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Review

Improving Indoor Air Quality through Standardization

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Abstract: Human beings experience a large fraction of their exposure to air pollutants in indoor environments. Air pollution is a large environmental health risk, and exposure to ambient air pollution and indoor air pollution contribute equally to the total number of fatalities worldwide. Although legislative authorities have established limit values for ambient outdoor air and stack emissions, there are inconsistent and variable national and regional limit values for gaseous substances and airborne particulate matter in the built environment (schools, homes, healthcare facilities, offices, and other public spaces). This lack of regulation is unsurprising, because indoor spaces are characterized by complex air chemistry, and their construction materials and types of activities vary significantly. The current understanding of indoor pollutants, including short-lived oxidants, degradation of VOCs, particle formation, and particle composition, is incomplete. It is necessary to identify and assess emerging pollutants and their toxicity, and to consider new consumer products and green construction materials and their impact on indoor air quality (IAQ). Learning from IAQ surveys and audit protocols, research methodologies should be regularized for cross-research comparisons. Some indoor air quality guidance and standards have been written, and several more are in development, with the international ISO 16000 series of indoor standards leading the way for improving indoor air data quality. The WHO has established some ambient air limit values which can mostly be translated into indoor limit values. The built environment needs to harmonize energy efficiency, thermal comfort and air quality standards and guidance. In this review, we discuss the next steps for improving international, regional and national standards and guidance, leading to better and more complete indoor air quality regulations.

Keywords: indoor air quality; IAQ; air quality standards; air quality regulations; air quality guidance; indoor pollutants; IAQ survey; indoor air data quality; limit value

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1. Introduction

In developed countries, people spend a large fraction of the day in indoor environments [1–4], with two important consequences:

- Indoor air quality (IAQ) directly affects human health and wellbeing, with airborne particulate matter (PM), oxidizing gases (ozone, nitrogen dioxide, chlorine) and volatile organic compounds (VOCs) all causing respiratory, pulmonary, and neural damage [5]. The resulting burden on national healthcare systems is very significant [6].
- The construction, usage, renovation and demolition of buildings account for 40% of the total energy consumption [7,8]; therefore, reducing building energy requirements is a climate change priority.

A large body of scientific studies has shown that exposure to indoor air pollutants has adverse effects on the human health. The known health impacts are reduced cognitive function, heart and respiratory symptoms, stroke, chronic obstructive pulmonary disease and lung cancer [9–11]. Requirements for future air quality management approaches must tackle the individual's exposure to airborne pollutants [12]. An individual's exposure strongly depends on temporal and spatial pollutant concentrations, fluctuations in pollutant emission patterns, the characteristics of the built environment, and human behavior [13,14]. Protecting human health and also conserving energy are two conflicting priorities; good ventilation is pursued for better air quality, but energy savings are also pursued through sealed buildings and the reduced performance of ventilation systems.

Society attempts to resolve such conflicts through legislation and standardization procedures. Governments set the maximum allowed pollutant concentrations and establish building regulations, mainly for ventilation; however, ensuring that these regulations are followed requires guidance documents (i.e., technical specifications and standards). Despite the fact that a comprehensive amount of scientific insight into the physico-chemical features of pollution in the built environment (and ventilation) is available, practical application of this scientific information via guidance documents to help building designers, building operators, and facility managers is incomplete or missing.

In this review, we assess the body of normative documents on IAQ, and how these documents are elaborated, either through legislation or standardization processes (Section 2). The selection criteria for normative documents of global recognition presented in this review are detailed in Section 3. The review results of documents from legislation processes and from standardization processes are presented in Sections 4 and 5, respectively. Finally, the review results are discussed (Section 6), and conclusions are drawn (Section 7).

2. The Body of Normative Documents on IAQ

Globally, many nations have enforced ambient air quality standards with legally binding force as a means to protect public health. In several countries, these ambient air quality standards are oriented towards the values proposed in the 'WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide'. The latest issue of the 'WHO air quality guidelines' is, for the first time, applicable to both ambient and indoor air [5]. Even though IAQ is of paramount importance for the health of the occupants of the built environment, there are no legally binding IAQ guidance documents. This situation represents a stark contrast to the legally binding character of ambient air quality guidance documents. The constitutional basis and legislation must cover all fields of law, and thus cannot focus on the technical details necessary to measure, assess, and improve air quality. Therefore, legislation and regulations are supported by administrative provisions, assuring the equal treatment of relevant persons by the executing administration. Following administrative provisions, technical specifications and standards provide practical guidance for people needing to fulfill the legal requirements laid down by regulations. This construction of the 'legal pyramid' allows for increasing attention to detail via technical specifications and standards. It is also easier to revise technical specifications and standards than regulations (see Figure 1).

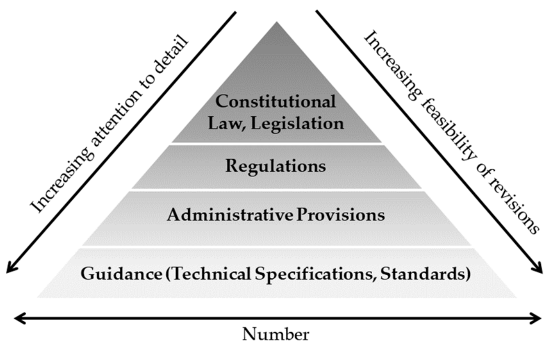

Figure 1. Construction of the 'legal pyramid' describing the body of normative documents comprising documents resulting from legislation processes (constitutional law, legal acts, regulations and administrative provisions), as well as guidance documents resulting from standardization processes (technical specifications and standards). The number of normative documents increases with increasing attention to technical details. Revising normative documents is also easier for documents paying greater attention to technical details.

The normative documents reviewed in this work result either from legislative processes (regulations) or from standardization processes (guidance documents comprising technical specifications and (pre-)standards).

Legislation comprises the exercise of power and the function of making rules (including laws) that have the force of authority by virtue of their promulgation by an official government body.

Standardization comprises all systematic activities executed by stakeholders with the overall aim to harmonize (im)material objects. These systematic activities can be at the national, regional or international level. A recognized Standards Developing Organization (SDO) uses dedicated processes to identify and involve stakeholders in the consensus-building process amongst all interested parties. Clear documentation of these processes by the recognized SDO and communication of them to the general public are mandatory. Furthermore, the FRAND criteria (fair, reasonable and non-discriminatory treatment of all stakeholder interests) have to be fulfilled in all standardization sub-processes. The consensus-building process assures general consent among all stakeholders involved in standardization. Finally, consent is characterized by the absence of implicit and explicit objection to the essential content. For this reason, a consensus-building process considers all aspects of the stakeholders, and tries to clear out all counter-arguments. Consensus does not necessarily mean unanimity [15]. Unlike peer-reviewed research articles which express the view of one or a few authors, guidance documents state the agreed view of a plurality of experts.

3. Methodology

This work focuses on the standardization process and analyzes how standardization is influenced by legislation, and how standardization can drive legislation on a national, regional and international level.

In the following, three essential types of normative documents are considered for determining the requirements to monitor and improve IAQ, namely in regulations, standards and pre-standards, and technical specifications for the management of IAQ.

- A **regulation** is a normative government-approved act with general application, which is addressed to abstract categories of persons. Regulations are legally binding in their entirety; they may not be applied incompletely, selectively, or partially, and they are directly applicable. For indoor air quality, regulations address fundamental key questions oriented towards general environmental protection approaches (the polluter pays principle, principle of sustainable development, principle of preventive action, principle of cooperation, principle of subsidiarity).
- A **standard** is a normative document published by an SDO. It results from a standardization activity hosted by an SDO on a national, regional or international basis. In this standardization activity, a full consensus amongst all stakeholders must be achieved via the consensus-building process. The resulting normative document provides specifications for general and/or recurrent activities, or for the results (immaterial and/or material) of these activities. Trusted scientific and technical results are the knowledge basis of standards (i.e., the state of the art). The overarching objective of a standard is to create social benefits. Standards make things work by providing specifications (guidance or requirements) for products, services and systems. Importantly, adherence to a standard is voluntary (unless laid down by a regulation or required by a business contract), but meeting the requirements of a standard does not confirm that legal requirements have been met [15,16].
- Standards are elaborated upon by SDOs with full membership in the International Organization for Standardization (ISO), and with corresponding mandates.
- A **pre-standard** is a normative document published by an SDO. It results from a standardization activity hosted by an SDO on a national, regional or international basis. In this standardization activity, a partial consensus is reached amongst a limited number of stakeholders. A pre-standard specifies recommendations for possible products,

processes or services. Rapidly evolving and newly emerging scientific and technical results form the knowledge basis of pre-standards. Certain objections about the content might lead to the situation in which a pre-standard will not be published as a standard. The intention of applying a pre-standard is to gain experience, which can then help to create a standard. Some pre-standards documents have a limited lifetime. Following a period of review by all members of the governing body of the SDO, a pre-standard can be converted into a standard, if approved, and after any agreed modifications by the SDO [15,16].

- **Technical specifications** expand the law. Technical specifications are normative documents that have not been fully ratified by the SDO, but are still useful, and can be used as guidance for regulators. They may be statutory (and must be followed) or not statutory; however, if they are not followed, a person or organization may still be liable to prosecution. Technical specifications and, frequently, annexes in standards provide guidance. In contrast to standards, technical specifications are not fully ratified by an SDO who has full ISO membership and corresponding mandates.

Most IAQ regulations, (pre-)standards, and technical specifications result in either emission reduction requirements (➔ exposure-driven approach) or ventilation requirements (➔ ventilation-driven approach), which are two different approaches for tackling the management of IAQ (see Table 1).

