow, temperature, and humidity, among others. Another way to control humidity is by selecting suitable building materials capable of moisture retention, such as wood, which is an alternative approach to humidity control (Simonson et al., 2002).

In building design, the most effective strategies for improving IAQ involve either increasing the ventilation rate, reducing air pollutants (Daisey et al., 2003), or minimizing pollution sources inside and outside the building (Wargocki, 1999). Another passive strategy is the use of natural ventilation (Al horr et al., 2016; Chenari et al., 2016), which can significantly lower cooling energy costs and reduce instances of Sick Building Syndrome (SBS) among occupants (Borgeson and Brager, 2011; Seppänen and Fisk, 2002).

TABLE 6 Critical synthesis across studies in IEQ. Main advances in research, common themes, differences and areas where further research is needed.

Indoor environmental quality (IEQ)				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Al horr et al. (2016)	SJR Q2 - 633 Cit.	Impact of indoor air quality and its various factors on health and wellbeing, with particular vulnerability among children and the elderly.	Most studies analyse the impact of IEQ on health and its link to wellbeing. Al horr et al. (2016) and Frontczak and Wargocki (2011) do so from a general review, and Altomonte et al. (2020) pose 10 guiding questions. In offices, Bluysen (2010), Bluysen et al. (2011a), (2011b) and Huang et al. (2012) study it from the perspective of sustainable certifications, as does Lee and Guerin (2010). From this perspective, but in more general building typologies, Schiavon and Altomonte (2014) also do so. In universities, Zuhaib et al. (2018). In a framework of healthy ageing, Beard et al. (2016).	There is a lack of consensus on how to measure IEQ and relate it to wellbeing in a standardised and comparable way across countries. It would be noteworthy to study more building types and different population groups.
Altomonte et al. (2020)	JCR Q1 - 214 Cit.			
Beard et al. (2016)	JCR Q1 - 2028 Cit.			
Bluysen (2010), Bluysen et al. (2011a); Bluysen et al. (2011b)	JCR Q1 - 140 Cit. JCR Q1 - 232 Cit. JCR Q1 - 109 Cit.			
Frontczak and Wargocki (2011)	JCR Q1 - 952 Cit.			
Huang et al. (2012)	JCR Q1 - 269 Cit.			
Lee and Guerin (2010)	JCR Q1 - 80 Cit.			
Schiavon and Altomonte (2014)	JCR Q1 - 2 Cit.			
Wu et al. (2023a)	JCR Q1 - 3 Cit.			
Zuhaib et al. (2018)	JCR Q1 - 109 Cit.			
Chiang et al. (2001)	JCR Q1 - 62 Cit.	Development of IEQ assessment indices and models, seeking standardisation.	With regard to IEQ assessment, different perspectives are provided. Chiang et al. (2001): methodology for elderly care centres, focusing on comfort and safety. Heinzerling et al. (2013): weighting scheme to systematise assessment. Lai et al. (2009): residential acceptance model based on occupants' perceptions. Laskari et al. (2016): quantitative index measuring fundamental environmental parameters in homes. Saad et al. (2017): index combining air quality and thermal comfort.	Lack of standardisation and consensus on metrics and indices applicable to different types of buildings, and how to weight each parameter, integrating subjective and objective factors.
Heinzerling et al. (2013)	JCR Q1 - 264 Cit.			
Lai et al. (2009)	JCR Q1 - 254 Cit.			
Laskari et al. (2016)	JCR Q3 - 22 Cit.			
Saad et al. (2017)	Congress - 22 Cit.			

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TABLE 6 (Continued) Critical synthesis across studies in IEQ. Main advances in research, common themes, differences and areas where further research is needed.

