Indoor air quality guidelines from across the world

An appraisal considering energy saving, health, productivity, and comfort

Dimitroulopoulou, Sani; Dudzińska, Marzenna R; Gunnarsen, Lars; Hägerhed, Linda; Maula, Henna; Singh, Raja; Toyinbo, Oluyemi; Haverinen-Shaughnessy, Ulla

Published in:
Environment International

DOI (link to publication from Publisher):
10.1016/j.envint.2023.108127

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Environment International 178 (2023) 108127

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Indoor air quality guidelines from across the world: An appraisal considering energy saving, health, productivity, and comfort

Sani Dimitroulopoulou [a], Marzenna R. Dudzińska [b], Lars Gunnarsen [c], Linda Hägerhed [d], Henna Maula [e], Raja Singh [f], Oluyemi Toyinbo [g], Ulla Haverinen-Shaughnessy [g,h,*]

[a] Air Quality and Public Health, UK Health Security Agency, UK
[b] Faculty of Environmental Engineering, Lublin University of Technology, Poland
[c] Department of the Built Environment, Aalborg University, Denmark
[d] Department of Resource Recovery and Building Technology, The University of Borås, Sweden
[e] Engineering and Business, Construction Industry, Built Environment Research Group, Turku University of Applied Sciences, Finland
[f] Department of Architecture, School of Planning and Architecture, New Delhi, India, ISAC CBEP, New Delhi & Tathatara Foundation, India
[g] Civil Engineering Research Unit, The University of Oulu, Finland
[h] Indoor Air Program, The University of Tulsa, USA

ARTICLE INFO

Keywords:
Energy consumption/efficiency/performance
Indoor climate/pollutants
Human requirements
HVAC
Permissible limits/target values
Well-being

ABSTRACT

Buildings are constructed and operated to satisfy human needs and improve quality of life. Good indoor air quality (IAQ) and thermal comfort are prerequisites for human health and well-being. For their provision, buildings often rely on heating, ventilation, and air conditioning (HVAC) systems, which may lead to higher energy consumption. This directly impacts energy efficiency goals and the linked climate change considerations. The balance between energy use, optimum IAQ and thermal comfort calls for scientifically solid and well-established limit values for exposures experienced by building occupants in indoor spaces, including homes, schools, and offices.

The present paper aims to appraise limit values for selected indoor pollutants reported in the scientific literature, and to present how they are handled in international and national guidelines and standards. The pollutants include carbon dioxide (CO_2), formaldehyde (CH_2O), particulate matter (PM), nitrogen dioxide (NO_2), carbon monoxide (CO), and radon (Rn). Furthermore, acknowledging the particularly strong impact on energy use from HVAC, ventilation, indoor temperature (T), and relative humidity (RH) are also included, as they relate to both thermal comfort and the possibilities to avoid moisture related problems, such as mould growth and proliferation of house dust mites.

Examples of national regulations for these parameters are presented, both in relation to human requirements in buildings and considering aspects related to energy saving. The work is based on the Indoor Environmental Quality (IEQ) guidelines database, which spans across countries and institutions, and aids in taking steps in the direction towards a more uniform guidance for values of indoor parameters. The database is coordinated by the Scientific and Technical Committee (STC) 34, as part of ISIAQ, the International Society of Indoor Air Quality and Climate.

1. Introduction

In both developing and developed countries, people spend an average of 80–90% of their time indoors, much of which is at home. The built environment has a tremendous impact on health, well-being and general quality of life, and much energy is spent to accommodate human requirements inside buildings. Global uncertainties, such as pandemic and war among nations, have rapidly increased the cost of energy. In 2021, according to the International Energy Agency (IEA), the operation of buildings accounted for 30% of global final energy consumption and 27% of total energy sector emissions; 8% being direct emissions in buildings and 19% indirect emissions from the production of electricity and heat used in buildings (Delmastro et al., 2022).

According to the 6th Assessment of the Intergovernmental Panel on

* Corresponding author.
E-mail address: ulla.haverinen-shaughnessy@oulu.fi (U. Haverinen-Shaughnessy).

https://doi.org/10.1016/j.envint.2023.108127
Received 30 April 2023; Received in revised form 27 June 2023; Accepted 31 July 2023
Available online 1 August 2023

Climate Change (IPCC, 2023), climate changes are projected to escalate across all regions of the world in the upcoming decades. The report indicates that even if global warming is limited to 1.5 °C, there will be a rise in heat waves with prolonged warm seasons, and shorter cold seasons. Furthermore, these climatic events are expected to intensify significantly with a warming of 2 °C. Following COP26 - The Glasgow Climate Pack (2021) and being aligned with the Paris Agreement temperature goal to limit global warming to well below 2 °C and pursue efforts towards 1.5 °C, many countries set ambitious targets to bring greenhouse emissions to net zero (e.g., BEIS, 2022 - UK). This goal cannot be achieved without near-complete elimination of greenhouse gas emissions from the building sector. To immediately act on these challenges, energy efficiency measures are introduced to reconsider the needs for heating, cooling, and ventilation (HVAC). In principle, the needs originate from human requirements for healthy, productive, and comfortable lives. Furthermore, in particular for humidity, they also relate to the resilience of buildings themselves.

In Europe, the revised Energy Performance of Buildings Directive (EPBD) sets out how a zero-emission and fully decarbonized building stock can be achieved by 2050 (European Commission, 2021). The revised directive facilitates more targeted financing to investments in the building sector, complementing other European Union (EU) instruments and supporting vulnerable consumers. The modernisation of the building stock, better indoor air quality (IAQ), and fighting energy poverty are all being considered.

Sociodemographic characteristics like age, education, gender, country of birth, and citizenship can all play an important role in shaping an individual's living conditions. It has been estimated that wider societal developments, coupled with a series of unprecedented events (e.g., the COVID-19 pandemic, the state of war between nations, and the subsequent global financial and economic crisis), can also have a considerable impact, possibly reinforcing or exacerbating patterns of inequality and exclusion. According to Eurostat regional yearbook, more than one fifth (21.7%) of the EU population was at risk of poverty or social exclusion in 2021 (Eurostat, 2022). The United States (US) Census reports poverty rate at 12.8% (US Census Bureau, 2022). On the other hand, in Africa, extreme poverty rates (below 1.90 U.S. dollars a day) have been estimated at around 50% among the rural population, compared to 10% in urban areas, whereas, in contrast, multidimensional poverty in India has been reported to decline from 55.1% to 16.4% in fifteen years (UNDP, 2022).

Even though the definitions of poverty may vary from place to place, the overall global poverty crises can result in sharp shifts, including for fuel and energy poverty. These at-risk populations also face increased risks of associated disease burdens, such as non-communicable diseases (e.g., respiratory and cardiovascular) as well as spread of infectious diseases (Iacobucci, 2020; Liddell and Morris, 2010). Furthermore, there is growing evidence that mitigation and adaptation measures, proposed for the housing/building sector to address climate change, can affect public health and well-being, by amplifying health risks and inequalities related to the indoor environment (Vardoulakis et al., 2015). The World Health Organization (WHO) proposed a series of mitigation measures to tackle inequalities in human health and exposure to air pollution, including improvements to spatial and land-use planning (to reduce emissions of air pollutants and exposure of most deprived groups); banning certain domestic heating fuels, like coal, combined with switching to cleaner heating options for low-income households; and taking short-term measures to reduce exposure of deprived people in the places where they live, are educated, play or work (WHO, 2019a, 2019b).

For decades to come, we must design and renovate buildings to reduce their environmental impact along with ensuring health and well-being. Within a much shorter time frame, we can modify the way we operate buildings with a focus to immediately reduce energy consumption, while simultaneously maintaining or even enhancing good indoor environmental quality (IEQ). While IEQ encompasses the overall indoor environmental factors (i.e., IAQ, ventilation, thermal comfort, noise, lighting) within a building, IAQ specifically pertains to the quality of the air circulating within that building.

There is evidence from past research as well as recent reviews showing that exposure to indoor air pollutants is associated with adverse health effects, including impacts on respiratory, nervous, and cardiovascular systems, as well as with carcinogenicity and endocrine disruption (e.g., RCPCH, 2020; Halios et al., 2022; Kumar et al. 2023). Further on, exposure to excess cold and excess heat indoors are associated with increased morbidity and mortality. Below 18 °C indoors, negative health effects may occur, such as increases in blood pressure and the risk of blood clots that can lead to strokes and heart attacks (PHE, 2014). If temperatures are high or continue to rise, they will place increased stress on the cardiovascular and respiratory systems. This can lead to hyperthermia, heat exhaustion, heat stroke and cardiovascular events such as an ischemic stroke, especially among vulnerable populations. Vulnerable population groups include the very young, the elderly, obese persons as well as those with pre-existing health conditions (e.g., WHO, 1989).

IEQ can be affected by current trends to radically decrease energy consumption in the housing and building sector. Guidelines are needed to ensure that health, productivity, and comfort resulting from IEQ conditions are maintained. The aim of this paper is to summarise for the first time the data that have been collected, as well as make a structured review of IEQ guidelines for selected pollutants around the world. This work underscores the need for adaptation/development and implementation of national and international health based IEQ guidelines/standards/regulations, to face the above challenges. We also aim to disseminate the existence of the ISIAQ STC34 database, mainly to attract attention from countries whose data are not included thus far.

2. Material and methods

The present paper includes structured review of guidelines on selected pollutants. The pollutants were selected due to their known health effects and the benchmark was the WHO (2010) list of indoor air pollutants. The effects on health and well-being are presented together with the health-based guideline values, which should not be exceeded. Since this work is not a systematic literature review, but a critical review of guidelines within the context of the impact of energy efficiency measures on IEQ, we relied on recent reviews and *meta*-analyses, as to provide the strongest possible evidence to stipulate health, productivity, and comfort-based values. We considered peer reviews but also reports from authoritative organisations, especially on the health side.