Table 1. Scope of normative documents for managing IAQ, grouped by intervention approach.

	Ventilation-Driven Approach	Exposure-Driven Approach
Regulations	▪ What to assess (IAQ parameter/pollutant) ▪ Where to assess IAQ (applicable environment/point of emission)	▪ Whom to protect from adverse indoor environmental parameters (applicable occupant/subject of protection) ▪ From what to protect the occupants (health effects)
	⇨ Legally binding requirements for permitted concentrations of airborne pollutants, pollutant emission rates and ventilation rates.	
(Pre-)Standards Technical Specifications	▪ Ventilation-related aspects (mechanical/non-mechanical ventilation, outdoor air quality)	▪ Activity-related aspects (e.g., basal metabolic rate (BMR), physical activity ratio (PAR), activity-specific emissions) ▪ Occupancy-related aspects (e.g., number of occupants, profiles of occupants, time of occupancy) ▪ Material-related aspects (e.g., pollution sources, construction materials, furnishing emissions)
	⇨ Guidance on how to fulfill legally binding requirements with standardized sampling and analysis, harmonized data quality objectives, standardized IAQ surveys, and consideration of specific and general building characteristics.	

The data presented in this review on IAQ-relevant regulations were retrieved from the databases of the International Society of Indoor Air Quality and Climate (ISIAQ), the World Health Organization (WHO), the United States Environmental Protection Agency (EPA), and the Occupational Safety and Health Administration (OSHA) of the United States Department of Labor (Section 4). Additionally, IAQ-relevant guidance documents retrieved from the databases of the ISO, European Committee for Standardization (CEN), American National Standards Institute (ANSI), American Society for Testing and Materials (ASTM), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), American Conference of Governmental Industrial Hygienists (ACGIH), and VDI/DIN (Verein Deutscher Ingenieure/Deutsches Institut für Normung) Commission on Air Pollution Prevention (Section 5) were analyzed to identify priority areas for future legislation and standardization and for future research directions. The scope of the legislative and resultant SDO documents covers both exposure-driven and ventilation-driven approaches. Generally, the reviewed documents pursue the overarching aim of monitoring and reducing indoor airborne pollutants to improve wellbeing, while also optimizing building ventilation. This paper concludes with a discussion of how legislation drives standardization, with recommendations on how to drive legislation through standardization, and identifying priority areas for future standardization (Section 6).

The scope of the reviewed normative documents comprises the built environment, specifically residential spaces, offices and workspaces, hospitals, schools, kindergartens, sports halls, restaurants and bars, theatres, cinemas and other public spaces. Workrooms and workplaces, which are already subject to national and regional regulations for health and safety inspections, are not considered in this review. This study focuses on normative documents published by international, European, and North American SDOs, and does not claim to be complete. This study has selected normative documents from these SDOs that have achieved global recognition:

- IAQ-relevant regulations reviewed by ISIAQ, subsequently prioritized and finally compared with guidance documents from WHO, EPA, USA Federal government rules, published in the Federal Code Register (eFCR) [17]. and OSHA (Section 4).
    - Parameters for the assessment of IAQ were identified and prioritized based on the Indoor Environmental Quality Guidelines Database of ISIAQ. This database on global indoor environmental quality guidelines is updated continuously.
      The IAQ parameters from the ISIAQ database are further compared with recommendations for policy-makers provided by the WHO. The WHO, through the guidelines review committee, ensures that WHO guidelines are based on the best available evidence and are consistent with internationally accepted best practices. Finally, the IAQ parameters are also complemented with recommendations from the US EPA and OSHA.
- Globally recognized IAQ-relevant guidance documents, standards and technical specifications retrieved from the databases of ISO, CEN, ANSI, ASTM, ASHRAE, ACGIH, and VDI/DIN (Section 5).
    - Citizen demands on consumer product manufacturers are driven by health effects related to IAQ. This is reflected by numerous product labels for 'low-emission' products used for marketing purposes. Standardization agencies encountered this situation, which comprises regulatory developments as well as market needs, and established a dedicated committee within the ISO. The ISO compendium on the characterization of IAQ comprises more than 45 ISO Standards for specific pollutants and IAQ parameters (ISO 16000 and ISO 12219 series of standards) to date. Selected ISO standards were jointly elaborated upon with CEN either through the so-called Vienna Agreement or through the transposition of an existing ISO standard into an EN ISO. Other IAQ standards were developed specifically by CEN. It is noteworthy that CEN technical specifications (CEN/TS), the precursor documents of full EN standards, may wait for extended periods for TS validation funding, which is required to raise a TS to EN standard. Moreover, standardization bodies, both ISO members (ANSI, VDI/DIN) and non-ISO members (ASTM, ASHRAE, ACGIH), have developed complementary standards and guidance documents; these are compiled in the subsections of Section 5.

4. IAQ-Relevant Regulations

4.1. Priority Parameters

In a review performed by ISIAQ, the government guidelines and regulations on different IAQ parameters of 35 nations were compiled. The results are reported in Figure 2 for each individual IAQ parameter.

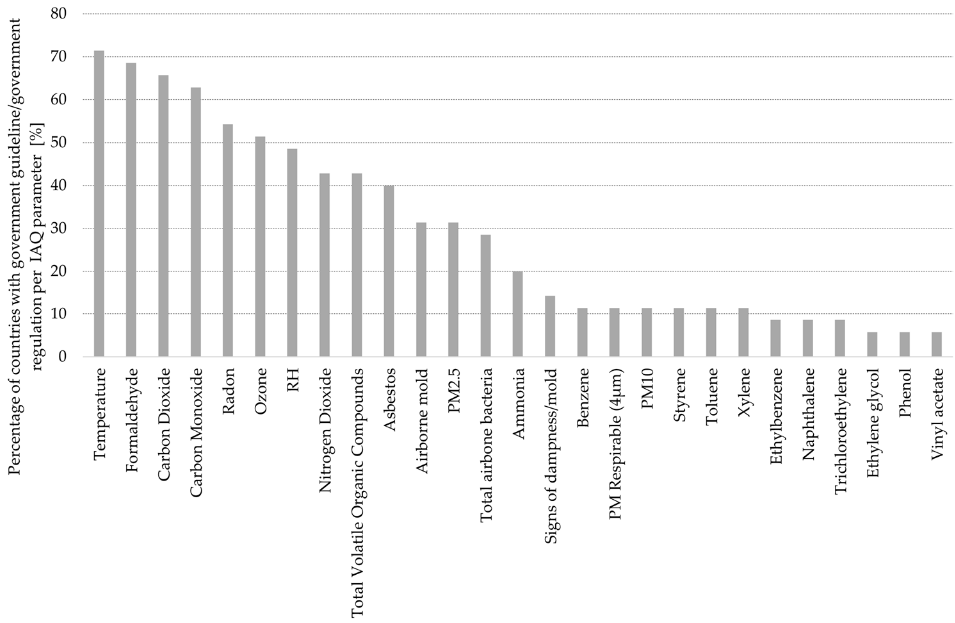

Figure 2. Percentage of countries that adopted government guidelines or government regulations for different IAQ parameters. Government guidelines/government regulations from 35 countries were reviewed. This figure is based on data extracted from the ISIAQ Indoor Environmental Quality Guidelines Database.

It is clear that temperature plus formaldehyde, carbon dioxide, carbon monoxide, radon and ozone concentrations are the dominantly legislated IAQ parameters. Each of these parameters are subject to government guidelines or government regulations in more than 50% of the countries considered in the review [18].

Based on the key questions (the scope of normative documents) defined in Table 1, IAQ parameters are grouped into different categories with respect to their scope, and in order of decreasing occurrence in Table 2. This list includes specific VOCs and bioaerosols which are not regularly monitored.

The list of priority parameters based on the ISIAQ review shown in Table 2 comprises all parameters for the assessment of ambient and indoor air quality proposed in the 'WHO global air quality guidelines' ($PM_{2.5}$, PM_{10}, O_3, NO_2, CO), except for SO_2. Dealing primarily with ambient outdoor air, the guidance limit values for particles and NO_2 were reduced in the latest 'WHO global air quality guidelines' [5]. Black carbon (BC), ultrafine particles (UFP), and sand and dust storms (SDS) were highlighted as important pollutants, but adequate data to set limit values were lacking. The 2010 'WHO guidelines for indoor air quality: selected pollutants', which focuses on IAQ, has highlighted specific VOCs including naphthalene, trichloroethylene, tetrachloroethylene and formaldehyde [19].

Asbestos, biological pollutants, CO, formaldehyde, NO_2, Rn, PM, and VOCs are listed by EPA as indoor pollutants, and are also covered by the ISIAQ ranking. In addition to the ISIAQ parameters, EPA also includes Pb, pesticides, environmental tobacco smoke (ETS), and wood smoke in the priority list of IAQ parameters [20].

The OSHA parameters for the assessment of IAQ (CO, CO_2, Rn, biological contaminants, and VOCs) are covered by the ISIAQ ranking, with the exceptions of pesticides, Legionella, and dampness [21].

Table 2. Priority parameters retrieved from government guidelines and government regulations grouped into different categories with respect to their scope, and in order of increasing occurrence (each in more than 5% of countries in the ISIAQ Indoor Environmental Quality Guidelines Database).