Indoor environmental quality (IEQ)				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Costa et al. (2013)	JCR Q1 - 338 Cit.	Monitoring methodologies with sensors and systems for measuring IEQ in real time.	There is agreement on the need for continuous and accessible IEQ measurement systems, although with different scopes. Costa et al. (2013): comprehensive toolkit for managing and optimising the energy performance of buildings. Karami et al. (2018): continuous monitoring system with Arduino. Tiele et al. (2018): portable, low-cost device.	Lack of standardisation of metrics and linking objective measurements with occupant perception.
Karami et al. (2018)	JCR Q2 - 126 Cit.			
Tiele et al. (2018)	JCR Q3 - 80 Cit.			
Aste et al. (2017)	JCR Q1 - 159 Cit.	Evaluation of architectural design decisions to improve IEQ, wellbeing and comfort.	Various approaches are observed that reflect the importance of design decisions. Aste et al. (2017) propose a design analysis framework based on automation and control to optimise building performance, while Catalina and Iordache (2012) place IEQ assessment in the design phase of schools, anticipating its impact before construction. In offices: Shafaghat et al. (2014). From a climate and energy efficiency perspective: Katafygiotou and Serghides (2015) and Steemers and Manchanda (2010). Wang et al. (2022) integrate physiological and psychological metrics into the design of spaces for older adults.	Most studies are one-off and do not include follow-up over time, which means that how comfort evolves after occupation remains unexplored. Vulnerable groups are given little consideration.
Catalina and Iordache (2012)	JCR Q1 - 109 Cit.			
Katafygiotou and Serghides et al. (2015)	JCR Q3 - 46 Cit.			
Shafaghat et al. (2014)	JCR Q3 - 25 Cit.			
Steemers and Manchanda (2010)	JCR Q1 - 72 Cit.			
Wang et al. (2016)	JCR Q2 - 12 Cit.			
Andersen et al. (2009)	JCR Q1 - 343 Cit.	Seeking occupant satisfaction through IEQ surveys based on occupant behaviour patterns or habits.	The studies in this group explore occupant satisfaction with IEQ through surveys and the analysis of habits or behaviours. In homes, Carton et al. (2022) and Zalejska-Jonsson and Wilhelmsson (2013) examine perceptions of comfort, while Andersen et al. (2009) focus on users' active control over their environment. In educational contexts, Wu et al. (2023a) combine psychosocial preferences with IEQ, and Serghides et al. (2015) show how habits change with the season. In offices, Frontczak et al. (2012) stand out for their correlations between design and satisfaction, Gunay et al. (2013) for their review of adaptive behaviours, Hua et al. (2014) for spatial mapping, and Kallio et al. (2020) for integrating sensor data and personality profiles. Finally, Borgeson and Brager (2011) show that comfort standards are not always reflected in the expectations of the users.	There is no direct relationship between objective measurements and subjective perceptions, which is limiting. While some studies measure environmental conditions, others are limited to surveys, but few combine both approaches systematically.
Borgeson and Brager (2011)	JCR Q3 - 69 Cit.			
Carton et al. (2022)	Congress - 8 Cit.			
Gunay et al. (2013)	JCR Q1 - 249 Cit.			
Frontczak et al. (2012)	JCR Q1 - 486 Cit.			
Hua et al. (2014)	JCR Q1 - 94 Cit.			
Kallio et al. (2020)	JCR Q1 - 57 Cit.			
Serghides et al. (2015)	JCR Q4 - 53 Cit.			
Wu et al. (2023a)	JCR Q2 - 9 Cit.			
Zalejska-Jonsson and Wilhelmsson (2013)	JCR Q1 - 90 Cit.			

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TABLE 6 (Continued) Critical synthesis across studies in IEQ. Main advances in research, common themes, differences and areas where further research is needed.

Indoor environmental quality (IEQ)				
Articles included	Quality index	Common theme	Contribution of each article	Areas to explore or investigate
Anda and Temmen (2014)	JCR Q1 - 113 Cit.	Relationship between indoor environmental quality, comfort, energy and consumption, seeking to ensure that buildings are also sustainable.	Most of these studies explore the relationship between energy efficiency and indoor environmental quality, but differ in their approach. Some focus on the energy analysis of the built environment [Anda and Temmen (2014)], while others integrate health and wellbeing from a broader perspective [Anderson et al. (2015)]. There is research that examines the gap between green buildings and occupant perception [Deuble and de Dear (2012); Kua and Lee (2002)], as well as applied work in green-certified schools and offices [Dias Pereira et al. (2017); Liang et al. (2014)]. Also noteworthy are methodological and multi-criteria decision-making approaches [Mancini et al. (2019); Mancini et al. (2020)] and reviews that offer a broader overview of automation, comfort, energy and health [Mikučionienė et al. (2014); Quang et al. (2014); Soares et al. (2017); Šujanová et al. (2019)].	There is little research on different building types and contexts such as homes, hospitals, and residences in different parts of the world. More longitudinal studies are needed to understand actual comfort in sustainable buildings.
Anderson et al. (2015)	JCR Q1 - 184 Cit.			
Deuble and de Dear (2012)	JCR Q1 - 219 Cit.			
Dias Pereira et al. (2017)	JCR Q1 - 30 Cit.			
Kua and Lee (2002)	JCR Q1 - 78 Cit.			
Liang et al. (2019)	JCR Q1 - 205 Cit.			
Liang et al. (2014)	JCR Q1 - 56 Cit.			
Mancini et al. (2019); Mancini et al. (2020)	JCR Q2 - 40 Cit.			
Mikučionienė et al. (2014)	JCR Q1 - 77 Cit.			
Quang et al. (2014)	JCR Q1 - 36 Cit.			
Soares et al. (2017)	JCR Q1 - 205 Cit.			
Šujanová et al. (2019)	JCR Q2 - 115 Cit.			