Recognising that not all countries apply health-based guidelines in their regulations/standards, data of national and international regulations, standards and guidelines for selected parameters are derived from the newly constructed International Society of Indoor Air Quality and Climate (ISIAQ) Scientific Technical Committee 34 (STC34) database (https://www.ieqguidelines.org). The background information on this database is presented by Toyinbo et al. (2022). The database is being continuously developed and updated, with data coming so far from over 30 countries around the world. A flowchart of the process is presented in Figure 1.

The database is currently focused on IAQ guidelines and standards, both mandatory and voluntary, and is being further extended to include standards, regulations, and guidelines related to outdoor air quality, ventilation, thermal comfort, acoustics, and lighting. Data collection is largely dependent on volunteering scientists from countries around the world, who help locate and translate data to be added to the database. The reason for data not shown from various countries can be due to guidelines not existing, not being known or not being accessible, e.g., due to language barriers.

Table 1 summarizes national guidelines from 34 individual countries included in the database to date. Only non-occupational governmental guidelines are included. For carbon dioxide (CO_2) some guidelines,

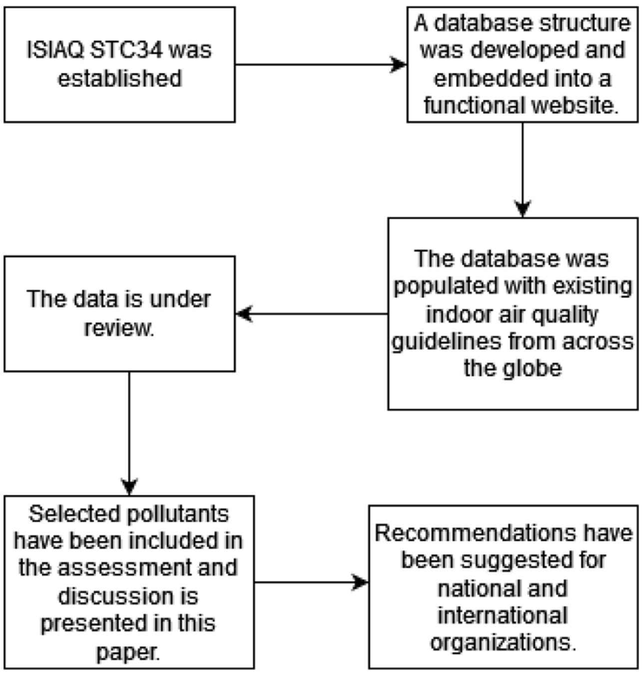

Fig. 1. Flow-chart of utilizing the ISIAQ STC34 database for reviewing existing guidelines and developing recommendations.

which are given in relation to outdoor levels, were calculated assuming outdoor CO_2 concentration as approximately 400 ppm (i.e., CO_2 concentration limit given as ambient + 350 ppm = 750 ppm). Radon (Rn) units were converted using 1 pCi/L is equivalent to 37 Bq/m^3 (Health Canada, 2008). For carbon monoxide (CO), formaldehyde (CH_2O), and nitrogen dioxide (NO_2), conversion factors from ppm to mg/m^3 were used at standard pressure of 760 mmHg and temperature of 20 °C (WHO, 2010).

Figure 2 shows the percentage of countries with government regulations and guidelines in the database. In addition, there are also some non-governmental guidelines, which are typically given by professional organizations. These are not included in Table 1 or Figure 2, but are referred to in the text, as applicable.

3. Results

Provision of thermal conditions to support the occupants' needs are primary considerations when designing building envelopes and building installations for ventilation provision. Aiming to improve the insulation of the building envelope and minimise unwanted heat losses, current energy efficiency measures increase the airtightness of the building envelope. However, increasing airtightness of buildings, without improvements in ventilation provision, could have unintended consequences by increasing moisture generated from normal occupant activities that can lead to damp and mould, heat that leads to building overheating, as well as increasing concentrations of air pollutants, chemicals and biological contaminants that are derived from indoor sources (Vardoulakis et al., 2015). The role of both background and controlled ventilation is of major importance.

The health-based guideline values and standards for thermal comfort parameters and indoor air pollutants are summarized below, starting from the impact of ventilation on both.

3.1. Ventilation

To maintain good IAQ, indoor air pollutants should be diluted by the supply of fresh outdoor air to the indoor environment. In poorly insulated buildings, the ingress of the outdoor air takes place through cracks and leakages in the building envelope but is not easy to quantify. Better air quality may also be achieved by airing out activities of the building users by opening of windows and/or doors, while always considering vector control, safety, and privacy issues. This type of natural ventilation may also be supplemented with vertical ducts which utilises the stack effect, where the warmer indoor air (that is less dense) is extracted from more polluted indoor spaces. In newer buildings, the air exchange may take place through balanced ventilation systems where fans circulate outdoor and extract indoor air through heat exchangers for heat recovery. The systems may also be supplied with heating and cooling panes to supply preconditioned outdoor air into the indoor space while extracting the hot, moist and/or polluted indoor air (Hunt et al. 2020).

Ventilation is also important for indoor thermal control. Previous research has shown that ventilation can have an inverse relationship with indoor temperature (T) in cold or temperate climates where building envelopes are more insulated and airtight. Whereas in tropical climates, the relationship is dependent on the utilisation of air conditioning systems. (Toyinbo et al., 2016, 2019).

To keep a balance between maximising the amount of air, which is drawn in to reduce air pollutant concentrations generated from indoor sources and minimising the ingress of outdoor originating air pollutants such as PM, especially in urban areas, can be challenging (NASEM, 2022). However, proper design, operation and maintenance of ventilation systems and the introduction of air cleaning devices could address potential design conflicts. Inadequate ventilation rates may not be able to dilute, exhaust, and eventually reduce the levels of pollutants generated from indoor sources and normal occupant activities. So, achieving good IAQ is a complex task that first requires control of emissions at their sources, and secondly the application of ventilation to maintain good IAQ.

The European funded HealthVent project recommended a health-based airflow rate of 4 L per second per person (l/s/p), if the indoor sources are eliminated and the WHO IAQ guidelines (WHO, 2010) are met. This is just to remove occupant emissions (bioeffluents) (Carrer et al., 2018). Control of infectious diseases has become an important, but sometime neglected consideration, when setting up ventilation limits (e.g., Rudnick & Milton, 2003; Li et al., 2007; Guo et al., 2021). More recently, due to the COVID-19 pandemic, there have been calls for the need to set health-based guidelines to control the transmission of airborne infectious diseases (e.g., REHVA, 2021).

Many ventilation and contaminant control measures are included in ventilation standards, such as the European Standards EN 13142:2021 and ANSI/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62.1 (2022). Often, ventilation related standards are written in the form of minimum requirements, defining ventilation rates in l/s per person or per floor area of the building. Ventilation recommendations have varied over time, as our understanding has increased. As an example, the history related to ASHRAE Standard 62 has been described by Persily (2015), concluding the need for more work to make the standards more successful in supporting better indoor environments, and the need for additional research into the health effects of contaminants and contaminant mixtures, source strengths in buildings, the performance of IAQ control technologies, and new design approaches.

ISIAQ STC34 is currently working on adding ventilation guidelines to the IEQ database. However, the database already includes guidelines for CO_2, which is considered as a surrogate measure or a proxy for ventilation performance in an occupied space. For example, under some circumstances, CO_2 can be used to estimate building air change rates and percent outdoor air intake at an air handler (Persily, 1997).

CO_2 is a colourless and odourless gas of extreme environmental and economic importance. It is produced as a by-product of respiration by humans and animals. Generally, the air we breathe in contains about 0.04% CO_2 while we exhale air containing about 4% CO_2 that is 100 folds that inhaled (Zhang et al. 2011). CO_2 is also produced through the combustion of carbon products such as fuel. The global average outdoor

Table 1
Summary of national guideline values in IEQ guidelines database.

Pollutant	Averaging time	Number of guidelines	Minimum	Maximum	Mode[a]
Temperature (T), °C	Undefined	25	16-23[b]	22-28[c]	20-26[d]
Relative humidity (RH), %	Undefined	12	20-40[b]	50-80[c]	40-70[d]
Carbon Dioxide (CO_2), ppm	Maximum[e]	5	1000	5000	1000
	8 hr	4	700	1500	
	24 hr	2	1000	1000	
	Undefined	17	900	5000	1000
Carbon Monoxide (CO), mg/m^3	Maximum[e]	2	12	31	
	15 min	7	10	125	100
	30 min	5	6	60	60
	1 hr	8	10	44	30
	8 hr	13	8	80	10
	24 hr	8	3	12	3
	1 yr	1	30	30	
	Undefined	4	5	11	
Formaldehyde (CH_2O), μg/m^3	Maximum[e]	2	80	100	
	15 min	1	130	130	
	30 min	10	35	100	100
	1 hr	2	120	123	
	8 hr	5	50	250	100
	24 hr	2	20	50	
	1 yr	2	10	50	
	Undefined	11	10	370	100
Nitrogen Dioxide (NO_2), μg/m^3	Maximum[e]	2	100	210	
	15 min	2	100	300	
	1 hr	8	40	288	200
	8 hr	2	40	150	
	24 hr	1	20	20	
	1 yr	2	20	40	
	Undefined	4	40	200	
Particulate matter ($PM_{2.5}$), μg/m^3	Maximum[e]	2	35	50	
	24 hr	7	15	40	25
	1 yr	2	8	15	
	Undefined	2	20	25	
Radon (Rn), Bq/m^3	Maximum[e]	2	148	148	
	8 hr	2	100	167	
	1 yr	3	200	300	
	Undefined	20	100	400	200

[a] Modes (i.e., the most frequent number), are presented for more than 5 values;
[b] Range for lower limit;
[c] Range for upper limit;
[d] Modes for lower and upper limits;
[e] Given as a ceiling limit over an unspecified period (i.e., a value that cannot be exceeded).

