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Review

A Systematic Review of Air Quality Sensors, Guidelines, and Measurement Studies for Indoor Air Quality Management

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Abstract: The existence of indoor air pollutants—such as ozone, carbon monoxide, carbon dioxide, sulfur dioxide, nitrogen dioxide, particulate matter, and total volatile organic compounds—is evidently a critical issue for human health. Over the past decade, various international agencies have continually refined and updated the quantitative air quality guidelines and standards in order to meet the requirements for indoor air quality management. This paper first provides a systematic review of the existing air quality guidelines and standards implemented by different agencies, which include the Ambient Air Quality Standards (NAAQS); the World Health Organization (WHO); the Occupational Safety and Health Administration (OSHA); the American Conference of Governmental Industrial Hygienists (ACGIH); the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); the National Institute for Occupational Safety and Health (NIOSH); and the California ambient air quality standards (CAAQS). It then adds to this by providing a state-of-art review of the existing low-cost air quality sensor (LCAQS) technologies, and analyzes the corresponding specifications, such as the typical detection range, measurement tolerance or repeatability, data resolution, response time, supply current, and market price. Finally, it briefly reviews a sequence (array) of field measurement studies, which focuses on the technical measurement characteristics and their data analysis approaches.

Keywords: indoor air quality; standards; guidelines; pollutants; sick building syndrome; low-cost sensor

1. Introduction

The WHO reported that poor air quality caused 4.2 million deaths in 2016, of which, primarily, 17% were due to strokes, 25% were due to COPD, and 26% were due to respiratory disease [1]. It is evident from many studies that the concentration levels of indoor air pollutants are two to four times higher than those of outdoor air pollutants [2–5]. In the U.S., on average, people spend 22.25 h per day inside buildings, and 1.44 h in cars or other transportation modes [6,7]. With higher concentrations of pollutants inside buildings, IAQ is one of the world's highest environmental health risks [8,9], which cannot be ignored.

The impact on human health owing to the indoor environment is, broadly speaking, either BRI or SBS. BRI relates to symptoms that are clinically defined, which are diagnosed with directly airborne building contaminants [5–8]. On the other hand, SBS is a collection of symptoms for which the cause is unclear [10–12]. It is to be noted that SBS is a consequence of poor indoor air quality [13]. Besides this, the symptoms caused by psychological illnesses—such as headaches, fatigue, nausea, hyperventilation, and fainting—are referred to as Mass Psychogenic Illness (MPI) [14]. Building-associated illnesses not only cause symptoms, but can also cause an enormous economic loss. In the U.S., SBS affects 10 to 25 million people, and results in an estimated $82 billion to $104 billion loss every year, owing to productivity loss [15–19]. The US EPA estimated a $140 billion annual direct medical expenditure related to IAQ problems [20,21].

SBS has become a widely-studied subject in recent years; the following health manifestations have been identified by medical studies: anxiety, depression, environmental discomfort and job strain (psychological symptoms); asthma, allergies, malaise, headache, throat dryness, coughs, sputum, ocular issues, rhinitis, wheezing, skin dryness, and eye pain (physical symptoms/psychosomatic symptoms) [22–24]. Klas et al. [25] found that SBS is related to temperature, air intake, building dampness, exposure to static electricity, indoor smoke, noise, and the building's age. In addition, the level of physical response is related to age, employment duration, asthma symptoms, and psychological states.

The contributors of SBS and BRI can be divided into four categories: (1) physical (e.g., temperature, humidity, ventilation, illuminance, noise, air quality, etc.); (2) biological; (3) chemical (e.g., radioactive substances, MVOCS, formaldehyde, plasticizer, fine dust, etc.) concentrations; (4) psychosocial and individual traits (e.g., gender, age, atopy, hereditary disease, smoking, psychological state, etc.) [26–28]. The indoor thermal comfort criteria were recommended by the ASHRAE Standard 55-2017, which specifies an indoor operative temperature between 68.5 °F and 75 °F in the winter, and between 75 °F and 80.5 °F in the summer [29]. Similarly, the recommended indoor relative humidity given by the by US EPA is between 30% and 60%, in order to reduce mold growth [30].