Key Question for IAQ Management	Priority Parameter
What to assess? (parameter/pollutant)	▪ temperature ▪ formaldehyde concentration ▪ carbon dioxide concentration ▪ carbon monoxide concentration ▪ radon concentration ▪ ozone concentration ▪ relative humidity ▪ total VOC concentration ▪ nitrogen dioxide concentration ▪ airborne asbestos fiber concentration ▪ airborne mold concentration ▪ total airborne bacteria concentration ▪ $PM_{2.5}$, PM_4 and PM_{10} concentration ▪ ammonia concentration ▪ sign of dampness/mold ▪ aromatic hydrocarbons concentration ▪ ethylene glycol concentration ▪ trichloroethylene concentration ▪ vinyl acetate concentration
Where to assess? (applicable environment/point of emission)	▪ offices ▪ schools ▪ residential buildings ▪ non-residential buildings ▪ commercial buildings ▪ care facilities ▪ all buildings
Whom to protect? (applicable occupant/subject of protection)	▪ children (< 16 years old) ▪ students ▪ adolescents (16–18 years old) ▪ adults (19–<65 years old) ▪ older adults (≥65 years old) ▪ workers ▪ general population ▪ immunocompromised people
From what to protect? (health effects)	▪ acute effects ▪ chronic effects ▪ cancer

4.2. Health Classifications

Different approaches are used when evaluating the impact of IAQ on health. Regulations and resulting guide values are usually based on either epidemiological or toxicological data. The derived guide values can lead to emission reductions and/or ventilation requirements. Guide values should be and are frequently accepted as the limit values in regulations.

It is necessary to distinguish between the four types of guide values [22]:

- **Hygienically justified guide values** are based on the observation that the probability of health problems increases with increasing concentration. Some examples are guide values for TVOC and CO_2.
- **Toxicologically justified guide values** are based on dose descriptors. Dose descriptors facilitate the identification of the interrelation between a specific effect of a substance and the dose at which the effect is observed. Such dose descriptors are the basis for deriving the so-called no-effect threshold levels for human health (i.e., the derived no-effect level (DNEL) or reference dose (RfD)) and the environment (the predicted

no-effect concentration (PNEC)). Toxicological studies are the knowledge base of dose descriptors. Typically, they are expressed as the lethal concentration (LC), lethal dose (LD), no-observed-adverse-effect Level (NOAEL), and lowest-observed-adverse-effect Level (LOAEL). They are used for hazard classification and risk assessment.

- **Risk-related guide values** are consulted for the health assessment of carcinogenic pollutants in indoor air, and for the specification for genotoxic carcinogens with the most sensitive endpoint.
- **Odor guide values** are used to report the concentration of a substance perceived by at least half of the test persons. One level of classification differentiates between a noticeable odor and a significantly annoying odor.

5. IAQ-Relevant Guidance Documents

Limit values for air quality in some workplaces are legally enforced. Unfortunately, although there are guidance documents for some pollutants and minimum fresh air rates, there are relatively few national or regional limit values for gaseous substances and airborne particulate matter that have broad legally binding force. Currently, the air quality in the built environment is mostly monitored and enforced by building and ventilation regulations. Owing to the significant health impacts of IAQ, related research has accelerated during the last two decades. This can be seen in the increasing number of scientific publications and international standards [23].

The Appendix A lists guidance documents from several SDOs. These normative documents are separated into 14 categories, defined by their target pollutant or purpose. Each category is discussed below.

5.1. Inorganic Gases

The guidance documents for specific pollutant gases, which either define the test method or the method of evaluating and validating the analyzers, are as follows.

Nitrogen dioxide can be measured using wet chemistry. ASTM D1607 and ISO 6768 detail the Griess–Saltzman reaction, while OSHA Method ID-214 and EN 16339 explain extraction and analysis using ion chromatography. Chemiluminescence is the reference method, as detailed in EN 14211. ISO 16000-15 gives guidance for a NO_2 sampling plan. Cavity-attenuated phase shift (CAPS) is rapidly becoming an accepted alternative technology for NO_2 measurements according to the federal equivalent method (FEM) or the federal reference method (FRM).

Ozone analyzers are calibrated using gas titration (ISO 15337) or using a transfer standard (ASTM D5011). Ozone is measured using the ultraviolet photometric method, as described in ISO 13964, EN 14625 and ASTM D5156. An alternative continuous method, ASTM D5149, uses ethylene chemiluminescence to measure ozone.

The **carbon monoxide** reference method is non-dispersive infrared spectroscopy (NDIR), as specified in EN 14626 and ASTM D3162. ASTM D6332 explains how to measure the response time of carbon monoxide alarms. EN 50291 and EN 50292 provide guidance for the validation, installation, use and maintenance of CO alarms.

Carbon dioxide concentration is measured using either NDIR, the reference method, or cavity ringdown spectroscopy (CRDS). ASTM is drafting WK74360, a standard for validating CO_2 monitors. The sampling strategy for CO_2 measurements is specified by ISO 16000-26, and the use of CO_2 as a tracer gas is explained in ISO 12569. EN 50543 describes the use of portable CO and CO_2 instrumentation.

Sulfur dioxide is measured either using ultraviolet fluorescence, EN 14212, or using wet chemistry, as described in ASTM D2914-15.

Ammonia is measured using a diffusive sampler; EN 17346 is the reference method for measuring NH_3.

Hydrogen sulfide can be continuously determined with a lower detection limit of 1 ppbv, using the change in reflectance, as explained in ASTM D4323.

References to these documents are listed in the Appendix A, Table A1.

5.2. Formaldehyde

Planning for formaldehyde concentration measurements in indoor air is explained in ISO 16000-2. Specifications for the analysis of formaldehyde emissions and the sorption characteristics of materials (and the products for their indoor application) are given in ASTM D6007-14, ISO 16000-23, and ISO 16000-24, respectively. The analytical procedures are defined in dedicated normative documents for the determination of formaldehyde (and other carbonyl compounds) using active (ISO 16000-3 and ASTM D5197-16) and diffusive (ISO 16000-4) samplers with solvent desorption and high-performance liquid chromatography (HPLC). These analytical procedures have been validated for the quantification of a range of aldehydes and ketones.

References to these documents are listed in the Appendix A, Table A2.

5.3. VOCs

Organic compounds eluting from n-hexane up to and including n-hexadecane on a gas chromatographic column (specified as a 5% phenyl 95% methyl polysiloxane phase capillary gas chromatographic column) are considered to be volatile organic compounds (VOCs: ISO 16000-6). Guidance documents specify sampling strategies as well as analytical methods for the determination of VOCs in indoor air, and in air sampled from test chambers (ISO 16000-5, ISO 16000-6, ASTM D7339-18, ASTM D6330). These methods are based on sorbent sampling tubes with subsequent thermal desorption and gas chromatographic analysis. Several guidance documents are also available for diffusive sampling techniques for VOCs (ISO 16017-1, -2, ASTM D3609, ASTM D4298, EN 14412), detector tubes (ASTM D4490), and canister sampling (EPA Method TO-15, ASTM D5466, ASTM D8283-19). Additional test procedures are described for ambient air measurements of gases and vapors (EN 13528-1, -2, -3) and benzene (EN 14662-1, -2, -4, -5). Complementary support for the determination of analytical parameters, for test methods for VOC detectors, for the determination of VOC emission profiles, and for the subsequent exposure risk characterization are given in ASTM D6196, ISO 16000-29, ASTM D6177-19, and ASTM D6485-18, respectively. Emissions from bedding sets can be measured by following ASTM D6485-18 and D6177-19.

References to these documents are listed in the Appendix A, Table A3.

5.4. Mould

Inhaling spores and metabolic products of mold can trigger allergic and/or irritating symptoms in humans. In addition, the growth of mold can lead to strong odor impairments. In rare cases, some types of mold can also trigger infections in certain at-risk groups.

Epidemiological studies have shown that damp and moldy buildings increase the risk of respiratory symptoms, respiratory infections and asthma symptoms in residents. Therefore, mold growth in buildings should be avoided. ASTM D7338 specifies procedures to assess fungal growth in buildings, whereas ASTM D6329 specifies the evaluation procedure of indoor materials to support microbial growth. The standard practice for collection of total airborne fungal structures via inertial impaction is described in ASTM D7788. The standards of the ISO 16000 series provide support for the detection and enumeration of mold sources in indoor areas using sampling by filtration (ISO 16000-16), a culture-based method (ISO 16000-17), sampling by impaction (ISO 16000-18), sampling strategy (ISO 16000-19), the determination of total spore count (ISO 16000-20), and sampling from materials (ISO 16000-21). The enzyme activity method (ISO 16000-22) and the total cell count method for building materials (ISO 16000-35) are under development, and ISO 16000-19 specifies the sampling strategy. Additional test procedures are described for ambient air measurements of airborne pollen grains and fungal spores (EN 16868) and molds (EN 16115-1). The sampling and analysis of bioaerosols are defined in CEN/TS 16115.

References to these documents are listed in the Appendix A, Table A4.

5.5. Particulate Matter

Oxidation of VOCs in the presence of nitrogen oxides (NO_x; corresponds to mostly the sum of NO and NO_2) leads to the formation of OVOCs (oxygenated volatile organic compounds) and oxidants such as O_3. Compared to their organic precursors, OVOCs have a lower vapor pressure and increased water solubility. Hence, they can deposit on surfaces, especially in indoor environments with high humidity (e.g., bathrooms, kitchens), wherein the surfaces can be contaminated with OVOCs. They can also condense by forming secondary organic aerosols (SOA). Many VOCs and OVOCs are toxic or carcinogenic, and can cause diseases of the respiratory tract and the cardiovascular system. Furthermore, airborne particles have adverse health effects at exposure levels determined in urban regions, wherein limit values for $PM_{2.5}$ and PM_{10} have been set. Test procedures for airborne particles in indoor environments address general sampling strategies (ISO 16000-34), the $PM_{2.5}$-fraction (ISO 16000-37), and the particle number concentration (PN or PNC: ISO 16000-42). Complementary guidance documents have been developed for ambient air measurements (EN 12341, CEN/TS 16976, CEN/TS 17434). ASTM D8405-21 specifies how to validate $PM_{2.5}$ particle monitors. Standards and guidance for ultrafine particles are being drafted by ISO, ASTM and CEN working groups.