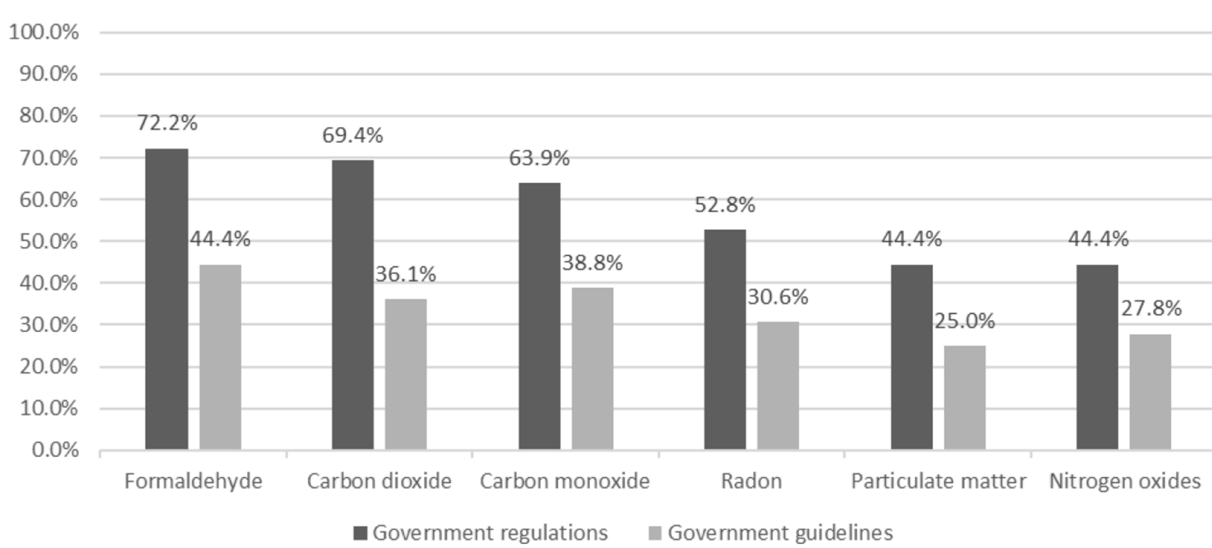

Fig. 2. Percentage of countries with government regulations and guidelines in IEQ Guidelines Database of ISIAQ STC34.

CO_2 concentration was reported to be around 415 ppm in 2021 (NOAA, 2023). CO_2 concentrations in occupied indoor spaces are higher due to occupants' respiration and other CO_2 generating processes such as cooking (Du et al. 2020).

'Rebreathing' exhaled air has been considered to facilitate the spread of infection if the replacement of the air does not consist of fresh outdoor air but rather recirculated nonfiltered indoor air. This is particularly the case when there is the presence of anyone infected with a disease, which can spread through the airborne route (Richardson et al., 2014; Taylor et al., 2016). This relationship has been shown by multiple studies (e.g., Vouriot et al., 2021; Nathavitharana et al., 2022), and due to correlation with exhaled CO_2, many studies have associated high CO_2 level with high probability of infection spread in indoor spaces (e.g., Li et al., 2007; Rudnick & Milton, 2003).

The WHO has not developed guidelines for indoor CO_2 concentrations. Many occupational health standards set CO_2 concentration limits in workplaces at 5000 ppm or higher, based on acute toxicity. When Lowther et al. (2021) reviewed the evidence to identify if CO_2 is a pollutant itself with known health impacts in indoor non-industrial environments, they were not able to conclude with confidence whether exposure to low CO_2 levels (<5000 ppm) is linked with health effects, due to shortcomings in the design of studies. Any reported health outcomes may be due to the presence of human bioeffluents, and other indoor air pollutants related to inadequate ventilation. The review concluded that the current consensus in various regulations suggesting CO_2 levels <1000 ppm, between 1000 and 1500 ppm, and greater than1500 ppm representing good, moderate, and poor IAQ, respectively, seems appropriate.

Selected national guidelines for CO_2 included in the database consist of some 28 values ranging from 700 to 5000 ppm (Table 1). Most of these do not have a specific averaging time, whereas in some cases the guidelines are referring to a maximum (ceiling) value, 8-hour, or 24-hour average. The most commonly occurring guideline value is 1000 ppm, which is a comfort-based guideline described in the ASHRAE standard 62 originally published in 1989, but subsequently removed from the updated ASHRAE standard 62 (now 62.1) due to recurrent misinterpretations (ANSI/ASHRAE, 2022).

3.2. Heating, cooling, and thermal environment

Heating and cooling of buildings is an important issue in many regions of the world due to changes in seasonal outside temperatures that affect human thermal comfort indoors. In colder regions, the heating systems play an important role in providing comfortable indoor T and to help minimize draft from cold surfaces such as windows or poorly insulated walls. In warmer regions, heat stress from warm outside temperatures may be reduced by cooling systems applied indoors. Cooling, as opposed to heating, is often integrated in the systems for mechanical ventilation.

The thermal environment is strongly linked to energy consumption via HVAC, using either passive or active methods. It is an important indoor factor that affects comfort, work performance and well-being (Rupp et al., 2015). Indoor thermal conditions are affected by air temperature, radiant temperature, air movement, and humidity together with clothing worn by building occupants and their metabolic heat production (Fanger, 1970). Therefore, air temperature, which is often used in guidelines, is just one of the six components of comfortable thermal conditions, and moderate changes can be made to air temperature without reducing comfort. For example, putting on a sweater allows indoor T to be lowered by 2 °C without reducing thermal comfort (ASHRAE 55, 2010).

Conditions which are too cool or too warm can cause discomfort and decrease work performance and well-being (Rupp et al., 2015; Seppänen et al., 2003). The effect of the thermal environment on cognitive performance is described as a U-shaped curve (Zhang et al., 2019). It means that instead of one single optimum temperature, there is a temperature range where cognitive performance is unaffected by the temperature, and outside this range cognitive performance decreases. Performance may also be impaired by poor sleep quality. Even moderate heat or cold exposure has been found to decrease sleep quality (Lan et al., 2017). Humid heat exposure during sleep has been found to increase heart rate, sweat rate, thermal load, and wakefulness (Lan and Lian, 2016). Thermal comfort also affects heart rate variability, which is commonly accepted as a marker of autonomic nervous system activity (Liu et al., 2008; Yao et al., 2009).

The optimal RH in indoor air for health and work performance is between 40 and 60% (Wolkoff et al., 2021). Low indoor RH may cause eye and airway desiccation and less efficient mucociliary clearance. Indoor RH has also been found to influence perceived IAQ, house dust mite allergens, infectivity of some viruses, and skin dryness (Derby et al., 2017; Wolkoff et al., 2021).

WHO reports recommended a range for indoor T between 18—–24 °C (WHO, 1987). There are no recommended limits for indoor RH, however, WHO has published guidelines for dampness and mould (WHO, 2009a). It reports equilibrium relative humidity (ERH) levels required for growth of selected microorganisms in construction, finishing and furnishing materials, divided to high (ERH > 90%), intermediate (EHR 80–90%) and low (ERH <80%), and concludes that effective moisture control includes control of liquid water, control of indoor RH levels and condensation, and selection of materials and hygrothermal assembly design that minimize mould growth and other moisture problems.

National guidelines for indoor T and RH in the database are presented in Table 1. These guidelines are usually given as ranges. For T, the lower limit often corresponds with the heating season and the upper limit with summertime. The lower limit range is 16–23 °C whereas the higher limit range is 22–28 °C. The most common value (mode) for a minimum indoor T is 20 °C, which corresponds to recommended minimum for vulnerable populations (e.g., the elderly) by WHO (1987).

With respect to RH, national guidelines set lower limits ranging between 20 and 40% and upper limits ranging between 50 and 80%. The most commonly recommended range is 40–70%. It is also noted that averaging time is usually not used for indoor T or RH. However, in the UK, maximum RH levels are indicated as follows: 65% for 1 month; 75% for 1 week, and 85% for 1 day; corresponding levels are set for surface water activity 0.75 (1 mo); 0.85 (1 wk); 0.95 (1 d).

3.3. Indoor air quality

Indoor air may have high levels of pollutants originating from outdoor air or ground sources, building and construction materials, appliances, furnishings and consumer products, or the occupants themselves, and their activities such as cooking, having bath or drying clothes indoors (e.g., AQEG, 2022). Some pollutants may be infiltrated from the outdoor environment (e.g., PM, NO_2, CO), or from soil or groundwater (e.g., Rn). The level of pollutants originating from outdoor sources can vary greatly by building location (Leung, 2015; Baeza-Romero et al. 2022).

The WHO (2006, 2021) presents a global approach to address air quality issues, considering different development levels of regions, local population characteristics, and time spent indoors and/or outdoors. Until recently, the WHO has published separate guidelines for indoor and outdoor air quality. Target values for some pollutants in outdoor air were established in 2000 for Europe (WHO, 2000), and updated globally in 2005 (WHO, 2006). The first WHO document about the right to indoor air was published for European countries, although without recommending levels of pollutants (WHO, 2000). The WHO guidelines for selected indoor air pollutants were released in 2010, with benzene, CO, CH_2O, NO_2, as well as polycyclic aromatic hydrocarbons (PAHs) being among the pollutants considered (WHO, 2010).

The recent WHO global air quality guidelines (WHO, 2021) on $PM_{2.5}$, PM_{10}, ozone, NO_2, sulphur dioxide and CO, were published without distinction between the indoor and outdoor levels. Target annual and 24-hour average concentrations are set at lower levels when compared with those in 2005, although "old" levels are recommended as interim for most compounds, and 1-hour levels remain the same. CH_2O and other organic pollutants listed in the document from 2010 (WHO, 2010), are not mentioned in the guidelines published in 2021 (WHO, 2021) and

Rn is regulated separately (WHO, 2009). The relevant guideline values for specific pollutants are discussed in greater detail in sections below.