The presence of indoor air pollutants is a major factor that directly affects human health [31]. Indoor air pollutants may include O_3, CO, CO_2, SO_2, NO_2, particulate matter (PM), and TVOC, which can cause tiredness, Acute Respiratory Infections (ARI), COPD, and lung cancer [28,32].

Indoor Air Quality, the Vulnerable Population, and Asthma

A 2015 report showed that air pollution does not affect everyone in the same way; certain vulnerable populations (e.g., children, the elderly, and cardiopulmonary patients, etc.) are more susceptible than others [33]. The US EPA defined the 'risk population' as being those who possess a significantly higher probability of developing a condition, illness or other abnormal status, and divided them into five groups, namely: (1) children aged less than or equal to 13 years; (2) older people aged greater or equal to 65 years; (3) a young person with asthma, who is less or equal than the age of 18 years; (4) legal adults with asthma; (5) people with COPD [34]. Children and older people are more sensitive than others with regards to indoor air pollution [35–39]. While the immune and metabolic systems of children are still developing, and their organs are immature, they are exposed to air pollutants due to which they suffer from frequent respiratory infections [40,41]. Older people are affected by IAQ due to weaker immune systems, undiagnosed respiratory conditions, and cardiovascular health conditions. A hazardous substance can aggravate heart diseases, strokes, and lung diseases such as chronic bronchitis and asthma [42,43].

Asthma is a chronic disease that often causes an exacerbation of disease activity, some of which result in hospitalizations. Air quality measures—such as $PM_{2.5}$, NO_2, O_3, and dampness-related contaminants—play a significant role in asthma exacerbation, as well as disease progression. Asthmatic children spend 60% of their waking hours in school. A recent large-scale study [44] showed that co-exposure to elevated endotoxin levels and $PM_{2.5}$ was synergistically correlated with increased emergency room visits, especially for asthma among children. Exposure to higher concentrations of endotoxin and NO_2 was also synergistically associated with increased asthma attacks, despite below-normal geometric mean concentrations of $PM_{2.5}$, O_3 and NO_2 compared to EPA NAAQ standards [44,45]. A 2015 update to the 2000 review of the Institute of Medicine [46] suggested that—in addition to endotoxin levels—dampness, and dampness-related agents are also important environmental quality indicators for asthma.

According to the ALA 'State of the Air® 2020' report, 45.8% of people in the U.S. live in counties with unhealthy levels of air pollution; among these, 22 million people are elderly (equal or over age 65), and 34.2 million are children (less than age 18); 2.5 million of the children, and more than 10.6 million of the elderly people, have asthma; 7 million people have COPD; 77,000 people have lung cancer; 9.3 million have cardiovascular issues; and 18.7 million live in poverty [47].

Particularly with an increase in urbanization, the importance of IAQ cannot be understated. For this reason, we conducted a systematic review of air quality sensors, guidelines, and measurement studies for IAQ management. Section 2 discusses common air pollutants—such as O_3, CO, CO_2, SO_2, NO_2, PM, and TVOCs—that affect IAQ. Section 3 provides a detailed review of the currently-used air quality sensors for O_3, CO, CO_2, SO_2, NO_2, PM, and TVOCs, their measurement tolerances, and their measuring ranges. Section 4 discusses air quality-related guidelines, such as U.S. EPA NAAQS, OSHA, WHO, ACGIH, ANSI/ASHRAE, CAAQS, and NIOSH. In addition to the discussions related to common air pollutants and air quality guidelines, we provide a thorough list of the air quality studies conducted between 2015 and 2019 in Section 5. This is followed by discussions and recommendations in Section 6, and the conclusion in Section 7.

2. Common Air Pollutants that Affect IAQ

The most common air pollutants that affect IAQ are O_3, CO, CO_2, SO_2, NO_2, PM, and VOCs. Here, we discuss the pathophysiologic mechanisms of each of these air pollutants:

O_3, as a pollutant, is the result of a chemical reaction between NO_2 and VOCs in exposure to sunlight. It can be worse in both hot and cold environments [48]. The sources are from the emission of chemical solvents, electric utilities, and gasoline vapors. It can lead to lung inflammation and airway narrowing [49]. People with underlying diseases, children, and the elderly are the highest risk populations for O_3 pollutants [50].