References to these documents are listed in the Appendix A, Table A5.

5.6. Other Pollutants

Various materials continuously emit trace substances into the indoor air. These can be contaminated surfaces such as wood preservatives and asbestos. Alternatively, newly introduced building materials and synthetic products are some of the strongest emitters of organic chemicals, and some of these are also nuisance odor sources. Since today's consumer behavior is determined by a pronounced awareness of health, manufacturers of consumer products brand their products as so-called 'low-emission' products, as a marketing tool. Despite the fact that most organic chemicals occur in very low concentrations, public interest in low-emission products has increased, as some of the identified organic compounds are irritating or even toxic, and in some cases have high odor intensities. These issues are tackled by dedicated guidance documents for the measurement of asbestos (ISO 16000-7, ISO 16000-27), flame retardants and plasticizers (ISO 16000-31, ISO 16000-12, -13, -14), phthalates (ISO 16000-33), amines (ISO 16000-38, ISO 16000-39), wood preservatives (ISO 16000-12, -13, -14), pesticides (ASTM D6333-17), radon (ASTM D6327-10), incomplete combustion products (ISO 16000-12), refrigerant gases (EN 50676), and odors (ISO 16000-28, ISO 16000-30). Additional test procedures are described for ambient air measurements of polycyclic aromatic hydrocarbons (EN 12884, EN 16362, ISO 12884, ASTM D6209), benzo[a]pyrene (EN 15549), and odors (EN 13725, EN 16841-1, -2). A new guidance standard for determination of airborne per- and polyfluorinated alkyl substances (PFAS) is under development by ASTM WK81752.

References to these documents are listed in the Appendix A, Table A6.

5.7. Ventilation

Ventilation guidance documents consider a ventilation system's design, control and testing, and performance. The guidance documents listed in the Appendix do not include detailed ventilation equipment requirements.

Most design guidance documents consider specific built environments. ANSI/ASHRAE/ASHE 170 provides guidance for healthcare facilities. ANSI/ASHRAE/IES 90.1 sets standards for energy usage in commercial and high rise buildings in the USA. VDI 2262-3 is the German guidance document for good air quality through ventilation in the workplace; BS 5925 explains the design of natural ventilated buildings in the UK, while BSI-BS PD CR 1752 gives general guidance for ventilation systems. ASHRAE 154 defines the requirements for commercial cooking operations. The ASHRAE handbooks are references for ventilation system design and the corresponding technical requirements.

US federal regulations for ventilation systems can be found in the 'ACGIH industrial ventilation manual'.

The most important sets of ventilation guidance documents are ASHRAE 62.1 and 62.2. ASHRAE 62 has gone through several revisions since 1989, and is the basis of using CO_2 for demand control ventilation, which is the compromise between energy efficiency and good air quality. ASHRAE 62 defines an acceptable level of outside air for good air quality by dilution, while allowing ventilation system turndown when the built environment is unoccupied or has low occupancy.

The surge in using CO_2 monitors to determine adequate ventilation for safer environments started with ASHRAE 62. There are now dozens of commercially available low-cost CO_2 monitors; almost all are based on NDIR optical technology. An undesirable addition to CO_2 monitoring is the use of metal oxide chemiresistors as very low-cost CO_2 surrogates; they are not validated, and there are no standards or guidance documents that support the use of this alternative technology. Unfortunately, a simple CO_2 concentration measurement is not adequate for understanding the functioning of the entire ventilation system without considering other parameters. ASTM D6245, recently rewritten, explains the capabilities and pitfalls of CO_2 measurements when evaluating room ventilation.

Ventilation systems in the USA are tested and balanced following ANSI/ASHRAE 111; in Europe, EN 16798 specifies the energy performance of buildings and its interrelation with indoor air quality, as well as how to measure ventilation flow rates for both mechanically ventilated and passive duct systems. ASTM E741 and ISO 12569 explain the use of tracer gas dilution to determine the air change rate in a single zone.

Ventilation equipment is tested and validated using several standards. Two relevant standards are ISO 16890 for air filters and EN 13141-2 for testing the components of residential ventilation systems.

Properly maintained air filters are critical to good air quality resulting from mechanical ventilation systems. EN 779 and EN 15780 explain the maintenance and performance inspection of air filters.

References to these documents are listed in the Appendix A, Table A7.

5.8. IAQ Surveys

IAQ is assured by considering the built environment from several aspects. Guidance documents are written for different purposes, including building design rules for optimum air quality, how to perform an IAQ audit, inspecting and measuring ventilation and air quality, and considering sustainability.

Good air quality begins with good design. ISO 17772-1, ASHRAE 55, and EN 15251 specify the requirements for thermal comfort, indoor air quality, and lighting and acoustics. For residential buildings, ASTM E267 suggests performance statements for both air quality and thermal comfort. The UK building services association, BSRIA, published TG12/2021, a general guide to IAQ.

Air quality surveys are undertaken either periodically as part of the building maintenance schedule, or when air quality problems or sick building syndrome are a concern. The 'EPA walkthrough inspection checklist' provides guidance for an IAQ audit. ASTM D7297 is a suitable standard when air quality problems arise in residential buildings, and ASTM D1357 explains more generally how to organize an IAQ audit. The requirements of a combined energy and air quality audit are specified in ANSI/BPI-1200-S-2017.

The method for performing the specific measurements required for building inspection is detailed for ventilation systems in ANSI/ASHRAE/ACCA 180. When measuring pollutants, ASTM D6306 explains where to locate diffusive samplers. ASTM D6245-18 is an important standard; closely allied with ASHRAE 62, it explains the use of CO_2 monitoring not only to evaluate the ventilation system but also to determine the air change rate (ACH), which is the simplest measurement for ensuring good air quality through dilution with fresh air.

IAQ surveys include examination of the ventilation system. EN 15780 and the UK institution CIBSE's publication KS 17 should be referenced when examining ventilation systems, and ISO 16000-8 when determining the local mean age of air in buildings for characterizing ventilation conditions. General aspects for sampling strategies, investigation of buildings for the occurrence of pollutants, and a management system for IAQ are specified in ISO 16000-1, ISO 16000-32, and ISO 16000-40, respectively. Specifications for the assessment and classification of indoor air quality are currently elaborated upon by ISO 16000-41. Ventilation for schools is specified in the UK in the 'ESFA building bulletin 101', and HSE HSG 258 is specific to workplace ventilation. REHVA, the Federation of European Heating, Ventilation and Air Conditioning Associations, has published 'guidebook no. 11', which defines how to monitor local exhaust ventilation (LEV).

A more inclusive approach to building audits is the 'NSF/ANSI sustainability assessment', which reviews all materials in the building, including flooring, walls, and soft furnishings. Each section of this exhaustive document covers specific pollution sources.

Due to the COVID-19 pandemic, many recent documents have emphasized the need for good ventilation with recommended ACH, based on recent results. These recommendations will change and improve as more data become available. A typical example of these documents is the 'REHVA COVID-19 guidance'.

References to these documents are listed in the Appendix A, Table A8.

5.9. Air Cleaners

Air purifiers and air cleaners remove contaminants from indoor air to improve IAQ. These devices are commonly marketed as being beneficial to allergy sufferers and asthmatics, and claim to reduce or eliminate second-hand tobacco smoke and microbiological contaminants (bacteria, fungi, viruses). Commercially graded air purifiers are either small stand-alone units or larger units that can be integrated into air-handling units or to heating, ventilation and air-conditioning (HVAC) system units found in the medical, industrial, and commercial sectors. Industrial air purifiers can also be used to remove impurities from air before processing; pressure swing adsorbers or other adsorption techniques are typically used for this purpose. Standardized test chamber procedures are available to test the suitability of air purifiers for reducing airborne bacteria (ISO 16000-36) and airborne fungi (ISO 16000-43), as well as increasing the perceived indoor air quality (ISO 16000-44, under development).

The 'EPA ENERGY STAR Program 2.0' sets performance requirements for room air cleaners.

References to these documents are listed in the Appendix A, Table A9.

5.10. Test Chambers

Low-emission materials and objects help to ensure that indoor air pollutants and odorous substances are minimized. Interior material testing (e.g., building products) plays a central role; the material selection is often not at the discretion of the room user, but is part of the building construction. A declared aim of European legislation is to protect the health of building users. A specification of this requirement can be found in a basic document drawn up by the scientific committee on health and environmental risks, published by the European Commission, in which the avoidance and limitation of pollutants in indoor areas are explicitly mentioned [24]. Adequate requirements of the health compatibility of construction products are determined, thereby enabling reliable product selection.