3.3.1. Formaldehyde

The colourless, pungent-smelling gas is an organic compound detected in almost every indoor premise. It was one of the emerging compounds recognized as a possible hazard considered to be the most abundant pollutant in indoor air (Villanueva et al., 2018). It is an important chemical, widely used in industry to manufacture building materials and numerous household products. Alone or in combination with other chemicals, CH_2O serves several purposes, e.g., as a component of glues and adhesives, as well as a preservative in some paints and coatings (Niu and Burnett, 2001, Gunschera et al., 2013).

CH_2O can be emitted from chipboard and other wood-based panels and from acid curing lacquers. It is also a by-product of combustion and certain natural processes. Thus, it may be present in substantial concentrations both outdoors and indoors, however, the indoor levels exceed the outdoor ones (Wolkoff, 1995). Indoor sources include building materials, smoking, household products, and the use of unvented fuel-burning appliances, like gas stoves or kerosene space heaters. It has been found to be a major secondary pollutant from cleaning products in the presence of ozone (Singer et al., 2006; Wolkoff et al., 2006; Milhem et al., 2021).

CH_2O is a sensory irritant, listed in Group 1 by The International Agency for Research on Cancer (IARC, 2006). Laboratory animals exposed to CH_2O suffer from nasal cavity cancer, but only at high levels of exposure (thousands of ppb, or higher). The exposure to moderate levels of CH_2O (hundreds of ppb, or higher) can cause irritant symptoms, including temporary burning of the eyes or nose, and sore throat (Wolkoff and Kjaergaard, 2007, Hodgson et al., 2002). Some studies have suggested that people exposed to CH_2O levels higher than 100 $\mu g/m^3$ for long periods of time are more likely to experience asthma-related respiratory symptoms, such as coughing and wheezing (e.g., Wolkoff et al., 2006; Lam et al., 2021). Such high levels are rather found in occupational environments, as most studies in the last decade found the concentration of CH_2O in living premises to be below 25 $\mu g/m^3$ (Blondel and Plainsence, 2011; Langer and Beko, 2013).

The WHO guideline value for CH_2O is 100 $\mu g/m^3$ (0.1 mg/m^3) based on 30 min averaging time (WHO, 2010). Selected national guidelines included in the database consist of approximately 35 values, for various averaging periods, ranging from 10 to 370 $\mu g/m^3$ (see Table 1). Most common averaging time is 30 min, and the most commonly occurring guideline value is 100 $\mu g/m^3$, corresponding to the WHO guideline. The levels are similar for other averaging times, including 1 h and 8 h, whereas lower levels are given for 24-hour and 1-year averaging times.

3.3.2. Particulate matter

Outdoor origin, primary PM include emissions from fuel combustion for road transport, industrial processes, domestic heating, agricultural activities (emissions of ammonia make significant contributions to the PM formation in the atmosphere), wildfire smoke, and marine vessels in coastal areas (NASEM, 2022; EEA, 2022). For wood burning, most emissions are in the respirable fraction of PM (i.e., $PM_{2.5}$ and PM_{10}) (AQEG, 2022). PM indoors may also originate from indoor occupant activities such as cooking, smoking, candle burning, and cleaning. PM generated from cooking can take up semi-volatile organic compounds (SVOCs) from building materials and other sources and could form secondary organic aerosols when dispersed into the ambient air (AQEG, 2022). In addition, the volatile fraction of cooking emissions can undergo reactions indoors that may produce particles.

Although in less developed countries, many households still rely on solid fuels for cooking, a shift towards cleaner fuels can lead to source control and reduction of PM exposure. According to the systematic analysis for the Global Burden of Disease Study 2019 of the risk factors around the world (GBD 2016 Occupational Chronic Respiratory Risk Factors Collaborators, 2020), the largest declines in exposure risk from 2010 to 2019 were strongly linked to socio-economic development. Global declines also occurred for tobacco smoking. However, the largest increases in risk exposure were, among others, for ambient PM pollution.

Most evidence on the health effects from exposure to particles is based on epidemiological studies, in-vivo and vitro toxicological studies, and controlled human exposure studies. Research is pointing to the possibility that particles smaller than 10 μm, especially 0.1 μm can enter the alveoli and may be able to get into the blood stream and reach other organs. Short term exposure to $PM_{2.5}$ is associated with hospital admissions due to cardiovascular effects (ischemic heart disease, stroke and heart failure), respiratory diseases, such as exacerbation of asthma and chronic obstructive pulmonary disease (COPD), and effects on metabolic and nervous system. Long-term exposure to $PM_{2.5}$ is associated with specific causes of mortality from cardiovascular and respiratory disease and from lung cancer, and growing evidence linking it with a range of health outcomes (Exley et al., 2022).

WHO air quality guidelines (2021) set limits for ambient air $PM_{2.5}$ concentrations at 25 $\mu g/m^3$ for 24-hour and 10 $\mu g/m^3$ for 1-year averages, respectively. Selected national guidelines for $PM_{2.5}$ included in the database consist of some 13 values ranging from 8 to 50 $\mu g/m^3$ (Table 1). Most of these specify 24-hour averaging time, where the most common value is 25 $\mu g/m^3$ corresponding to WHO guideline value.

3.3.3. Nitrogen dioxide

Among many nitrogen oxides, NO_2 is an air pollutant of the most interest for human health. It is a reddish-brown gas of strong oxidizing properties, which plays an important role in the atmosphere, as it absorbs visible solar radiation. It is a main regulator (together with nitric oxide) of the oxidizing capacity impacting the production and fate of free radicals (including hydroxyl radicals), as well as determining ozone concentration. Therefore, NO_2 is a precursor of many secondary pollutants (Monn, 2001; Baruah et al., 2022).

The primary sources of NO_2 indoors are combustion processes, such as unvented combustion appliances (e.g., gas stoves), vented appliances with defective installations, tobacco smoke, and kerosene heaters. In houses without combustion appliances, NO_2 may originate from outdoor sources (combustion facilities, diesel engines, etc.). In such cases, its levels do not exceed half of those outdoors (Ielpo et al., 2019; Vu et al, 2022). In a house with gas stoves or kerosene heaters, or an attached garage (especially when poorly ventilated), the indoor levels usually exceed outdoor levels (Vu et al., 2022). The Netherlands Organisation for Applied Scientific Research (Toegepast Natuurwetenschappelijk Onderzoek-TNO) modelling work (https://airqualitymodeling.tno.nl/) simulated a typical household in Europe that uses gas for cooking. Their results shows that the WHO daily NO_2 guideline value of 25 $\mu g/m^3$ was regularly exceeded in nearly all gas cooking scenarios. The current EU outdoor hourly limit value of 200 $\mu g/m^3$ NO_2 was also exceeded indoors multiple times each week.

Although many kitchens in Europe include a range hood, the ventilation and filtration technologies are not equally effective, and people may not use them every time while cooking, as they raise the energy bills. When used correctly, range hoods ducted to the outside can effectively reduce concentrations of harmful pollutants. NO_2 has a direct effect on human health, as it is an irritant for eyes, nose, throat, and lower respiratory tract. Exposure to higher levels may result in pulmonary oedema and lung injury, while continued exposure may lead to chronic bronchitis. Lower levels may cause increased symptoms of bronchial reactivity among asthmatics, decreased lung function in the patients with chronic obstructive pulmonary disease, and increased risk of respiratory infections, mainly among young children. The new WHO guidelines are based on the epidemiological evidence published in the review by Huangfu and Atkinson (2020). In addition, WHO (2021) recommends interim targets as incremental steps in a progressive reduction of air pollution, with intention to be used in the areas where pollution is high.

WHO guidelines for NO_2 are given for short-term (1-hour) and long-term (1-year) average indoor concentrations at 200 μg/m^3 and 40 μg/m^3 respectively (WHO, 2006). In the new guidelines, the WHO (2021) did not change the 1-hour concentration limit (200 μg/m^3 remains) but recommended the annual average to be 10 μg/m^3 with interim 40 μg/m^3 (WHO, 2021). The 24-hour average was set at 25 μg/m^3 with interim 120 μg/m^3.

Selected national guidelines for NO^2 included in the database consist of some 21 values ranging from 20 to 300 μg/m^3 (see Table 1). The most common averaging time is 1 h, and the corresponding most commonly occurring guideline value for 1-hour average is 200 μg/m^3, same as WHO (2021) guidelines. Other averaging times are seldom used.

3.3.4. Carbon monoxide

The colourless, odourless, and tasteless gas that is slightly less dense than air, CO is also poisonous and flammable. The main source of CO exposure and poisoning in the home is the incomplete combustion from incorrectly installed, poorly maintained, or malfunctioning and poorly ventilated, unflued or with blocked flues, heating and cooking appliances using carbon-based fuels (e.g., oil, gas, coal, or wood), especially gas boilers (Close et al. 2022), or through short circuits and indoor vehicle garages. CO may also originate from the outdoor environment (power plants, car engines, fires, either natural or anthropogenic) or smoking activity. Typical outdoor levels of CO are low; for example, Naghizadeh et al. (2019) recorded an average outdoor CO concentration of 0.27 ± 0.92 ppm in Iran.

Exposure to CO may be acute or chronic. Acute exposure can impact cardiovascular and neurological systems and may lead to death. It can also cause harm to an unborn child (Myers, 2022). Symptoms of CO poisoning include headache, dizziness, fatigue, disorientation, memory loss, and coma (UKHSA, 2022).

WHO guidelines for indoor CO based on acute health effects are 100 mg/m^3, 35 mg/m^3, 10 mg/m^3, and 7 mg/m^3 for averaging times of 15 min, 1 h, 8 h, and 24 h, respectively (WHO, 2006). For ambient air, the concentration limit for 24-hour averaging time is 4 mg/m^3 (WHO, 2021).