CO is a toxic gas that is odorless, colorless, and tasteless. Various sources of this gas are from unvented fuel and gas type space heaters, leaky chimneys and furnaces, tobacco smoke, furnace backdraft, gas-type water heaters, wood stoves and fireplaces, gas-powered equipment, and worn or poorly-adjusted and maintained combustion devices. It can cause fatigue, chest pain, angina, reduced brain function, impaired vision and coordination, dizziness, nausea, flu-like symptoms, and fetal death [51].

CO_2 is defined by both the EPA and IPCC as an anthropogenic air pollutant, which is colorless and odorless. The primary source of indoor CO_2 pollutants is the occupant's respiration. The US EPA BASE shows that high CO_2 concentrations are associated with an increased prevalence of many SBS symptoms [52,53].

SO_2 is the major precursor to the ambient $PM_{2.5}$ level [54]. The combustion of coal, oil, and gas that contains sulfur are the leading sources of the indoor SO_2 concentration [55]. Mostly, outdoor SO_2 concentrations are 20% to 70% higher than indoors [56]. Short-term exposure to SO_2 can cause respiratory illnesses, airway inflammation, and varying degrees of toxic symptoms [57–59]. Asthmatics, children, and older adults are potentially susceptible to this pollutant [54,55].

NO_2 is a highly reactive gas which is related to the development of ozone and $PM_{2.5}$. NO_2 primarily gets into the air from the burning of fuel. Similarly to sulfur dioxide, it can cause respiratory symptoms and airway inflammation. Asthmatics, children, and older adults are at higher risk from this pollutant [60].

PM is a mixture of solid and liquid particles embodied in the air, including acids, organic chemicals, soot, metals, soil, and dust. Particle pollution can be categorized by its size (diameter), which includes PM_{10} (2.5 μm to 10 μm), $PM_{2.5}$ (less than 2.5 μm) and $PM_{1.0}$ (less than 1.0 μm) [61]. PM_{10} affects the nasal and oral cavities, the pharynx, the larynx, and the upper trachea. $PM_{2.5}$ are fine inhalable particles that form sediments on the surface of epithelial cells in the bronchioles and alveoli. $PM_{1.0}$ can lead inward to internal organs, including the heart and brain [62,63]. "$PM_{2.5}$ and $PM_{1.0}$ can lead to pulmonary infection and generate vascular and endothelial dysfunction, alterations in heart rate variability, coagulation, and cardiac autonomic function" [64]. PM is estimated to cause of 3.3 million deaths per year worldwide [65]. Children, the elderly, and people with heart and lung disease are the high-risk populations for PM pollutants [50].

VOCs represent a diverse set of hazardous organic chemicals that participate in atmospheric photochemical reactions, which are considered to be one of the major contributors to SBS [6,66,67]. The WHO classifies both indoor and outdoor VOCs as Very-VOCs (VVOCs), VOCs, and Semi-VOCs (SVOCs) according to their boiling points [68]. Many studies have shown that the concentrations of many indoor VOCs were markedly higher than their outdoor counterparts [69–71]. The main indoor VOC sources include high-emission building materials, furnishings, aerosol sprays, pesticides, dry knitted products, office equipment such as copiers, and laser printers [6,67,70,72]. The US EPA issued a list of hazardous air pollutants, which include a total of 187 VOCs [73]. In addition, the ANSI/ASHRAE 62.1-2016 standard provides the Reference Exposure Levels (RELs) of 32 specific types of indoor VOCs for the general population [74]. The most common indoor VOCs—such as benzene, ethylene, formaldehyde, methylene chloride, tetrachloroethylene, toluene, xylene, and 1,3-butadiene—have been proven to be contributors of human carcinogens, irritants and toxicants [75–77]. TVOCs are used as a measure of the total volume of indoor VOC concentrations [78,79]. "Acute exposure to indoor TVOCs can cause eye, nose and throat irritation, headaches, loss of coordination and nausea, damage to the liver, kidney and central nervous system, respiratory disease and some cause cancer" [67]. Asthmatics, young children, and elderly people are more vulnerable to the effects of exposure to TVOCs [6,77,79,80].

In addition to common air pollutants, the indoor temperature and relative humidity significantly affect IAQ. Fang et al. (1998) found out the overt linear correlation between the acceptability and enthalpy of IAQ. The results also identified that, under a constant pollution level, IAQ would decline with the increase of temperature and relative humidity [81]. Berglund and Cain (1989) concluded that the temperature's effect on IAQ was linear and stronger than humidity; the effect of the relative humidity on the acceptability of IAQ was higher in the dew point range of 11–20 °C than in the range of 2–11 °C, and relative humidity under 50% was acceptable to the IAQ performance [82].