In addition to indoor air measurements, the characterization of indoor materials and building products can contribute to the development of sustainable materials and products for indoor applications. Emission test procedures are carried out in test chambers/test cells to determine emissions of VOCs (ISO 16000-9, -10, ASTM D5116-17, ASTM D7143-17, ASTM D6803, ANSI/BIFMA M7.1, CDPH/EHLB V1.2 2017, ASTM D7706-17, ASTM D6670-18, ASTM D7706-17), semi-volatile organic compounds (ISO 16000-25), and odors (ISO 16000-28). Specific procedures for the investigation and assessment of the interior air of road vehicles are given in the ISO 12219 series of standards. The test piece is placed in a test chamber and then exposed to defined conditions. Air samples are taken from the test chamber, and are treated in the same way as air samples from indoor environments. In addition to the requirements for test chambers and test cycles (ISO 16000-3, ISO 16000-4, ISO 16000-6, ISO 16000-9, ISO 16000-10), separate standards also specify sample management (ISO 16000-11) and performance testing for sorbent building materials for the reduction of formaldehyde (ISO 16000-23) and VOCs (ISO 16000-24).

European Standard EN 16516 specifies a horizontal reference method for determining the emission of regulated hazardous substances from construction products into indoor air. This method can be used for volatile organic compounds, semi-volatile organic compounds, volatile aldehydes, and ammonia. It is based on the use of a test chamber and subsequent analysis of the trace gases and VOCs.

References to these documents are listed in the Appendix A, Table A10.

5.11. Diffusive Samplers

Since diffusive samplers are used almost exclusively for monitoring VOCs, the relevant guidance documents are reviewed in VOC Section 5.3.

References to these documents are listed in the Appendix A, Table A11.

5.12. Analytical Methods

EPA 40 details test methods and procedures for testing gases, VOCs and particles. ASTM D3249 is a general guide for using air quality analyzers.

More specifically, ASTM D7911 explains use of reference materials when determining bias error for VOC measurement. ASTM D8141 is the standard to use when determining the area-specific emission rates of VOCs and SVOCs when modelling indoor VOC concentrations.

References to these documents are listed in the Appendix A, Table A12.

5.13. Limit Values

Threshold limit values (TLVs, frequently called limit values, or LVs) are the maximum permissible concentrations set for gases, PM and VOCs. These limit values are set by regional, national or local governments, and should be part of legislation, making them legally binding; however, limit values and their enforcement are different for each country. Limit values are set for different averaging periods: a 15 min short term exposure level (STEL), a 1 h STEL, an 8 h time weighted average (TWA), a 24 h TWA or an annual TWA.

The 'WHO global air quality guidelines' historically set the accepted reference limit values for ambient air in most countries. The guidelines were updated in September 2021, with tighter levels for NO_2, $PM_{2.5}$ and VOCs [5]. These guidelines are for ambient, not indoor air, but are frequently used as both indoor and outdoor LVs. 'WHO guidelines for indoor air quality: selected pollutants' (2010) reviews NO_2, radon, polycyclic aromatic hydrocarbons (PAHs), naphthalene, trichloroethylene and tetrachloroethylene, with recommended TLVs where possible.

EU Directive 2008/50/EU set the limit values for ambient air in all European countries. This directive is currently under review, and will consider the 2021 'WHO guidelines' when reviewing this directive.

EPA 40 CFR PART 50 sets the legal requirement for ambient air in the USA, and OSHA CFR Part 1910 sets the limit values for workers. These LVs include gases, particles and many VOCs. ASHRAE 55 and ISO 17772 set the limit values for thermal comfort in the built environment, but these do not include gases, particles or VOCs. The USA relies on the OSHA LVs for the built environment, but these exclude residential buildings, which are included in the US EPA Building Air Quality Guide.

There are few limit values for indoor air. Most countries default indoor air LVs to the ambient outdoor air LVs, but these include only a few VOCs, the most common being benzene and formaldehyde.

References to these documents are listed in the Appendix A, Table A13.

5.14. Data Quality

Data quality is paramount to indoor air studies. Many algorithms and models are used for IAQ data analysis, and comparison of these different methodologies relies on guidance documents for data analysis. There are many guidance documents for general data analysis, and there are two guidance documents that are specific to air quality. The common use of machine learning (ML) to analyze air quality data does not remove the need for statistical analysis of the ML-corrected data.

Estimation theory, originally proposed by Fisher in 1925, is the basis of the statistics used to analyze air quality data. The accepted single measurement of data quality is expanded uncertainty, and the central document is 'JCGM guide to the expression of uncertainty in measurement (GUM)'. JCGM members include ISO, International Union of Pure and Applied Chemistry (IUPAC), and International Electrotechnical Commission (IEC), as well as other groups. ISO 20988 and ASTM D7440 both detail the use of GUM when applied to air quality data. ASTM D22 work item WK21341 is developing a guidance document for determining uncertainty in VOC measurements.

Detailed statistical analysis is specified in ASTM D5289 and CEN TC264 CR 14377. These two guidance documents cover the level of confidence, confidence intervals, bias, instability and upper and lower limits of detection. ISO 5725-1 and -3 specify the accuracy of measurement methods and results. ASTM D5280 specifies the evaluation of performance characteristics of air quality measurement methods using linear calibration functions.

To ensure clarity, ASTM D1356 details the correct terminology when reporting air quality, and ASTM D1914 defines the correct units and factors. ASTM D5791 explains how to use statistics when planning an IAQ investigation, and ASTM D5157 shows use of statistics to evaluate air quality models.

References to these documents are listed in the Appendix A, Table A14.

6. Results and Discussion

6.1. How to Select National, Regional or International Standardization

National standards differ between nations due to different views about what needs to be standardized. Standards with national scope are most frequently prepared in conjunction with unique national legislation. Globally, most nations have agreed to a centralized approach on standardization, and implemented a national SDO that is also a full member of ISO. In contrast, several countries follow a decentralized and thus sector-specific approach. The standardization system of the United States is very diverse, with at least 600 non-governmental SDOs. Germany, with around 150 non-governmental SDOs, is in the middle of the spectrum that ranges from diverse to centralized [15].

Several regional SDOs have global impact, such as the Association of Southeast Asian Nations (ASEAN), the Arab Industrial Development and Mining Organization (AIDMO), and CEN. Most deal with issues such as promoting trade by harmonizing standards in the given region. CEN is, i.a., strongly committed to standardization in the field of air quality. Generally, there are two specialties in the European standardization system: (i) forced harmonization, meaning the European standard must be adopted, unchanged, by all members, and they must also withdraw all conflicting national standards; and (ii) standards as policy tools, meaning the European Commission can ask CEN to draft a European standard by means of a standardization mandate, leading to a harmonized standard that applies to specific EU legislation [15].

The main goal of international standardization is to facilitate the global exchange of goods and services, and to promote international cooperation in technical, economic, scientific, and intellectual fields. ISO standardizes topics of global relevance so that the international standard can be used as broadly as possible in global markets. ISO sets voluntary standards which do not legally demand harmonization. Difficulties in harmonization may arise if the current situation is stable and not everyone is willing to accept the voluntary ISO standard. Hence, voluntary standards are best suited to markets in which standards are widely variable or rapidly changing [15].

6.2. How to Use Standardization to Ideally Drive Legislation

Considering Section 6.1, three avenues of standardization can be identified that provide unique opportunities for successful standardization in the field of IAQ. These avenues follow the principle of subsidiarity; thus, each of the three avenues comprises national, regional and international standardization and is oriented towards a dedicated scientific question:

- How can we protect occupants from adverse health effects due to indoor air pollution?
  - Specific national needs for the protection of building occupants from the adverse health effects caused by indoor air pollution are ideally addressed through national standardization efforts, since the indoor exposure strongly depends on, e.g., the typical prevailing exposure pattern, building infrastructure, and demography. This is reflected by various national limit value concepts.
  - The specific regional characteristics of building products and materials for indoor applications demand regional harmonization for material-related emissions. EN 16516 is a widely accepted example of regional standardization in the field of assessment of the release of dangerous substances from construction products.
  - Putting sampling and measurement techniques on an equal basis is best addressed on an international level to elaborate minimum requirements acting as starting point for further regional and/or national standardizations, meeting specific regional and/or national needs. This is the underlying approach of the development of many standards of the ISO 16000 series.
- How can we accomplish energy-efficient building operations for improved IAQ?
  - Specific national needs for the accomplishment of energy-efficient building operations for improved IAQ are ideally addressed through national standardization efforts, since the energy-efficiency of a building operation strongly depends on, e.g., the availability of energy, building infrastructure, and climate. This is reflected by various national minimum air exchange rates.
  - The specific regional characteristics of occupancy, room use, and room setup (furnishing) demand regional harmonization of ventilation requirements. EN 16798 is a widely accepted example of regional standardization in the field of harmonized ventilation approaches.
  - Putting design, sampling and measurement techniques on an equal international basis is also best addressed on an international level, as outlined above.
- How can we create awareness and acceptance of IAQ management requirements?
  - Specific national needs depend on, e.g., socio-economic status, availability and access to information, as well as the societal distribution of the environmental burden of disease and wellbeing. Therefore, these needs should be addressed on a national basis by providing national guidance documents on IAQ management for a specific target group.
  - Regional harmonization for a roadmap towards, e.g., environmental justice, sustainable development, and energy efficiency should be tailored to world regions that exhibit comparable pre-conditions in the mentioned policy fields.
  - IAQ assessment approaches should be put on an equal basis by defining minimum international limit values that can in due course be adapted to specific regional and/or national needs.

6.3. Priority Areas for Future Standardization

Support for guidance documents on short lived oxidants and particles is needed. Measurement methods for monitoring long-lived airborne pollutants (e.g., O_3, NO_x, and particulate matter) both indoors and outdoors are standardized and internationally recognized (EN 14211; ISO 13964; EN 12341). However, there is a lack of standardized methods and strategies for the measurement of airborne short-lived trace gases [25,26].