Selected national guidelines for CO included in the database consist of some 48 values ranging from 3 to 125 mg/m^3 (Table 1). Most common averaging time is 8 h, and the most commonly occurring guideline value for the 8-hour average is 10 mg/m^3, corresponding to WHO guidelines. Also, a mode value of 15-minute average of 100 mg/m^3 corresponds with the WHO guidelines, whereas small deviations from WHO guidelines can be seen for 30-minute averaging time (mode: 30 mg/m^3) and 24-hour averaging time (mode: 8 mg/m^3).

3.3.5. Radon

The odourless, invisible but radioactive noble gas originates from the natural decay of uranium in bedrock soil. Rn enters indoor air mainly through cracks in foundation due to convection forces, but in some cases the source is well-water or building materials containing certain bedrock (Bruno, 1983). Concentrations in indoor air can vary within a building, usually being higher in basements than upper floors, due to convection forces and being closer to the main source (Li et al., 2022).

National radon surveys and measurements initiated in the mid-20th century led to national programs and action plans in many countries more than 20 years later (Hultqvist, 1956; UNSCEAR, 2000). The WHO Global Health Observatory radon database visualizes data status of countries, action plans and regulations, national reference levels, and concentration measurements (WHO, 2023). European Commission Joint Research Centre (JRC) has, within the program of European Atlas of Natural Radiation, published 12 digital open to public maps on concentration of indoor Rn, and soil concentrations of Uranium, Thorium, and Potassium (Tollefsen et al, 2017). There is a positive correlation between indoor Rn and uranium concentrations in bedrock (e.g., UKHSA, 2022) even though other local regions with other bedrock or soil might have high values due to cracks (Cinelli et al 2019, Olstoorn et al. 2022, Nazarof, 1992).

There is a 16% increase in the risk of lung cancer for every 100 Bq/m^3 of Rn and the risk of developing lung cancer due to Rn exposure is approximately 25 times greater in active smokers than in non-smokers (Seo et al, 2019). It is crucial to note that Rn is the primary risk factor for lung cancer among individuals who do not smoke and is responsible for up to 14% of the cases (WHO, 2009b). However, it is worth noting that the combination of Rn and cigarette smoke creates a greater risk of lung cancer than exposure to either factor alone. Additionally, there is a correlation between Rn exposure and tumour mutation burden (TMB), whereby patients with high exposure levels exhibit nearly double the number of mutations per megabase (Mb) compared to those with low exposures (Lim et al, 2019).

WHO proposes a maximum value of 100 Bq/m^3 to be used as national regulation limit value in homes to minimize health hazards, but 300 Bq/m^3 can be accepted if specific regional circumstances are not possible before remediation and actions (WHO, 2006). Selected national guidelines included in the database consist of some 27 values ranging from 100 to 400 Bq/m^3 (see Table 1). Most of these do not have a specific averaging time, whereas in some cases the guidelines are referring to maximum (ceiling) value, 8-hour, or 1-year average. The most commonly occurring guideline value is 200 Bq/m^3.

4. Discussion

Differences exists between use of guidelines, standards, regulations, and the other related terms, the definitions of which may vary in jurisdictions across the world. A health-based guideline value is often released by a health organisation, and it is voluntary, and comes with a suggestion for it to be followed by the public or the stakeholders involved (e.g., WHO, 2010; 2021). They usually represent upper limits of air pollutants, which should not be exceeded to protect human health from adverse effects.

Some guidelines have been developed into standards, are adopted by professional organisations, including ASHRAE (e.g., Standard 62.1, 2022), ISHRAE (e.g., Standard 10001, 2019), and WELL (2017) standards. In such cases, a standard may be the result of a scientific or a commonly accepted protocol. In Finland, there is a commonly adopted, three level indoor climate classification providing guideline values for “individual”, “good”, and “satisfactory” indoor climate, where the latter fulfils the national guidelines (Sisäilmastoluokitus, 2018). It appears that commonly these standards set more rigorous target levels for IEQ parameters than health-based guidelines, as they are often driven by, for example, the ventilation industry, aiming at higher performing buildings.

A standard may also be a guideline value, which is used within the body of legislation. For example, the European Union (EU) established standards, and objectives are politically agreed for several outdoor air pollutants. The WHO health-based guideline values are generally stricter than the comparable EU standards for outdoor air but not enforceable.

When the concept of a regulation comes in, there can be a penalty or action against the violator of a standard. A synonym of a regulation may be an Act, a law, a rule, or a notification in the official gazette of the government. We may speculate that any scientific recommendation, or a related guideline, can be more effectively implemented when it becomes enforceable.

Figure 2 shows the percentage of countries with government regulations and guidelines in the IEQ Guidelines Database of ISIAQ for the selected pollutants presented in this paper. The exact status of enforceability will vary across jurisdictions, based on their respective legal arrangements. A few countries have made guidelines that become enforceable regulations. For example, Taiwan implemented the Indoor Air Quality Act in 2020. In India, there is an ongoing exercise being performed to develop national Indoor Air Quality standards into regulations and then become enforceable (Singh and Dewan, 2022).

As discussed in this paper, WHO guidelines exist for CH_2O, $PM_{2.5}$,

NO_2, CO, and Rn. For indoor T, WHO has performed reviews and issued some recommendations. Furthermore, WHO guidelines for dampness and mould provide indirect guidance related to the risk of excess moisture induced exposures (WHO, 2009a). WHO guidelines do not exist for CO_2 as a pollutant. It is considered as an indicator or proxy for ventilation, but as a pollutant, health effects are known at levels experienced in non-occupational indoor environments ($<$ 5000 ppm). The need for health-based guidelines for minimum ventilation has become more recognised since COVID-19, and the need is also evident in terms of protecting occupant health when energy conservation targets are rightfully being set high.

It appears that the WHO guidelines, when they exist, are commonly followed in national guidelines and regulations. However, there are also deviations from those values, indicating that the health-based guidelines may not be readily accepted by regulatory bodies for many reasons, including environmental and economic ones. Whereas the WHO's newest air quality guidelines are mainly set for ambient air, they are claimed to also be applicable indoors. However, due to the limited inclusion of indoor studies, there is yet a consensus to be developed on the acceptable levels for most indoor air pollutants, many of which are not included in this paper.

From the energy point of view, we can conclude that energy saving measures can have an impact on the concentrations of pollutants via multiple mechanisms. For example, emissions from building materials, e.g., CH_2O, are dependent on indoor T and RH. Also changes in ventilation can change infiltration rates as well as how quickly the pollutants are exhausted from indoors. In lieu of clean sources of energy, using alternative methods for heating and cooking can reduce exposure to combustion related pollutants.

Energy saving potential in the thermal environment is related to decreasing heating during winter or cooling during the summer (Hoyt et al., 2015), or improving the building envelope in terms of thermal resistance and leakage. Existing guideline values can be used for setting the thermal conditions within ranges that are not compromising health, productivity, or increasing the risk of dampness and mould. In addition, there are different passive or low-energy solutions, such as personal comfort systems (PCS) and mixed-mode (MM) ventilation, which reduces energy use while still maintaining comfort (Kim and de Dear, 2021; Rawal et al., 2020).

As compared to older buildings, newer or retrofitted buildings tend to have increased airtightness and are more thermally insulated. They are more often accompanied with various types of mechanical HVAC systems, such as balanced ventilation, demand control ventilation, mechanical heat recovery ventilation (MVHR), and heat pumps. Modernising and retrofitting the building stock has, after the initial investment, the potential to reduce fuel poverty, making the heating of homes more affordable, and reduce the risk of dampness and mould, improving both physical and mental health (Wang et al., 2022; Maidment et al., 2014). However, installation of new HVAC systems has also been associated with various issues related to the system (energy consumption, ducts, filters, maintenance, noise) and issues with inadequate specification, incorrect commissioning, poor installation and performance, lack of maintenance, occupant interference and a lack of knowledge and awareness of the systems that may eventually compromise IEQ (Ortiz & Bluyssen 2022; Sharpe et al., 2016; WHO, 2011). There is also concern of retrofitting older buildings with multiple packaged units leading to recirculation of indoor air. It is also important to consider the applicability of existing guidelines in the context of performance assessment of buildings built or retrofitted at a certain time.

Some energy efficient HVAC technologies, like packaged air conditioners mentioned before, rely on recirculation of indoor air, which may lead not only to a lesser 'flushing' of indoor contaminants but may also contribute to airborne infection spread (Vouriot et al., 2021; Nathavitharana et al., 2022). The 2019 update of the 'WHO Guidelines on tuberculosis infection prevention and control' states four research priorities, among them 1) effect of different exchange rates in mechanical ventilation systems on transmission of TB and 2) effect of mechanical ventilation modes on microclimate of mechanically ventilated settings. Post COVID-19, research has focused on prevention of transmission of infectious airborne diseases, and additional guidance related to recirculation has been presented (e.g., REHVA, 2021).

With respect to ambient pollutants entering indoors, $PM_{2.5}$ is one of the biggest contributors of environmental burden of disease (Hänninen et al., 2014). Whereas outdoor originating $PM_{2.5}$ is estimated to be responsible for a larger part of the adverse health effects, most of the exposure occurs indoors. The old mantra "build tight, ventilate right" points towards efficient filtration to prevent PM from outdoor sources from entering indoors. Increasing the airtightness of the building envelope and filtering intake air (required for health ventilation) can provide means of reducing indoor PM originating from outdoor air. Yet these principles are not commonly addressed in the national or international guidelines. The Finnish Society for Indoor Air Quality and Climate have set targets for indoor/outdoor ratio of $PM_{2.5}$ as 0.5 in Class 1 and 0.7 in Class 2 (Sisäilmastoluokitus, 2018). With indoor sources controlled, I/O - ratio could be considered one way to rate $PM_{2.5}$ infiltration through building envelope and ventilation.

It should be noted that the finest particulate matter as well as gaseous pollutants can find their ways regardless of the sealing in the envelope, due through crevices and other entry points (Wang et al., 2016). In addition, a completely sealed building may also become a trap for the indoor generated pollutants (such a $PM_{2.5}$ and VOCs) that may not be able to escape from the inside due to reduced air exchange rates.