3. Air Quality Sensors, Measurement Tolerances, and Ranges

In recent years, LCAQS technology has emerged from several laboratories for practical application, as they can be used to support real-time, spatial, and temporal data resolution for the monitoring of air concentration levels [83–85]. Additionally, more and more companies provide their own LCAQS products. The principles of operation for the low-cost gas-phase sensors are typically based on five major components, which are OPC, MOS, EC, NDIR, and PID [86,87]. Studies have shown that modern LCAQS provide useful qualitative information for scientific research, as well as for end-users [85,88,89]. However, due to the embedded technical uncertainties and lack of cross-validation and verification, there are certain limitations when comparing them to the expensive conventional equipment [87,90–92]. The US EPA has colloquially identified such devices to be low cost when their costs are less than US $2500, because this is often the limit when they are considered for capital investment by scientists and end-users [83]. The price includes the sensor module, its networks, the interactive platform, and other supply services. Therefore, hereafter, we assert that LCAQs should be less than US $500. Table 1 summarizes a series of commercially available LCAQs for primary air pollutants, such as O_3, CO, CO_2, SO_2, NO_2, PM, TVOCs. Furthermore, the specifications from the datasheet provided by the sensor companies—such as the repeatability, measuring range, circuit voltage, and response times—have been listed. The price of these LCAQS ranges between US $1 and $500, and they are capable of detecting an acceptable range of concentrations of each pollutant identified by the existing guidelines (See Table 2).

Table 1. Commercially available LCAQs for the primary air pollutants.

Measured Parameter	Example Product	Manufacturer	Measurement Tolerance/ Repeatability	Measuring Range	Circuit Voltage	Response Time	Approx. Price (USD). 2019
O_3	SR-G04 [93]	BW Technologies/ Honeywell	±5%	0~1 ppm	Not Provided	Not Provided	≈$500
	uHoo-O_3 [94]	uHoo	±10 ppb or 5% of reading	0~1000 ppb	5.0 V	Not Provided	$300–500
	ME3-O_3 [95]	Winsen	<2% (/Month)	0~20 ppm	Not Provided	≤120 s	$100–300
	DGS-O_3 968-042 [96]	SPEC	±15%	0~5 ppm	3.3 v	<30 s	$50–100
	ULPSM-O_3 968-005 [97]	SPEC	±2%	0~20 ppm	2.7 V~3.3 V	<30 s	$1–50
	ZE25-O_3 [98]	Winsen	Not Provided	0~10 ppm	3.7 V~5.5 V	≤90 s	$1–50
	MQ131 [99]	Winsen	Not Provided	10~1000 ppm	≤24 V DC	Not Provided	$1–50
	MiCS-2610 [100]	SGX SensorTech	Not Provided	10~1000 ppb	5.0 v	Not Provided	$1–50
CO	uHoo-CO [101]	uHoo	±10 ppm	0~1000 ppm	5.0 v	Not Provided	$300–500
	CO-B4 [102,103]	Alphasense	±1 ppm	0~1000 ppm	Not Provided	1 s	$100–300
	MNS-9-W2-GS-C1 [104]	Monnit	±2% of reading or 1 ppm	0~1000 ppm	2.0~3.6 v	<40 s (at 20 °C)	$100–300
	DGS-CO 968-034 [105]	SPEC	<±3% of reading or 2 ppm	0 to 1000 ppm	3.3 v	<30 s	$50–100
	MiCS-4514/CJMCU4541 [106]	SGX SensorTech	Not Provided	1~1000 ppm	5.0 v	Not Provided	$1–50
	TGS 5342 [107]	FIGARO	±10 ppm	0~10,000 ppm	5.0 v	60 s	$1–50
	TGS 2442 [108]	FIGARO	Not SProvided	30~1000 ppm	5.0 v	1 s	$1–50
	HS-134 [109]	Sencera	Not Provided	20~1000 ppm	5.0 v	<2 s	$1–50
	MiCS-5524 [110]	SGX SensorTech	Not Provided	1~1000 ppm	5.0 v	<25 s	$1–50
	TGS5042 [111]	FIGARO	<±10 ppm	0~10,000 ppm	5.0 v	5.0 v	$1–50
	MQ-7 [112]	HANWEI	Not Provided	20~2000 ppm	5.0 v	≤150 s	$1–50
CO_2	uHoo-CO_2 [101]	uHoo	±50 ppm or 3% of reading	400~10,000 ppm	5.0 v	Not Provided	$300–500
	GC0028/CM-40301 [113]	The SprintIR®-6S	±70 ppm ±5% of reading	0–5%	3.25~5.5 v	Flow Rate Dependent	$100–300
	AW6404 [114]	AWAIR	±75 ppm (400 to 6000 ppm)	0~4000 ppm	5.0 v	3 min	$100–300
	B-530 [115]	ELT SENSOR	±30 ppm ±3% reading	0~50,000 ppm	9~15 v	120 s	$100–300
	FBT0002100 [116]	Foobot (Airboxlab)	±1.0 ppm (400 to 6000 ppm)	400~6000 ppm	Not Provided	Not Provided	$100–300
	8096-AP [117]	Air Mentor Pro	±5%	400~2000 ppm	3.7 v	Not Provided	$100–300
	Yocto-CO_2 [118]	Yoctopuce	±30 ppm ±55%	0–10,000 ppm	4.75~5.25	2 s @ 0.5 L/min	$100–300
	NWS01-EU [119]	Netatmo	±5% (1000 to 5000 ppm)	0~5000 ppm	5.0 v	Not Provided	$100–300
	CozIR®-LP2 [120]	GSS	±30 ppm ±3% reading	0–5000 ppm	3.25–5.5 v	30 s	$100–300
	K-30 [121]	CO2Meter	±30 ppm/ ±3% of reading	0~5000 ppm	4.5–14 v	2 s @ 0.5 L/min	$50–100
	D-400 [122]	ELT SENSOR	±30 ppm ±3% of Reading	0~2000 ppm	4.75~12 v	30 s	$100–300