TABLE 7 Estimated thresholds for vulnerable population according to regulations. Four most important domains within IEQ.

Estimated thresholds for vulnerable population groups: Indoor air quality						
Population	CO ₂ (ppm)	TVOC (µg/m ³)	PM2.5 (µg/m ³)	PM10 (µg/m ³)	Formaldehyde (mg/m ³)	Regulation
Healthy adults	≤900-1000	≤300	≤10	≤20	≤0.1	UNE-EN 16798-1, OMS, ASHRAE 62.1
Elders or adults over 65	≤800	≤200	≤5–10	≤15–20	≤0.05–0.08	OMS, UNE 171330-2, ISO 16000
Disabled people	≤800	≤200	≤5–10	≤15–20	≤0.05–0.08	OMS, UNE 171330-2
Pregnant women	≤800	≤150–200	≤5–10	≤15	≤0.05	OMS, EPA
Babies and children	≤700–800	≤150	≤5	≤10–15	≤0.03–0.05	OMS, EPA
Estimated thresholds for vulnerable population groups: Thermal comfort						
Population	Temperature (°C)	Relative humidity (%)	Air velocity (m/s)	Metabolic activity (MET)	Clothing insulation (Clo)	Regulation
Healthy adults	20–24 (w), 23–26 (s)	40–60	<0.15	1.0–1.2	0.5–1.0	ISO 7730, ASHRAE 55, UNE 171330
Elders or adults over 65	21–24	40–60	<0.15	0.9–1.1	0.7–1.1	ISO 7730
Disabled people	21–24	40–60	<0.15	0.9–1.1	0.7–1.1	ISO 7730
Pregnant women	21–24	40–60	<0.15	1.0	0.6–1.0	ASHRAE 55
Babies and children	22–25	40–60	<0.15	0.8–1.0	0.5–0.8	ISO 7730, ASHRAE 55
Estimated thresholds for vulnerable population groups: Visual comfort						
Population	Lux	Melanopic EDI	Ugr unified glare rating	CRI colour rendering index	Regulation	
Healthy adults	500	≥ 250	<19	>80	CIE S 026, UNE-EN 12464-1, WELL	
Elders or adults over 65	500	≥ 250	<19	>80	WELL v2, CIE S 026, DIN SPEC 67600	
Disabled people	300–500	≥ 200–250	<19	>80	CIE S 026, WELL	
Pregnant women	300	≥ 250	<19	>90	WELL, DIN SPEC 67600	
Babies and children	300–500	≥ 200–250	<19	>80	WELL, CIE	
Estimated thresholds for vulnerable population groups: Acoustic						
Population	Sound level (dB(A))		Reverberation T60 (s)		Regulation	
Healthy adults	≤45-55		≤0.6		UNE-EN ISO 22955:2021	
Elders or adults over 65	≤35		≤0.5		OMS, UNE 74201	
Disabled people	≤35		≤0.5		UNE 74201	
Pregnant women	≤35		≤0.5		OMS	
Babies and children	≤30–35		≤0.4		OMS, UNE 74201, ISO 3382	

TABLE 8 Comparative framework: the impact of different IEQ domains on different vulnerable groups.