For controlling indoor Rn, resistant construction techniques are most effective, but if those are not in place, adequate ventilation is the main control mechanism (Dupleac, 2022). Effectiveness of Rn mitigation intervention has been summarised in a review by Khan et al. (2019). Long term tests of Swedish residential properties have shown decreasing Rn exposure, likely because of improved construction techniques. However, an opposite trend seen in Canada could be attributed to energy conservation coupled with lack of intervention (Khan et al., 2021). Similar results were also shown in a German study where houses refurbished for energy efficiency had a nearly doubled Rn concentration compared to un-refurbished ones (Meyer, 2019). In a multinational study, naturally ventilated buildings that underwent energy retrofitting without changes in ventilation system were found to have higher Rn concentrations post-retrofitting as compared to pre-retrofitting, whereas such higher concentrations were not found in mechanically ventilated buildings (Du et al., 2019).

As described, management of the energy efficiency of airtight buildings requires complex balancing of costs and benefits; energy consumption, thermal environment and IEQ should be addressed at the same time. In contrast, in the past, energy conservation may have been promoted by decreased heating and ventilation, which has led to the lowering of IEQ, and consequently health, comfort, and productivity of the occupants. A lead in one direction is taken by green building rating systems, which have started to include the criteria for IEQ and insist on real time monitoring (Licina et al., 2021). This initiative could be seen as an attempt to resolve the conflict between energy conservation and good IAQ.

To conclude, successful management of economic, environmental and health aspects related to buildings requires regulation and guidance. The ISIAQ STC34 IEQ database which spans across countries and institutions aims to help with taking steps in the direction of having more uniform guidance for the values of indoor parameters. Persistently developing guidelines/standards/regulation in collaboration with scientists, decision makers and other stakeholders should help in creating a greater balance between energy conservation and indoor environmental quality.

5. Disclaimer

The views expressed are the authors and do not necessarily represent the views of their organisations.

CRediT authorship contribution statement

Sani Dimitroulopoulou: Writing – review & editing, Supervision, Writing – original draft. **Marzenna R. Dudzińska:** Writing – review & editing, Supervision, Writing – original draft. **Lars Gunnarsen:** Writing – original draft, Writing – review & editing, Conceptualization, Supervision. **Linda Hägerhed:** Writing – review & editing, Project administration, Writing – original draft. **Henna Maula:** Writing – original draft. **Raja Singh:** Writing – original draft. **Oluyemi Toyinbo Visualisation:** Writing – original draft, Data curation, Formal analysis. **Ulla Haverinen-Shaughnessy:** Conceptualization, Data curation, Formal analysis, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

The data that support the findings of this article are available at www.ieqguidelines.org.

Acknowledgments

The authors thank Mr. Abate Belachew for making the figure for graphical abstract based on the ISIAQ STC34 database. The authors also wish to thank the members of the ISIAQ STC34 and colleagues who have contributed to the database. A full list of active members can be found from https://www.ieqguidelines.org/about.html.

Funding

Halton Foundation has provided a grant for ISIAQ for developing the database.

References

ANSI/ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2022. Standard 62.1. Ventilation and acceptable indoor air quality. Available at https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2. Accessed June 26, 2023.

AQEG - Air Quality Expert Group. 2022. Indoor Air Quality. Report by Defra's Air Quality Expert Group (AQEG), prepared for the Department for Environment, Food and Rural Affairs (Defra), UK. Available at https://uk-air.defra.gov.uk/library/reports?report_id=1101. Accessed June 26, 2023.

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2010. Standard 55. Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating, and Air-conditioning, Inc., Atlanta.

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2022. ASHRAE position document on indoor carbon dioxide. Available at https://www.ashrae.org/file%20library/about/position%20documents/pd_indoorcarbondioxide_2022.pdf. Accessed February 14, 2023.

Baeza-Romero, M.T., Dudzinska, M.R., Amouei Torkmahalleh, M., Barros, N., Coggins, A. M., Ruzgar, D.G., Kildsgaard, I., Naseri, M., Rong, L., Saffell, J., Scutaru, A.M., Staszowska, A., 2022. A review of critical residential buildings parameters and activities when investigating indoor air quality and pollutants. Indoor Air 32 (11), 13144.

BEIS - Department for Business, Energy and Industrial Strategy. 2022. 2020 UK Greenhouse Gas Emissions, Final Figures. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1051408/2020-final-greenhouse-gas-emissions-statistical-release.pdf. Accessed June 26, 2023.

Baruah, U.D., Robertson, S.M., Saikia, A., Mili, S.K., Chand, P., 2022. Spatio-temporal characterization of tropospheric ozone and its precursor pollutants NO2 and HCHO over South Asia. Sci. Total Environ. 809, 151135.

Blondel, A., Plaisance, H., 2011. Screening of formaldehyde indoor sources and quantification of their emission using passive sampler. Build. Environ. 46, 1284–1291.

Bruno, R.C., 1983. Sources of Indoor Radon in Houses: A Review. J. 1 of the Air Pollut. Contr. 2 Assoc. 33 (2), 105–109.

Carrer, P., de Oliveira Fernandes, E., Santos, H., Hänninen, O., Kephalopoulos, S., Wargocki, P., 2018. On the Development of Health-Based Ventilation Guidelines: Principles and Framework. Int. J. Environ. Res. Public Health 15 (7), 1360.

Cinelli, G., Tollefsen, T., Bossew, P., Gruber, V., Bogucarskis, K., De Felice, L., De Cort, M., 2019. Digital version of the European Atlas of natural radiation (Open Access). J. Environ. Radioact. 196, 240–252.

Delmastro C., Bienassis T. D., Goodson T., Lane K., Le Marois J-B, Martinez-Gordon R, Husek M. (2022). International Energy Agency, IEA Buildings Sectorial Overview. https://www.iea.org/reports/buildings. Accessed June 26, 2023.

Derby, M.M., Hamehkasi, M., Eckels, S., Hwang, G.M., Jones, B., Maghirang, R., Shulan, D., 2017. Update of the scientific evidence for specifying lower limit relative humidity levels for comfort, health, and indoor environmental quality in occupied spaces (RP-1630). Sci. Technol. Built Environ. 23 (1), 30–45.

Du, L., Leivo, V., Prasauskas, T., Täubel, M., Martuzevicius, D., Haverinen-Shaughnessy, U., 2019. Effects of energy retrofits on Indoor Air Quality in multifamily buildings. Indoor Air 29 (4), 686–697.

Du, B., Tandoc, M.C., Mack, M.L., Siegel, J.A., 2020. Indoor CO2 concentrations and cognitive function: a critical review. Indoor Air 30 (6), 1067–1082.

Dupleac, D., 2022. The impact of ventilation rate of radon concentration inside high-rise apartment buildings. Radiat. Prot. Dosim. 198 (5), 290–298.

EEA – European Environment Agency. 2022. Europe's air quality status 2022. https://www.eea.europa.eu/publications/status-of-air-quality-in-Europe-2022/europes-air-quality-status-2022 (Accessed June 26, 2023).

European Commission. 2021. Proposal for a directive of the European Parliament and of the council, on the energy performance of buildings (recast) COM/2021/802 final. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0802 (Accessed November 9, 2022).

European Standards EN 13142:2021. Ventilation for buildings. Components/products for residential ventilation. Required and optional performance characteristics. Available at https://www.en-standard.eu/bs-en-13142-2021-ventilation-for-buildings-components-products-for-residential-ventilation-required-and-optional-performance-characteristics/ (Accessed June 26, 2023).

Eurostat. 2022. Over 1 in 5 at risk of poverty and social exclusion. Available at https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220915-1 (Accessed March 3, 2023).

Exley, K., Dimitroulopoulou, S., Gowers, A., Waite, T., Hansell, A. 2022. Air pollution and how it harms health; in Chief Medical Officer's annual report 2022 on Air Pollution. Available from: https://www.gov.uk/government/collections/chief-medical-officer-annual-reports?msclkid=4eaafe9ab4f211ecb739d1b4a4226e0c. Accessed June 26, 2023.

Fanger, P.O., 1970. Thermal comfort, Analysis and applications in environmental engineering. McGrawHill. ISBN:0-07-019915-9.

GBD 2016 Occupational Chronic Respiratory Risk Factors Collaborators, 2020. GBD 2016 occupational chronic respiratory risk factors collaborators. Global and regional burden of chronic respiratory disease in 2016 arising from non-infectious airborne occupational exposures: a systematic analysis for the Global Burden of Disease Study 2016. Occup. Environ. Med. 77 (3), 142–150.

Gunschera, J., Mentese, S., Salthammer, T., Andersen, J.R., 2013. Impact of building materials in indoor formaldehyde levels: Effect of ceiling tiles, mineral fiber insulation and gypsum board. Build. Environ. 64, 138–145.

Guo, M., Xu, P., Xiao, T., He, R., Dai, M., Miller, S.L., 2021. Review and comparison of HVAC operation guidelines in different countries during the COVID-19 pandemic. Build. Environ. 187, 107368.

Halios, C.H., Landeg-Cox, L.SD., Middleton, A., Marczylo, T., Dimitroulopoulou, S., 2022. Chemicals in European Residences – Part I: a review of emissions, concentrations, and health effects of Volatile Organic Compounds (VOCs). Sci. Total Environ. 156201.

Hänninen, O., Knol, A.B., Jantunen, M., Lim, T.A., Conrad, A., Rappolder, M., EBoDE Working Group, et al., 2014. Environmental burden of disease in Europe: assessing nine risk factors in six countries. Environ. Health Perspect. 122 (5), 439–446.

Hodgson, A.T., Beal, D., McIlvaine, J.E.R., 2002. Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house. Indoor Air 12, 235–242.

Hoyt, T., Arens, E., Zhang, H., 2015. Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings. Build. Environ. 88, 89–96.