Table 1. *Cont.*

Measured Parameter	Example Product	Manufacturer	Measurement Tolerance/ Repeatability	Measuring Range	Circuit Voltage	Response Time	Approx. Price (USD). 2019
CO_2	GC-0015 [123]	MinIR™	±70 ppm ±5% of reading	0–5%	3.3 ± 0.1 v	4~2 min	$100–300
	ELT T110 [124]	ELT SENSOR	±50 ppm ±3% reading	400~2000 ppm	3.2 v~3.55 v	90 s	$50–100
	MT-100 [125]	ELT SENSOR	±70 ppm ±3% of reading	0~10,000 ppm	3.5~5.2 V	120 s	$50–100
	S-300 [126]	ELT SENSOR	±30 ppm, ±3% measure	0~2000 ppm	5.0 V ± 5%	60 s	$50–100
	T6713 [127]	Telaire	±3%	0~5000 ppm	4.5–5.5 v	3 min	$50–100
	T6615 [128]	Telaire	±10% of reading	0~50,000 ppm	5 v	2 min	$50–100
	MG811 [129]	Winsen	±75 ppm	350~10,000 ppm	7.5–12 v	Not Provided	$1–50
	TGS4161 [130]	FIGARO	±20% at 1000 pm	350~10,000 ppm	5.0 ± 0.2 v	1.5 min	$1–50
	MH-Z16 NDIR CO_2 [131]	Winsen	±50 ppm ±5% of reading	0~5000 ppm	3.3 v	30 s	$1–50
	MH-Z19 [132]	Winsen	±50 ppm ±5% reading	0~5000 ppm	3.3 v	60 s	$1–50
SO_2	B4 SO_2 [133]	Alphasense	±5 ppb	0~100 ppm	3 v	30 s	$100–300
	ME4-SO_2 [134]	Winsen	±2%	200 ppm	Not Provided	30 s	$100–300
	DGS-SO_2 968-038 [135]	SPEC	±15%	0~20 ppm	3.0 v	30 s	$50–100
	EC-4SO_2-2000 [136]	Qingdao Scienoc Chemical	±2%	0~2000 ppm	Not Provided	60 s	$50–100
	MQ-136 [137]	HANWEI	±2%	1–100 ppm	5 v ± 0.1	60 s	$1–50
	FECS43-20 [138]	FIGARO	±2%	0~20 ppm	Not Provided	25 s	Not Provided
NO_2	uHoo-NO_2 [101]	uHoo	±10 ppb ±5% of reading	0~1000 ppb	5.0 v	Not Provided	$300–500
	DGS-NO_2 968-043 [139]	SPEC Sensors	±15%	0~10 ppm	3 v	30 s	$50–100
	Mics-6814 [140]	SGX SensorTech	±10 ppb	0.05–10 ppm	5.0 v	30 s	$1–50
	MiCS-4514/CJMCU4541 [106]	SGX SensorTech	Not Provided	1~1000 ppm	5.0 v	Not Provided	$1–50
	MiCS-2714 [141]	SGX SensorTech	Not Provided	0.05~10 ppm	4.9~5.1 v	30 s	$1–50
	B4 NO_2 [142]	Alphasense	±12 ppb	0~50 ppm	3.5~6.4 v	25 s	$1–50