Short-lived oxidants yield highly oxidized organic compounds in reactions with VOCs. Highly oxidized species are subsequently involved in new particle formation through condensation. Additionally, epidemiological and toxicological studies show that many organic compounds and ultrafine particles as trace constituents cause adverse health effects. In this context, oxidative stress is the common underlying biological mechanism [27–29]. This fact has initiated initial future regulatory activities by ISO and CEN, but guidelines on sampling and analysis need further development.

Therefore, standardized methods for real-time, continuous indoor measurements of VOCs, as well the predominant radical precursor in indoor environments, HONO, are required. Complementary standardized methods for the in situ measurement of short-lived oxidants such as OH, HO_2, RO_2, NO_3, and other reactive oxygen species are needed to facilitate new scientific insights into indoor air chemistry and resultant health effects. These measurement techniques are commonly used for the investigation of photochemistry in the lower troposphere [25–32].

IAQ guidance documents need to adapt to the dynamic changes of the portfolio of products for indoor application. Steadily shortened market cycles of new consumer products with indoor applications are leading to swiftly changing emission patterns in indoor environments. Consequently, future analytical methods for assessing IAQ need to be very flexible. Current ISO standards exclusively focus on discontinuous target-screening for characterizing IAQ. Conventional target-screening resorts to a pre-defined analytical parameter set to enable interference-free measurements of the target species. Following this approach of conventional target-screening does not allow for adaptation to swiftly changing exposure scenarios. Complementary guidance documents for online measurement methods is just one future requirement.

The development of online measurement strategies for emerging indoor pollutants is urgently needed. Emerging indoor pollutants are substances that are not yet considered in routine monitoring programs, and which may be candidates for future regulation, depending on research into their toxicity, potential health effects, and occurrence in the environment, as well as our ability to monitor them with the required uncertainty and within the limit of detection (LOD or LDL). Non-target-screening enables simultaneous measurement of a vast amount of substances by identifying environmental pollutants without a preceding selection of the compounds of interest (an open set of unknown or untargeted substances). This approach provides a plethora of analytical information in a short time period. Detection sensitivities that can be very different for each group of substances, resulting in considerably lower sensitivity and a higher LDL compared to target-screening, are the subject of ongoing research in the field of non-targeted analysis [33]. Future guidance documents for IAQ assessment will need to confront the potential and the limitations of non-target screening.

Air quality guide values need global harmonization. Guide values normally rely on dose–response assessment, described by the terms NOAEL and LOAEL. However, to date, there are no harmonized European or international guide values; rather, each country uses different approaches. National variations can be seen, for example, with formaldehyde and α-pinene, wherein various guide values differ by a factor of 10 [34].

Existing guide values need to be revised and re-evaluated for several reasons:

- Chemicals are being reclassified constantly;
- There is a lack of harmonization of global, regional and national guide and limit values;
- Guide values are missing for emerging indoor air pollutants (e.g., VOCs and PFAS);
- Ultrafine particles in the built environment are not regulated;
- There is a lack of distinction between the different indoor environments: residences, public spaces and commercial premises;
- Existing guide values have been derived for single substances or substance classes without considering real environments, which have complex mixtures of different pollutants.

There is a continuing need to standardize field measurement campaigns for indoor air research. Buildings are unfortunately very heterogeneous with respect to building materials, construction, occupancy and activity. To be efficient, intensive field measurement campaigns are feasible only at a limited number of measurement sites. Prior definition of scientific objectives, the indoor environment type, and the minimum number of investigation sites and buildings is mandatory. International standards can assist the systematic categorization of indoor environments, ensure compliance with consistent measurement strategies, and thus support dataset comparability. This approach is similar to outdoor field studies, wherein the chemical regime—defined by the prevailing NO_x concentration and the reactivity of air masses towards OH—is consulted for the sake of the comparability of measurement datasets. The categorization outlined above does not exist for the oxidative capacity of indoor environments.

IAQ measurement campaigns are typically performed for physico-chemical characterization [23,35–38]. Box models for the prediction of expected pollutant levels in buildings can complement IAQ measurement campaigns and assist the model evaluation [39–44]. However, this requires a consistent database of indoor field measurement results [4].

Future ISO standards need to be developed for IAQ modelling, and therefore have to comprise data quality objectives, corresponding quality indicators, emission factors, and emission inventories.

Implementing a management system for controlling different aspects of IAQ can have enormous benefits in terms of comfort and health. Managing IAQ must anticipate and resolve the target conflict between energy management, thermal comfort, and hygienically acceptable air quality. A management system for controlling different aspects of IAQ was recently addressed in ISO 16000-40. This "Indoor Air Quality Management System" (IAQ-MS) was designed to be integrated with other management systems, including ISO 9001, ISO 14001 (environmental management) and ISO 50001 (energy management). The goal of IAQ-MS is to define an integrated building system that ensures the building management system is environmentally friendly, energy-efficient, and provides a healthy and comfortable air quality for the building occupants [45]. Specific technical guidance for the implementation of an IAQ-MS is still required.

7. Summary and Conclusions

Regulations and guidance documents are intertwined, operating on international, regional and national levels. National and regional regulatory differences should be confronted and normalized, possibly following the ISO's lead on standards through the ISO 16000 series, and the WHO's lead on guidance and limit values.

Guidance documents for ambient outdoor air are already established. Work continues on UFPs and VOCs, but the bulk of the required test methods and sampling methods are in place.

Test and sampling methods for the gases and particles found in both outdoor and indoor air are in place, but established indoor limit values to drive forward regulations are unfortunately missing. Indoor air chemistry is subject to specific boundary conditions; the required guidance documents for indoor-specific pollutants need to be developed. This is a difficult task, considering the abundance of VOCs in indoor air.

The indoor environment is dynamic and complex, both in the short term and long term, and considering the problems of solid–gas partitioning onto surfaces and particles. Research on indoor air is not standardized, meaning the opportunity for cross-study comparisons is missed. IAQ audit control documents exist and should be used as templates for IAQ research. These audit templates need to be extended for research to cover both short-term and long-term exposure in homes, offices, schools and hospitals.

Standardization can drive legislation. New IAQ guidance documents are being drafted and current documents updated, based on current and emerging scientific evidence. Scientists, local activists, trade associations, and politicians must organize to define the limit values for pollutants that are neglected health risks.

A concerted effort may lead to national or regional legislation for indoor air pollutants. However, it is necessary to consider the specific requirements for air quality management approaches in different indoor environments. In private homes, it is challenging to implement IAQ compliance strategies on a voluntary basis. In this context, it is important to understand that CO_2 is a major factor when it comes to IAQ assessment, but is only an indicator of ventilation rate; information on the indoor air pollutants discussed in Sections 4 and 5 must be made available and communicated effectively to the general public. In indoor public spaces, different air quality management approaches are required to address both the building operational costs as well as the costs of absenteeism and presenteeism. These approaches balance the dual requirements of air pollutant abatement in the building and in the immediate vicinity of the building, as well as minimizing energy usage while implementing adequate mechanical ventilation.

Finally, it is important to prioritize future air quality management approaches from a health risk management perspective. It is impossible to regulate exposure limits and/or to standardize the measurement of the hundreds of airborne trace constituents that exist in indoor air. A threefold approach differentiating between (i) ubiquitous airborne pollutants, for which exposure limits are already in place (CO_2, CO, NO_2, O_3, $PM_{2.5}$); (ii) highly hazardous substances (carcinogenic, mutagenic, toxic substances), for which exposure limits partially exist and potentially need to be adapted to permanent occupancy situations, also considering vulnerable groups; and (iii) low-to-moderate health risk substances, the regulation of which is expected to reduce the burden on healthcare systems.

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Appendix A

Guidance document references and descriptions are listed below in the same order as Section 5. At the time of publication of this study, some guidance documents are under review or revision (WK refers to ATMS Work Items). Generally, Tables A1–A14 represent references to the latest guidance document issue at the time of publication of this study.

Table A1. Guidance documents for **inorganic gases**.

Guidance Document Reference	Description
ISO 6768	Ambient air—determination of the mass concentration of nitrogen dioxide—modified Griess–Saltzman method
ASTM D1607-91	Standard test method for the nitrogen dioxide content of the atmosphere (Griess–Saltzman Reaction)
EN 14211	Ambient air—standard method for the measurement of the concentration of nitrogen dioxide and nitrogen monoxide using chemiluminescence
EN 16339	Ambient air—method for the determination of the concentration of nitrogen dioxide using diffusive sampling

Table A1. *Cont.*

Guidance Document Reference	Description
ISO 16000-15	Indoor air—sampling strategy for nitrogen dioxide (NO_2)
ISO 13964	Air quality—determination of ozone in ambient air—ultraviolet photometric method
EN 14625	Ambient air—standard method for the measurement of the concentration of ozone using ultraviolet photometry
OSHA Method ID-214	Ozone in workplace atmospheres (Impregnated glass fiber filter)
ASTM D5149	Test method for ozone in the atmosphere—continuous measurement using ethylene chemiluminescence
ASTM D5156	Test methods for continuous measurement of ozone in ambient, workplace, and indoor atmospheres using ultraviolet absorption
ISO 15337	Ambient air—gas phase titration—calibration of analyzers for ozone
ASTM D5011	Standard practices for calibration of ozone monitors using transfer standards
EN 14626	Ambient air—standard method for the measurement of the concentration of carbon monoxide using non-dispersive infrared spectroscopy
ASTM D6332-12	Standard guide for testing systems for measuring the dynamic responses of carbon monoxide detectors to gases and vapors
ASTM D3162	Test method for carbon monoxide in the atmosphere—continuous measurement using nondispersive infrared spectrometry
ISO-16000-26	Indoor air—sampling strategy for carbon dioxide (CO_2)
EN 50291	Electrical apparatus for the detection of carbon monoxide in domestic premises—test methods and performance requirements
EN 50292	Electrical apparatus for the detection of carbon monoxide in domestic premises Electrical apparatus for continuous operation in a fixed installation in recreational vehicles and similar premises, including recreational craft
ASTM D2914-15	Standard test methods for sulfur dioxide content of the atmosphere (West–Gaeke method)
EN 14212	Ambient air—standard method for the measurement of the concentration of sulfur dioxide using ultraviolet fluorescence
ASTM D4323-15	Standard test method for hydrogen sulfide in the atmosphere using the rate of change of reflectance
EN 17346	Ambient air—standard method for the determination of the concentration of ammonia using diffusive samplers
ASTM WK 74360	Test method for evaluating CO_2 indoor air quality sensors or sensor systems used in indoor applications
ISO 12569	Thermal performance of buildings and materials—determination of specific airflow rate in buildings using the tracer gas dilution method
EN 50543	Electronic portable and transportable apparatus designed to detect and measure carbon dioxide and/or carbon monoxide in indoor ambient air—requirements and test methods

Table A2. Guidance documents for **formaldehyde**.