Vulnerable group	Thermal comfort	Indoor air quality	Lighting/visual comfort	Acoustic comfort
Children	Sensitive to rapid temperature changes; poor thermoregulation increases risk of discomfort in schools and homes.	High prevalence of asthma and respiratory diseases linked to poor ventilation and VOC exposure.	Adequate daylight and circadian lighting essential for learning and eye development.	Noise negatively affects cognitive performance, language development, and concentration.
Elderly	Reduced perception of thermal changes; higher risk of overheating and hypothermia due to physiological decline.	Strong association with cardiovascular and respiratory morbidity when exposed to pollutants.	Higher light intensity required due to visual decline; glare sensitivity is common.	Noise disturbs sleep and increases risk of cardiovascular stress; age-related hearing loss complicates perception.
Pregnant women	Increased sensitivity to heat stress; thermal discomfort may impact sleep quality.	Exposure to pollutants (PM2.5, CO, VOCs) linked to adverse birth outcomes.	Proper lighting supports circadian rhythm and mental wellbeing during pregnancy.	Excessive noise associated with maternal stress, hypertension, and sleep disruption.
People with disabilities	Limited capacity to adapt behaviorally (e.g., mobility impairments limit thermoregulation strategies).	Often highly dependent on indoor air due to reduced mobility; poor IAQ exacerbates existing conditions.	Visual impairments require adapted lighting solutions; cognitive disabilities may increase sensitivity to visual discomfort.	Noise particularly disruptive for individuals with cognitive or sensory disabilities, exacerbating stress and behavioral issues.

Nevertheless, natural ventilation is not always adequate if there is a significant temperature difference between the indoors and outdoors, which limits its effectiveness in removing indoor pollutants (Zhang et al., 2022). Other passive ventilation systems include solar chimneys on the facade or roof, Trombe walls, and pipes with geothermal air, which are based on solar energy and the residual heat of buildings, increasing the ventilation rate and air temperature. However, those strategies are ineffective in eliminating indoor pollutants and depend on an unstable value of variable solar radiation (Zhang et al., 2022). A more reliable solution may be mechanical ventilation. This solution controls the airflow and starts and stops ventilation to control the pollutants. Additionally, underground ducts can help preheat incoming cold air using the ground's temperature, improving air quality and enhancing the overall benefits of the ventilation system (Bluyssen, 2010; Wang et al., 2016).

It is essential to ensure visual comfort inside buildings, as it affects the wellbeing of users throughout the day. Some researchers estimate that 30% of energy consumption corresponds to building lighting (Budhiyanto and Chiou, 2022). Decisions such as the geometry and location of windows, surface photometry, the amount of glass, the dense distribution of space, the use of colors, and shading devices are critical for achieving high-quality interior lighting (Al horr et al., 2016; Serghides et al., 2015). By focusing on these elements, building designers can avoid some of the negative impacts associated with poor lighting, such as compromised sleep quality, vision loss, and glare (Chang and Chen, 2005; Serghides et al., 2015; Veitch, 2001). Natural light is considered an essential factor to consider when designing buildings (Optimizing et al., 2022). It not only enhances aesthetic appeal but also reduces the energy demand for electric lighting (Wu et al., 2022b). In renovations, especially in protected facades, the entry of natural light through ceiling openings must be incorporated whenever possible (Wu et al., 2022a). Light

control sensors are a system that is implemented in building design, which achieves optimal results and reduces consumption by up to 60% (Jia et al., 2023).

An effective interior design must balance visual comfort with acoustic design without neglecting key acoustic control methods in the form of physical barriers, which often occur in open spaces (98). The geometry of a room plays a significant role. A square area will provide greater acoustic comfort than a long, narrow one, creating a “bowling alley” effect and causing the sound to bounce between the walls (Acoustics in Educational Settings, 2005). ASHRAE Standard 50 recommends minimizing hard surfaces, as these can reduce sound absorption and increase interior noise levels (Anderson, 2008). Therefore, traditional methods include using sound-absorbing materials such as textiles on ceilings, walls, and floors to enhance the acoustic environment.

The selection of appropriate building materials is essential for ensuring good IEQ (Takigawa et al., 2009). The selected materials can significantly impact a space's thermal, visual, and acoustic comfort (Al horr et al., 2016).

Acoustics is an essential domain to avoid problems in the health and comfort of users (Andersen et al., 2009; Anderson, 2008). A comprehensive assessment of acoustic performance must encompass internal and external noise factors and consider anticipated occupancy patterns within the rooms (Bluyssen et al., 2011a; Bluyssen et al., 2011b). Different strategies can be adopted depending on the source of the noise. If the noise comes from outside, using absorbent materials and acoustic insulation in the ceiling, façade, and windows is advisable. Incorporating absorbent materials and acoustic insulation in the ceiling, façades, and window assemblies is recommended for external noise sources (Qu et al., 2022). If the noise comes from the interior space, physical barriers such as panels in the distribution or electronic sound masking techniques will be used (Loewen and Suedfeld, 1992). The volume, spatial configuration, and the selection of

materials or barriers are decisive in achieving acoustic comfort (Šujanová et al., 2019). Despite an increasing emphasis on acoustic comfort factors, the criteria for efficient certifications are often not mandatory in this area, and their indications and guidelines are often incomplete (Schiavon and Altomonte, 2014).