Huangfu, P., Atkinson, R., 2020. Long-term exposure to NO2 and O3 all-cause and respiratory mortality: systematic review and meta-analysis. Environ. Int. 144, 105998.

Hultqvist, B., 1956. Studies on naturally occurring ionising radiation, with special reference to radiation doses in Swedish houses of various types K. Royal Swedish Academy. Sven. Vetenskapsakad. dissertation. 4, 6.

Hunt, D., Mac Suibhne, N., Dimache, L., McHugh, D., Lohan, J., 2020. Advances in multifunctional balanced ventilation technology for dwellings and arising challenge to quantify energy efficiency and renewable generation contributions using international test standards. Renew. Sustain. Energy Rev. 134, 110327.

Iacobucci, G., 2020. Covid-19: Increased risk among ethnic minorities is largely due to poverty and social disparities, review finds. BMJ: British Medical Journal (Online) Oct 22 (371).

IARC - International Agency for Research on Cancer. 2006. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxypropan-2-ol, Volume 88.

Ielpo, P., Mangia, C., Marra, G.P., Comite, V., Rizza, U., Uricchio, V.F., Fermo, P., 2019. Outdoor spatial distribution and indoor levels of NO2 and SO2 in a high environmental risk site of the South Italy. Sci. Total Environ. 648, 787–797.

IPCC - Intergovernmental Panel on Climate Change. 2023. AR6 Synthesis Report: Climate Change 2023. https://www.ipcc.ch/report/sixth-assessment-report-cycle (Accessed June 26, 2023).

ISHRAE - The Indian Society of Heating, Refrigerating and Air Conditioning Engineers. 2019. Standard 10001. https://ishrae.in/Content/Download/ISHRAE_IEQ_Feb_26_2019_public_draft.pdf (Accessed June 26, 2023).

Khan, S.M., Gomes, J., Krewski, D.R., 2019. Radon interventions around the globe: A systematic review. Heliyon 5 (5).

Khan, S.M., Pearson, D.D., Rönnqvist, T., Nielsen, M.E., Taron, J.M., Goodarzi, A.A., 2021. Rising Canadian and falling Swedish radon gas exposure as a consequence of 20th to 21st century residential build practices. Sci. Rep. 11 (1), 17551.

Kim, J., de Dear, R., 2021. Is mixed-mode ventilation a comfortable low-energy solution? A literature review. Build. Environ. 205, 108215.

Kumar, P., Singh, A.B., Arora, T., Singh, S., Singh, R., 2023. Critical review on emerging health effects associated with the indoor air quality and its sustainable management. Sci. Total Environ. 872, 162163.

Lam, J., Koustas, E., Sutton, P., Padula, A.M., Cabana, M.D., Vesterinen, H., Griffiths, C., Dickie, M., Daniels, N., Whitaker, E., Woodruff, T.J., 2021. Exposure to formaldehyde and asthma outcomes: A systematic review, meta-analysis, and economic assessment. PLoS One 16 (3), e0248258.

Lan, L., Lian, Z., 2016. Ten questions concerning thermal environment and sleep quality. Build. Environ. 99, 252–259.

Lan, L., Tsuzuki, K., Liu, Y.F., Lian, Z.W., 2017. Thermal environment and sleep quality: A review. Energ. Buildings 149, 101–113.

Langer, S., Beko, G., 2013. Indoor air quality in the Swedish housing stock and its dependence on building characteristics. Build. Environ. 69, 44–54.

Leung, D.Y., 2015. Outdoor-indoor air pollution in urban environment: challenges and opportunity. Front. Environ. Sci. 2, 69.

Li, Y., Leung, G.M., Tang, J.W., Yang, X., Chao, C.Y.H., Lin, J.Z., Lu, J.W., Nielsen, P.V., Niu, J., Qian, H., Sleigh, A.C., Su, H.J.J., Sundell, J., Wong, T.W., Yuen, P.L., 2007. Role of ventilation in airborne transmission of infectious agents in the built environment—A multidisciplinary systematic review. Indoor Air 17 (1), 2–18.

Li, L., Stern, R.A., Blomberg, A.J., Kang, C.M., Wei, Y., Liu, M., Koutrakis, P., 2022. Ratios between Radon Concentrations in Upstairs and Basements: A Study in the Northeastern and Midwestern United States. Environ. Sci. Technol. Lett. 9 (2), 191–197.

Licina, D., Wargocki, P., Pyke, C., Altomonte, S., 2021. The future of IEQ in green building certifications. Buildings and Cities 24 (2 (1)).

Liddell, C., Morris, C., 2010. Fuel poverty and human health: a review of recent evidence. Energy Policy 38 (6), 2987–2997.

Lim, S.M., Choi, J.W., Hong, M.H., Jung, D., Lee, C.Y., Park, S.Y., Shim, H.S., Sheen, S., Im Kwak, K., Kang, D.R., Cho, B.C., 2019. Indoor radon exposure increases tumor mutation burden in never-smoker patients with lung adenocarcinoma. Lung Cancer 131, 139–146.

Liu, W., Lian, Z., Liu, Y., 2008. Heart rate variability at different thermal comfort levels. Eur. J. Appl. Physiol. 103, 361–366.

Lowther, S.D., Dimitroulopoulou, S., Foxall, K., Shrubsole, C., Cheek, E., Gadeberg, B., Sepai, O., 2021. Low level carbon dioxide indoors—a pollution indicator or a pollutant? A health-based perspective. Environments 8 (11), 125.

Maidment, C.D., Jones, C.R., Webb, T.L., Hathway, E.A., Gilbertson, J.M., 2014. The impact of household energy efficiency measures on health: a meta-analysis. Energy Policy 65, 583–593.

Meyer, W., 2019. Impact of constructional energy-saving measures on radon levels indoors. Indoor Air 29 (4), 680–685.

Milhem, S.A., Verriele, M., Nicolas, M., Thevenet, F., 2021. Indoor use of essential oil-based cleaning products: Emission rate and indoor air quality impact assessment based on a realistic application methodology. Atmos. Environ. 246, 118060.

Monn, C., 2001. Exposure assessment of air pollutants: a review on spatial heterogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen dioxide and ozone. Atmos. Environ. 35, 1–32.

Myers, I. 2022. The efficient operation of regulation and legislation: An holistic approach to understanding the effect of Carbon Monoxide on mortality. A report for the CO Research Trust. CO Research Trust. Available from: https://www.coresearchtrust.org/assets/uploads/images/CORT-Report-Medical-Examiners-Coroners-and-CO.pdf (Accessed June 26, 2023).

Naghizadeh, A., Sharifzadeh, G., Tabatabaei, F., Afzali, A., Yari, A.R., Geravandi, S., Mohammadi, M.J., 2019. Assessment of carbon monoxide concentration in indoor/outdoor air of Sarayan city, Khorasan Province of Iran. Environ. Geochem. Health 41, 1875–1880.

NASEM - National Academies of Sciences, Engineering, and Medicine, 2022. Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches: Proceedings of a Workshop. The National Academies Press, Washington, DC.

Nathavitharana, R.R., Mishra, H., Sullivan, A., Hurwitz, S., Lederer, P., Meintjes, J., Theron, G., 2022. Predicting airborne infection risk: Association between personal ambient carbon dioxide level monitoring and incidence of tuberculosis infection in South African health workers. Clin. Infect. Dis. 75 (8), 1297–1306.

Nazaroff, W.W., 1992. Radon transport from soil to air. Rev. Geophys. 30 (2), 137–160.

Niu, J.L., Burnett, J., 2001. Setting up the criteria and credit- awarding scheme for building interior material selection to achieve better indoor air quality. Environ. Int. 26, 573–580.

Olsthoorn, B., Rönnqvist, T., Lau, C., Rajasekaran, S., Persson, T., Månsson, M., Balatsky, A.V., 2022. Indoor radon exposure and its correlation with the radiometric map of uranium in Sweden. Sci. Total Environ. 811, 151406.

Ortiz, M., Bluyssen, P.M., 2022. Indoor environmental quality, energy efficiency and thermal comfort in the retrofitting of housing: A literature review. Routledge Handbook of Resilient Thermal Comfort 433–445.

Persily, A., 1997. Evaluating building IAQ and ventilation with indoor carbon dioxide. Trans.-Am. Soc. Heat. Refrig. Air Condit. Eng. 103, 193–204.

Persily, A., 2015. Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62. Build. Environ. 91, 61–69.

NOAA - National Oceanic and Atmospheric Administration (2023). Climate Change: Atmospheric Carbon Dioxide. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide (Accessed June 26, 2023).

PHE - Public Health England (2014) Minimum home temperature thresholds for health in winter - a systematic literature review. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/776497/Min_temp_threshold_for_homes_in_winter.pdf (Accessed June 26, 2023).

Rawal, R., Schweiker, M., Kazanci, O.B., Vardhan, V., Jin, Q., Duanmu, L., 2020. Personal comfort systems: A review on comfort, energy, and economics. Energ. Buildings 214, 109858.

RCPCH. 2020. The inside story: Health effects of indoor air quality on children and young people. Report by the Royal College of Paediatrics and Child Health in collaboration with the Royal College of Physicians https://www.rcpch.ac.uk/resources/inside-story-health-effects-indoor-air-quality-children-young-people (Accessed June 26, 2023).

REHVA - Federation of European Heating, Ventilation and Air Conditioning Associations. 2021. COVID19 Guidance. How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces version 4.1. https://www.rehva.eu/fileadmin/user_upload/REHVA_COVID-19_guidance_document_V4.1_15042021.pdf (Accessed November 9, 2022).

Richardson, E.T., Morrow, C.D., Kalil, D.B., Bekker, L.G., Wood, R., 2014. Shared air: A renewed focus on ventilation for the prevention of tuberculosis transmission. PLoS One 9 (5), 1–7.