Guidance Document Reference	Description
ISO16000-2	Sampling strategy for formaldehyde
ISO 16000-3	Determination of formaldehyde and other carbonyl compounds in indoor air and test chamber air—active sampling method
ISO 16000-4	Determination of formaldehyde—diffusive sampling method
ISO 16000-23	Performance test for evaluating the reduction of formaldehyde and other carbonyl compounds concentrations using sorptive building materials
ISO 16000-24	Performance test for evaluating the reduction of formaldehyde and other carbonyl compounds concentrations using sorptive building materials

Table A2. *Cont.*

Guidance Document Reference	Description
ASTM D5197-16	Standard test method for determination of formaldehyde and other carbonyl compounds in air (active sampler methodology)
ASTM D6007-14	Standard fest method for determining formaldehyde concentrations in air from wood products using a small-scale chamber
OSHA 29 CFR 1910.1048	Formaldehyde

Table A3. Guidance documents for **VOCs**.

Guidance Document Reference	Description
ISO16000-5	Sampling strategy for volatile organic compounds (VOCs)
ISO 16000-6	Determination of volatile organic compounds in indoor and test chamber air using active sampling on Tenax TA® sorbent, thermal desorption, and gas chromatography using MS or MS-FID
ISO 16000-29	Test methods for VOC detectors
EPA Method TO-15	Compendium of methods for the determination of toxic organic compounds in ambient air using the second edition compendium method TO-15. Determination of volatile organic compounds (VOCs) in air collected in specially prepared canisters
ASTM D6196	Practice for choosing sorbents, sampling parameters, and thermal desorption analytical conditions for monitoring volatile organic chemicals in air
ASTM D7339-18	Standard test method for determination of volatile organic compounds emitted from carpet using a specific sorbent tube and thermal desorption/gas chromatography
ASTM D6330	Standard practice for determination of volatile organic compound (excluding formaldehyde) emissions from wood-based panels using small environmental chambers under defined test conditions
ASTM D6485-18	Standard guide for risk characterization of acute and irritant effects of short-term exposure to volatile organic chemicals emitted from bedding sets
ASTM D6177-19	Standard practice for determining emission profiles of volatile organic chemicals emitted from bedding sets
EN 14662-1	Ambient air quality—standard method for measurement of benzene concentrations—pumped sampling followed by thermal desorption and gas chromatography
EN 14662-2	Ambient air quality—standard method for measurement of benzene concentrations—pumped sampling followed by solvent desorption and gas chromatography
EN 14662-4	Ambient air quality—standard method for measurement of benzene concentrations—diffusive sampling followed by thermal desorption and gas chromatography
EN 14662-5	Ambient air quality—standard method for measurement of benzene concentrations—diffusive sampling followed by solvent desorption and gas chromatography
EN15980	Air quality—determination of the deposition of benz[a]anthracene, benzo[b]fluoranthene, benzo[j]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, dibenz[a,h]anthracene and indenol[1,2,3-cd]pyrene
ISO 16000-33	Determination of phthalates with gas chromatography/mass spectrometry (GC/MS)
ISO 16000-38	Determination of amines in indoor and test chamber air—active sampling on samplers containing phosphoric acid impregnated filters
ISO 16000-39	Determination of amines—analysis of amines using (ultra-) high-performance liquid chromatography coupled to MS

Table A4. Guidance documents for **mold**.

Guidance Document Reference	Description
ISO 16000-16	Detection and enumeration of molds—sampling by filtration
ISO 16000-17	Detection and enumeration of molds—culture-based method
ISO 16000-18	Detection and enumeration of molds—sampling by impaction
ISO16000-19 [1]	Sampling strategy for molds
ISO 16000-20	Detection and enumeration of molds—determination of total spore count
ISO16000-21	Detection and enumeration of molds—sampling from materials
ISO 16000-22	Detection and quantification of mold through beta- N-acetyl hexosaminidase enzyme activity
ISO 16000-35	Determination of total cell count in building materials
ASTM D6329	Standard guide for developing a methodology for evaluating the ability of indoor materials to support microbial growth using static environmental chambers
ASTM D7338	Standard guide for the assessment of fungal growth in buildings
ASTM D7788	Standard practice for the collection of total airborne fungal structures via inertial impaction methodology
EN 16868	Ambient air—sampling and analysis of airborne pollen grains and fungal spores for networks related to allergy—volumetric Hirst method
CEN/TS 16115	Ambient air quality measurement of bioaerosols—determination of molds using filter sampling systems and culture-based analyses

Table A5. Guidance documents for **particulate matter**.

Guidance Document Reference	Description
ISO 16000-27	Determination of settled fibrous dust on surfaces using SEM (scanning electron microscopy) (direct method)
ISO16000-34	Strategies for the measurement of airborne particles
ISO 16000-37	Measurement of $PM_{2.5}$ mass concentration
ISO 16000-42	Measurement of particle number concentration using condensation particle counters (CPC)
EN 12341	Ambient air—Standard gravimetric measurement method for the determination of the PM_{10} or $PM_{2.5}$ mass concentration of suspended particulate matter
CEN/TS 16976	Ambient air—determination of the particle number concentration of atmospheric aerosol
CEN/TS 17434	Ambient air—determination of the particle number size distribution of atmospheric aerosol using a mobility particle size spectrometer (MPSS)
ASTM D8405-21	Standard test method for evaluating $PM_{2.5}$ sensors or sensor systems used in indoor air applications
ASTM D7439-21	Standard test method for determination of elements in airborne particulate matter by inductively coupled plasma–mass spectrometry

Table A6. Guidance documents for **other pollutants**.

Guidance Document Reference	Description
ISO16000-7	Sampling strategy for determination of airborne asbestos fiber concentrations
ISO16000-12	Sampling strategy for polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and polycyclic aromatic hydrocarbons (PAHs)
ISO 16000-13	Determination of total (gas and particle-phase) polychlorinated dioxin-like biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs)—collection on sorbent-backed filters
ISO 16000-14	Determination of total (gas and particle-phase) polychlorinated dioxin-like biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs)—extraction, clean-up and analysis using high-resolution gas chromatography and mass spectrometry
ISO 16000-27	Determination of settled fibrous dust on surfaces using SEM (scanning electron microscopy) (direct method)
ISO 16000-30	Sensory testing of indoor air
ISO 16000-31	Measurement of flame retardants and plasticizers based on organophosphorus compounds—phosphoric acid ester
EN 13725	Determination of odor concentration using dynamic olfactometry
EN 16841-1	Ambient air—determination of odor in ambient air using field inspection—grid method
EN 16841-2	Ambient air—determination of odor in ambient air using field inspection—Plume method
ASTM D6333-17	Standard practice for collection of dislodgeable pesticide residues from floors
ASTM D6327-10	Standard test method for determination of radon decay product concentration and working level in indoor atmospheres using active sampling on a filter
ISO 12884	Ambient air—determination of total (gas- and particle-phase) polycyclic aromatic hydrocarbons—collection on sorbent-backed filters with gas chromatographic/mass spectrometric analyses
ISO 16362	Ambient air—determination of particle-phase polycyclic aromatic hydrocarbons using high performance liquid chromatography
ASTM D6209	Standard test method for determination of gaseous and particulate polycyclic aromatic hydrocarbons in ambient air (collection on sorbent-backed filters with gas chromatographic/MS analysis)
EN 15549	Air quality—standard method for the measurement of the concentration of benzo[a]pyrene in ambient air

Table A7. Guidance documents for building **ventilation**.