9 Discussion

A building design process that integrates social, environmental, and economic factors into the building can lead to enhanced energy performance and improve IEQ (Steemers and Manchanda, 2010; Kua and Lee, 2002; Iwaro and Mwasha, 2013). However, a conflict between these buildings' performance and users' wellbeing remains. A lower ventilation rate means high energy efficiency but also increases the concentration of suspended particles indoors (Lai et al., 2009; Koponen et al., 2001). Moreover, optimizing ventilation rates to prioritize occupants' comfort might increase acoustic issues due to airflow background noise (Deuble and de Dear, 2012). Decisions regarding ventilation and choices about materials, lighting levels, and other factors ultimately affect occupant wellbeing. Unfortunately, it is a general practice for building designers to promote energy efficiency over the wellbeing of the user (Lai et al., 2009; Koponen et al., 2001; Liang et al., 2014). This practice often leads to pursuing certifications for sustainable design, such as LEED, BREEAM, and GSAS, at the expense of the user's experience (Elsarrag and Alhorr, 2012).

The use of these certifications generates a contemporary metric depending on the energy efficiency of the building, thanks to simulation tools of the proposed design (WBDG Home), which prioritizes low energy consumption (Šujanová et al., 2019). Usually, one-third of the buildings with these certifications consume more energy than those that do not have it because they typically fail to account for the behavioral patterns of the building's occupants (Liang et al., 2014; Liang et al., 2019). The introduction of smart controls could lead to a reduction in energy consumption by as much as 10% (Costa et al., 2013; Dean et al., 2016; Anda and Temmen, 2014), compared with the percentage of consumption in the sector in developed countries (Šujanová et al., 2019; Liang et al., 2014). The implementation of renewable energy could favor these buildings since results yielded that 15% of the energy demand is consumed in residential buildings in the European Union (Šujanová et al., 2019).

A building can only be deemed genuinely energy efficient when it neither induces nor exacerbates health issues among its occupants, concurrently ensuring their comfort while minimizing energy expenditures to achieve optimal conditions, as outlined by the Health Optimization Protocol for Energy Efficient Buildings (HOPE) (Cox, 2025).

According to HOPE (Health Optimization Protocol for Energy Efficient Buildings), a building can only be deemed energy efficient when it does not cause or aggravate health issues among its occupants, guarantees comfort, and minimizes the use of energy to achieve the desired conditions (Cox, 2025). The building must be used consciously, without exceeding the occupation, and using efficient technology for its maintenance (Costa et al., 2013; Liang et al., 2019). The IEQ must be evaluated throughout the building's life cycle, with sustainable strategies at the early design stages and appropriate maintenance of this building until the

disposal of materials at the end of its cycle (Alhorr et al., 2016). This evaluation must focus on the occupants, considering various user profiles influencing needs based on gender, age, and vulnerabilities. In addition, the quality of the interior environment has been related not only to the wellbeing of these users but also to its impact on health and diseases in the short and long term, being relevant to the development of adequate actions to reduce or eliminate harmful effects on health (Srinivasan et al., 2003).

Despite the advances summarised in this review, it is important to recognise the limitations that make it difficult to draw definitive conclusions about the relationship between IEQ and the health of vulnerable populations. Firstly, the observed associations and relationships may be influenced by uncontrolled confounding factors with a significant impact on indoor environments, which are rarely considered in studies. These factors include external variables, such as outdoor air quality, the presence of urban vegetation or proximity to sources of pollution; internal variables related to the use of everyday items, such as air fresheners or recent renovations; and other factors, such as exposure to electromagnetic fields generated by devices both indoors and in the immediate outdoor vicinity. Secondly, the heterogeneity in the classification and definition of vulnerable groups, as well as in measurement methods, makes it difficult to compare results. Future research must consider these factors in order to reduce bias, improve the validity of findings and establish a more accurate framework.