Rudnick, S.N., Milton, D.K., 2003. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. Indoor Air 13 (3), 237–245.

Rupp, R., Vásquez, N., Lamberts, R., 2015. A review of human thermal comfort in the built environment. Energ. Buildings 105, 178–205.

Seo, S., et al., 2019. Health effects of exposure to radon: Implications of the radon bed mattress incident in Korea. Epidemiology and Health 41.

Seppänen, O., Fisk, W.J., Faulkner, D. 2003. Cost benefit analysis of the night-time ventilative cooling in office building. In: Proceedings of the Healthy Buildings Conference, Singapore.

Sharpe, T., Mawditt, I., Gupta, R., McGill, G. and Gregg, M. 2016. Characteristics and performance of MVHR systems A meta study of MVHR systems used in the Innovate UK Building Performance Evaluation Programme. https://pureportal.strath.ac.uk/en/publications/characteristics-and-performance-of-mvhr-systems-a-meta-study-of-m (Accessed June 26, 2023).

Singer, B.C., Coleman, B.K., Destaillats, H., Hodgson, A.T.H., Lunden, M.M., Weschler, C. J., Nazaroff, W.W., 2006. Indoor secondary pollutants from cleaning products and air freshener use in the presence of ozone. Atmos. Environ. 40, 6696–6710.

Singh, R., Dewan, A., 2022b. Progress on indoor air quality regulation in India. The Int. J. Tuberculosis Lung Dis.: Off. J. Int. Union Against Tuberculosis Lung Disease 26 (8), 801b–802b.

Sisäilmastoluokitus. 2018. RT 07-11299, Building Information. Available at https://www.rakennustietokauppa.fi/sivu/tuote/rt-07-11299-sisailmastoluokitus-2018-sisaympariston-tavoitearvot-suunnitteluohjeet-ja-tuotevaatimukset/2742604 (Accessed June 26, 2023).

Well Standard. 2017. Demand controlled ventilation. Available at https://standard.wellcertified.com/v8/demand-controlled-ventilation-0 (Accessed February 14, 2023).

Taylor, J., Yates, T., Mthethwa, M., Tanser, F., Abubakar, I., Altamirano, H., 2016. Measuring ventilation and modelling M. tuberculosis transmission in indoor congregate settings, rural KwaZulu-Natal. Int. J. Tuberc. Lung Dis. 20 (9), 1155–1161.

Tollefsen, T, De Cort, M, Cinelli, G, Gruber, V., Bossew, P. 2017. European Atlas of Natural Radiation, Ispra (Italy): European Commission - Joint Research Centre; JRC106967.

Toyinbo, O., Shaughnessy, R., Turunen, M., Putus, T., Metsämuuronen, J., Kurnitski, J., Haverinen-Shaughnessy, U., 2016. Building characteristics, indoor environmental quality, and mathematics achievement in Finnish elementary schools. Build. Environ. 104, 114–121.

Toyinbo, O., Phipatanakul, W., Shaughnessy, R., Haverinen-Shaughnessy, U., 2019. Building and indoor environmental quality assessment of Nigerian primary schools: A pilot study. Indoor Air 29 (3), 510–520.

Toyinbo, O., Hägerhed, L., Dimitroulopoulou, S., Dudzinska, M., Emmerich, S., Hemming, D., Committee, S.T., 2022. Open database for international and national indoor environmental quality guidelines. Indoor Air 32 (4), e13028.

UKHSA - UK Health Security Agency (2022). Carbon monoxide: General information https://www.gov.uk/government/publications/carbon-monoxide-properties-incident-management-and-toxicology/carbon-monoxide-general-information (Accessed June 26, 2023).

UKHSA - UK Health Security Agency (2022) UK maps of radon. https://www.ukradon.org/information/ukmaps (Accessed June 26, 2023).

UNDP - United Nations Development Programme and Oxford Poverty and Human Development Initiative (2022). Global Multidimensional Poverty Index 2022. https://www.undp.org/sites/g/files/zskgke326/files/2022-10/2022mpireportenpdf.pdf (Accessed April 2, 2023).

United State Census Bureau (2022). Poverty rate of children higher than national rate, lower for older populations. Available at https://www.census.gov/library/stories/2022/10/poverty-rate-varies-by-age-groups.html#:~:text=The%20national%20poverty%20rate%20was,Census%20Bureau%20report%20released%20today (Accessed February 14, 2023).

UNSCEAR - United Nation Scientific Committee on the Effects of Atomic Radiation (2000). Report Annex B: Exposure Due to Natural Radiation Sources, vol. 1.
Vardoulakis, S., Dimitroulopoulou, C., Thornes, J., Lai, K.-M., Taylor, J., Myers, I., Heaviside, C., Mavrogianni, A., Shrubsole, C., Chalabi, Z., Davies, M., Wilkinson, P., Haines, A., 2015. Impact of climate change on the domestic indoor environment and associated health risks in the UK. Environ. Int. 85, 299–313.
Villanueva, F., Tapia, A., Lara, S., Amo-Salas, M., 2018. Indoor and outdoor air concentrations of volatile organic compounds and NO_2 in schools of urban, industrial and rural areas in Central-Southern Spain. Sci. Total Environ. 622–623, 222–235.
Vouriot, C.V., Burridge, H.C., Noakes, C.J., Linden, P.F., 2021. Seasonal variation in airborne infection risk in schools due to changes in ventilation inferred from monitored carbon dioxide. Indoor Air 31 (4), 1154–1163.
Vu, T.V., Stewart, G.B., Kitwiroon, N., Lim, S., Barratt, B., Kelly, F.J., Thompson, R., Smith, R.B., Toledano, M.B., Beevers, S.D., 2022. Assessing the contributions of outdoor and indoor sources to air quality in London homes of the SCAMP cohort. Build. Environ. 222, 109359.
Wang, F., Meng, D., Li, X., Tan, J., 2016. Indoor-outdoor relationships of PM2.5 in four residential dwellings in winter in the Yangtze River Delta, China. Environ. Pollut. 215, 280–289.
Wang, C., Wang, J., Norback, D., 2022. A Systematic Review of Associations between Energy Use, Fuel Poverty, Energy Efficiency Improvements and Health. Int. J. Environ. Res. Public Health 19 (12), 7393.
WHO World Health Organization Regional Office for Europe (2019b). Environmental health inequalities resource package. A tool for understanding and reducing inequalities in environmental risk. Available at https://apps.who.int/iris/bitstream/handle/10665/346223/WHO-EURO-2019-3505-43264-60635-eng.pdf?sequence=3 (Accessed June 26, 2023).
WHO - World Health Organization. 1987. Health impact of low indoor temperatures. Regional Office for Europe: World Health Organization. Air quality guidelines for Europe. Copenhagen: WHO Regional Office for Europe; 1987. (WHO Regional Publications, European Series, No. 23).
WHO - World Health Organization (2000). Right to Healthy Indoor Air. Available at https://www.euro.who.int/_data/assets/pdf_file/0019/117316/E69828.pdf (Accessed March 16, 2023).
WHO - World Health Organization. 2006. Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Copenhagen: WHO Regional Office for Europe; 2006. https://www.euro.who.int/_data/assets/pdf_file/0005/78638/E90038.pdf (Accessed March 20, 2023).
WHO- World Health Organization (2009a). WHO guidelines for indoor air quality: dampness and mould. Heseltine, Elisabeth, and Jerome Rosen, eds. https://apps.who.int/iris/handle/10665/164348 (Accessed March 20, 2023).
WHO - World Health Organization. 2009b. WHO handbook on indoor radon. A public health perspective. Available at https://www.ncbi.nlm.nih.gov/books/NBK143216/ (Accessed June 26, 2023).
WHO - World Health Organization. 2010. WHO guidelines for indoor air quality: selected pollutants. World Health Organization. Regional Office for Europe. Available at https://www.euro.who.int/_data/assets/pdf_file/0009/128169/e94535.pdf (Accessed March 16, 2023).
WHO - World Health Organization. 2011. Health co-benefits of climate change mitigation-Housing sector. Health in the green economy. https://www.who.int/hia/green_economy/housing_report/en/ (Accessed April 2, 2023).
WHO - World Health Organization Regional Office for Europe. 2019a. Environmental Health Inequalities in Europe. Second Assessment Report. Available at http://www.euro.who.int/en/publications/abstracts/environmental-health-inequalities-in-europe.-second-assessment-report-2019 (Accessed June 26, 2023).
WHO - World Health Organization. 2021. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at https://apps.who.int/iris/handle/10665/345329 (Accessed June 26, 2023).
WHO - World Health Organization. 2023. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/gho-phe-radon-database-national-radon-concentration-levels (Accessed June 26, 2023).
Wolkoff, P., 1995. Volatile organic compounds – sources, measurements, emissions, and the impact on indoor air quality. Indoor Air (Suppl. No 3), 1–73.
Wolkoff, P., Kjaergaard, S.K., 2007. The dichotomy of relative humidity on indoor air quality. Environ. Int. 33, 850–857.
Wolkoff, P., Wilkins, C.K., Clausen, P.A., Nielsen, G.D., 2006. Organic compounds in office environments- sensory irritation, odor, measurements and the role of reactive chemistry. Indoor Air 16, 7–19.
Wolkoff, P., Azuma, K., Carrer, P., 2021. Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation. Int. J. Hyg. Environ. Health 233, 113709.
Yao, Y., Lian, Z., Liu, W., Jiang, C., Liu, Y., Lu, H., 2009. Heart rate variation and electroencephalograph - the potential physiological factors for thermal comfort study. Indoor Air 19 (2), 93–101.
Zhang, F., de Dear, R., Hancock, P., 2019. Effects of moderate thermal environments on cognitive performance: A multidisciplinary review. Appl. Energy 236, 760–777.
Zhang, T.T., Yin, S., Wang, S., 2011. Quantify impacted scope of human expired air under different head postures and varying exhalation rates. Build. Environ. 46 (10), 1928–1936.