Guidance Document Reference	Description
ISO 16890-1	Air filters for general ventilation—technical specifications, requirements and classification system based upon particulate matter efficiency (ePM)
ISO 12569	Thermal performance of buildings and materials—determination of specific airflow rate in buildings—tracer gas dilution method
EN 16798-3	Energy performance of buildings—ventilation for buildings. For non-residential buildings—performance requirements for ventilation and room-conditioning systems
EN 16798-7	Energy performance of buildings—ventilation for buildings. Calculation methods for the determination of air flow rates in buildings including infiltration

Table A7. *Cont.*

Guidance Document Reference	Description
ANSI/ASHRAE 62.1	Ventilation for acceptable indoor air quality
ANSI/ASHRAE 62.2	Ventilation and acceptable indoor air quality in residential buildings
ASHRAE 154	Ventilation for commercial cooking operations
BS 5925	Code of practice for ventilation principles and designing for natural ventilation
BSI PD CR 1752	Ventilation for buildings—design criteria for the indoor environment
EN 13141	Ventilation for buildings
EN 779	Particulate air filters for general ventilation—determination of the filtration performance
EN 15780	Inspection of air filters, air-handling units and ducts
ACGIH Industrial Ventilation Manual	Industrial ventilation manual of recommended practices
ANSI/ASHRAE 111	Measurement, testing, adjusting and balancing of building HVAC systems
ANSI/ASHRAE/IES 90.1	Energy standard for buildings except low-rise residential buildings
ANSI/ASHRAE 170	Ventilation for healthcare facilities
VDI 2262-3	Workplace air—reduction in exposure to air pollutants—ventilation technical measures
ASTM E741	Standard test method for determining air change in a single zone by means of tracer gas dilution

Table A8. Guidance documents for **IAQ surveys**.

Guidance Document Reference	Description
ISO 16000-1	General aspects of sampling strategy
ISO 16000-8	Determination of local mean ages of air in buildings for characterizing ventilation conditions
ISO-16000-26	2012: Indoor air—Part 26: sampling strategy for carbon dioxide (CO_2)
ISO 16000-32	Investigation of buildings for the occurrence of pollutants
ISO 16000-40	Indoor air quality management system
ISO 16000-41	Assessment and classification
ASTM D6245-18	Standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation
ASTM D7297-14	Standard practice for evaluating residential indoor air quality concerns
ASTM D6306-17	Standard guide for placement and use of diffusive samplers for gaseous pollutants in indoor air
EPA IAQ Checklist	Indoor air quality management checklist and indoor airPLUS
ASTM D1357	Standard practice for planning the sampling of the ambient atmosphere
ISO 17772-1	Energy performance of buildings—indoor environmental quality—indoor environmental input parameters for the design and assessment of energy performance of buildings
ANSI/BPI-1200-S	Standard practice for basic analysis of buildings
ANSI/ASHRAE/ACCA 180	Standard practice for inspection and maintenance of commercial building HVAC systems
ANSI/ASHRAE 55	Thermal environmental conditions for human occupancy
EN 15251	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics

Table A8. *Cont.*

Guidance Document Reference	Description
EN 15780	Ventilation for buildings—ductwork and cleanliness of ventilation systems
CIBSE KS 17	Indoor air quality and ventilation
ESFA Building Bulletin 101	Guidelines on ventilation, thermal comfort and indoor air quality in schools
HSE HSG 258	Controlling airborne contaminants at work—a guide to local exhaust ventilation (LEV)
BSRIA TG 12	Indoor air quality
REHVA Guidebook No 11	Air infiltration in HVAC systems
NSF/ANSI 140, 332, 336, 342, 347	Sustainability assessment for carpet, resilient floor coverings, commercial furnishing fabrics, wallcovering products, single-ply roofing membranes

Table A9. Guidance documents for indoor **air cleaners**.

Guidance Document Reference	Description
ISO 16000-36	Standard method for assessing the reduction rate of culturable airborne bacteria by air purifiers using a test chamber
ISO 16000-43	Standard method for assessing the reduction rate of culturable airborne fungi by air purifiers using a test chamber
ISO 16000-44	Test method for measuring perceived indoor air quality for use in testing the performance of gas phase air cleaners
EPA ENERGY STAR 2.0	ENERGY STAR Program requirements for room air cleaners

Table A10. Guidance documents for **test chambers**.

Guidance Document Reference	Description
ISO 16000-3	Determination of formaldehyde and other carbonyl compounds in indoor and test chamber air—active sampling method
ISO 16000-4	Determination of formaldehyde—diffusive sampling method
ISO 16000-9	Determination of the emission of volatile organic compounds from building products and furnishing—emission test chamber method
ISO 16000-10	Determination of the emission of volatile organic compounds from building products and furnishing—emission test cell method
ISO 16000-11	Determination of the emission of volatile organic compounds from building products and furnishing—sampling, storage of samples and preparation of test specimens
ISO 16000-23	Performance test for evaluating the reduction of formaldehyde and other carbonyl compounds concentrations using sorptive building materials
ISO 16000-24	Performance test for evaluating the reduction of volatile organic compound concentrations by sorptive building materials
ISO 16000-25	Determination of the emission of semi-volatile organic compounds by building products—micro-chamber method
ISO 16000-28	Determination of odor emissions from building products using test chambers
ISO 12219	Interior air of road vehicles
ASTM D5116-17	Standard guide for small-scale environmental chamber determinations of organic emissions from indoor materials/products
ASTM D7143-17	Standard practice for emission cells for the determination of volatile organic emissions from indoor materials/products
ASTM D6803	Standard practice for testing and sampling of volatile organic compounds (including carbonyl compounds) emitted from architectural coatings using small-scale environmental chambers

Table A10. *Cont.*

Guidance Document Reference	Description
EN 16516	Construction products—assessment of release of dangerous substances—determination of emissions into indoor air
ANSI/BIFMA M7.1	Standard test method for determining VOC emissions from office furniture systems, components and seating
CDPH/EHLB V1.2	Standard method for the testing and evaluation of volatile organic chemical emissions from indoor sources using environmental chambers
ASTM D7706-17	Standard practice for rapid screening of VOC emissions from products using micro-scale chambers
ASTM D6670-18	Standard practice for full-scale chamber determination of volatile organic emissions from indoor materials/products

Table A11. Guidance documents for **diffusive samplers**.

Guidance Document Reference	Description
ISO 16017-1	Indoor, ambient and workplace air—sampling and analysis of volatile organic compounds using sorbent tube/thermal desorption/capillary gas chromatography—pumped sampling
ISO 16017-2	Indoor, ambient and workplace air—sampling and analysis of volatile organic compounds using sorbent tube/thermal desorption/capillary gas chromatography—diffusive sampling
EN 13528-1	Ambient air quality—diffusive samplers for the determination of concentrations of gases and vapors—requirements and test methods—general requirements
EN 13528-2	Ambient air quality—diffusive samplers for the determination of concentrations of gases and vapors—requirements and test methods—specific requirements and test methods
EN 13528-3	Ambient air quality—diffusive samplers for the determination of concentrations of gases and vapors—requirements and test methods—guide to selection, use and maintenance
EN 838	Workplace exposure—procedures for measuring gases and vapors using diffusive samplers—requirements and test methods
ASTM D5466	Standard test method for determination of volatile organic compounds in atmospheres using a canister sampling methodology
ASTM D8283-19	Standard practice for cleaning and certification of specially prepared canisters
ASTM D4490	Practice for measuring the concentration of toxic gases or vapors using detector tubes
ASTM D3609	Standard practice for calibration techniques using permeation tubes
ASTM D4298	Standard guide for intercomparing permeation tubes to establish traceability
EPA Method TO-05	Determination of volatile organic compounds (VOCs) in air collected in specifically prepared cannisters
EN 14412	Indoor air quality—diffusive samplers for the determination of gases and vapors—guide to selection, use and maintenance

Table A12. Guidance documents for **analytical methods** for IAQ-assessment.

Guidance Document Reference	Description
EPA 40 CFR 53	Ambient air monitoring reference and equivalent methods
EPA 40 CFR 60	Standards of performance for new stationary sources—Appendix A: Test methods
ASTM D8141-17	Standard guide for selecting volatile organic compound (VOCs) and semi-volatile organic compound (SVOCs) emission testing methods to determine emission parameters for the modeling of indoor environments
ASTM D7911	Standard guide for using reference material to characterize measurement bias associated with using a volatile organic compound emission chamber test
ASTM D3249	Standard practice for general ambient air analyzer procedures

Table A13. Guidance documents for air quality **limit values**.

Guidance Document Reference	Description
WHO Guidelines	Global Air Quality Guidelines (2021)
WHO Guidelines	Guidelines for Indoor Air Quality: Selected Pollutants (2010)
US EPA Guide	US EPA Building Air Quality (1991)
EPA 40 CFR 50	National Ambient Air Quality Standards
OSHA 29 CFR 1910.1450	Occupational exposure to hazardous chemicals in laboratories
CFR Part 1910	Occupational Health and Safety Standards
ASHRAE 55	Thermal environmental conditions for human comfort
OSHA 29 CFR 1910.1000	Air contaminants

Table A14. Guidance documents for air quality **data quality**.

Guidance Document Reference	Description
JCGM 100	Evaluation of measurement data—guide to the expression of uncertainty in measurement
ISO 20988	Air quality—guidelines for estimating measurement uncertainty
ISO 5725-1	Accuracy (trueness and precision) of measurement methods and results—general principles and definitions
ISO 5725-3	Accuracy (trueness and precision) of measurement methods and results—intermediate measures of the precision of a standard measurement method
ASTM D5157-19	Standard guide for statistical evaluation of indoor air quality models
ASTM D5791-95	Standard guide for using probability sampling methods in studies of indoor air quality in buildings
ASTM D1356	Terminology relating to the sampling and analysis of atmospheres
ASTM D1914	Practice for conversion units and factors relating to the sampling and analysis of atmospheres
ASTM D5289	Standard practice for evaluation of performance characteristics of air quality measurement methods with linear calibration functions
ASTM D7440	Standard practice for characterizing uncertainty in air quality measurements
UNE-CR 14377 IN	Air quality—approach to uncertainty estimation for ambient air reference measurement methods

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