10 Conclusion

It is important to bear in mind the heterogeneity that exists between the different types of groups considered vulnerable, as well as within each of them. Table 8 contrasts how different vulnerable groups (children, elderly people, pregnant women, and people with disabilities) are affected by the main IEQ domains (thermal, air quality, lighting, acoustics). While there is a significant impact at different stages of life, children are affected in their cognitive development, while older people suffer from chronic diseases. All groups are highly sensitive to poor air quality.

In the case of older people, for example, age is not the only parameter to consider; other parameters must also be taken into account, such as lifestyle, home characteristics, gender, and physiological characteristics such as mobility and chronic diseases (Beard et al., 2016). This highlights the need for an IEQ index model adapted to this heterogeneity, incorporating weights for both variability and environmental domains. While some studies (Laskari et al., 2016; Tiele et al., 2018) have begun to propose such indices and interpret the related weights, further research is needed.

The elderly population is significantly vulnerable due to limited mobility and the high prevalence of chronic diseases. However, there is insufficient scientific literature connecting IEQ with its effects on the physical health of older adults. Building designers need to tackle variables affecting indoor and outdoor environments, as these domains significantly impact the health of vulnerable adults. For instance, studies have shown the importance of bedrooms, indoor gardens, green roofs, and patios, but evidence in this area is limited. Besides involving vulnerable adults in creating inclusive buildings, additional studies need to establish assessment criteria and monitoring standards that can lead to well-rounded design

recommendations for housing where vulnerable adults reside. Empirical research on social and economic impacts will help facilitate the sustainable development of aging societies and create more inclusive and healthy designs.

Beyond the energy credentials granted to green and sustainable buildings, specific considerations are required, often insufficient to guarantee user comfort and wellbeing. This document presents a review of current knowledge on user wellbeing and comfort related to IEQ. To address existing research gaps and challenges, a holistic framework for building environment design guidelines should be developed, in addition to future lines of research. These guidelines should provide recommendations for building designers and urban planners that are applicable across various contexts rather than confined to specific locations.

1. Building designs for vulnerable people should prioritize spatial distribution, focusing on places such as bedrooms, dining areas, and other rooms frequented by occupants, ensuring thermal comfort, adequate ventilation, and natural lighting. Future research should prioritize establishing the quantitative relationship between IEQ, comfort conditions, and occupant health, as this remains unclear.

Quantifying the spatial distribution of green spaces in relation to air pollution and extreme heat is imperative, as they act as comfort modulators. In addition, it is a priority to optimise ventilation and air quality through hybrid systems that combine natural and mechanical ventilation to ensure adequate levels of air renewal in spaces that are used for long periods of time. Similarly, the thermal design of buildings should be based on passive strategies, such as insulation, cross ventilation and solar protection, complemented by low-energy technologies. Specific comfort ranges must be defined that take into account the greater sensitivity of certain groups. Lighting is another fundamental aspect: natural light should be encouraged in frequently used rooms and supplemented with adjustable artificial lighting that respects circadian rhythms and reduces glare, thereby contributing to the visual health and rest of the occupants. At the same time, noise exposure must be reduced through more stringent acoustic standards, the use of insulating materials, and landscaping solutions that act as sound barriers.

2. Environmental monitoring and modelling methods can be used to verify and improve the building environment. This can be achieved by installing low-cost, accessible sensors that allow residents to monitor the environmental quality of their homes in real time.
3. It is essential to consider the perspectives of vulnerable individuals through systematic surveys in order to identify the needs and habits of occupants and adjust design solutions accordingly. This information can then be used to establish reference limits and comfort ranges adapted to the vulnerability of occupants, as well as to create design guidelines applicable to vulnerable groups with an adapted IEQ index.
4. Future findings should not only be applied to new constructions, but also to housing renovations and energy efficiency. This will ensure that comfort and health are not neglected in favour of energy-saving criteria.

5. Further studies should be conducted to measure the impact of poor IEQ on the health of vulnerable groups and its relationship with their habits. Generating quantitative models that integrate IEQ, health and occupant habits will help formulate new regulatory frameworks.
6. Finally, it is a priority to develop systematic guidelines with generic conclusions that can be transferred between different climatic and social contexts, and that support the creation of inclusive societies adapted to ageing. To this end, it is necessary to link IEQ research with urban, social, and public health policies at multiple scales, which can be explored in future research.

Author contributions

MH-M: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. FD: Conceptualization, Data curation, Formal Analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. RG-L: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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