Table 1. *Cont.*

Measured Parameter	Example Product	Manufacturer	Measurement Tolerance/ Repeatability	Measuring Range	Circuit Voltage	Response Time	Approx. Price (USD). 2019
PM	uHoo-$PM_{2.5}$ [101]	uHoo	±20 µg/m^3	0~200 µg/m^3	5.0 v	Not Provided	$300–500
	DC1100 Pro [143]	Dylos	Not Provided	0~1000 µg/m^3	9 v	Not Provided	$100–300
	OPC-N2 [144]	Alphasense	Not Provided	0.38~17 µm	4.8~5.2 v	Not Provided	$100–300
	FBT0002100 [145]	Foobot (Airboxlab)	±20%	0~1300 µg/m^3	Not Provided	Not Provided	$100–300
	AW6404 [146]	AWAIR	±15 µg/m^3 15% of reading	0~1000 µg/m^3	5 V/2.0 A	Not Provided	$100–300
	8096-AP [147]	Air Mentor Pro	Not Provided	0~300 µg/m^3	3.7 v	Not Provided	$100–300
	SPS30 [148]	Sensirion	±10 µg/m^3	0~1000 µg/m^3	4.5~5.5 v	60 s	$1–50
	PMS7003 [149]	Plantower	±10 @ 100~500 µg/m^3	0~500 µg/m^3	5.0~5.5 v	10 s	$1–50
	PMS5003 [150]	Plantower	±10 @ 100~500 µg/m^3	0~500 µg/m^3	5.0~5.5 v	10 s	$1–50
	HPMA115S0-XXX [151]	Honeywell	±15 µg/m^3	0~1000 µg/m^3	5 ± 0.2 v	6 s	$1–50
	DN7C3CA006 [152]	Sharp Microelectronics	±0.2	25~500 µg/m3	5 ± 0.1 v	Not Provided	$1–50
	SDS011 [153]	Nova Fitness	15% ±10 µg/m^3	0.0–999.9 µg /m^3	5 V	Not Provided	$1–50
	Shinyei PPD42NS [154]	Shinyei	Not Provided	0~28,000 pcs/liter	5.0~5.5 v	60 s	$1–50
	TIDA-00378 [155]	TI Designs	75% Over Detection Range	12~35 pcs/cm^3	3.3 V	Not Provided	Not Provided
t-VOCs	uHoo-TVOC [101]	uHoo	10 ppb or 5%	0–1000 ppb	5.0 v	Not Provided	$300–500
	8096-AP [117]	Air Mentor Pro	Not Provided	0~300 µg/m^3	3.7 v	Not Provided	$100–300
	AW6404 [146]	AWAIR	±10%	0~60,000 ppb	5.0 v	60 s	$100–300
	FBT0002100 [145]	Foobot (Airboxlab)	±10%	0~1000 ppb	Not Provided	Not Provided	$100–300
	ZMOD4410 [156]	IDT	±10%	0~1000 ppm	1.7~3.6 v	5 s	$50–100
	Yocto-VOC-V3 [157]	Yoctopuce	Not Provided	0~65,000 ppb	Not Provided	Not Provided	$50–100
	uThing::VOC™- [158]	Ohmetech.io	±15%	0–500	5.0 v	3 s	$50–100
	MiCS-5524 [159]	SGX SensorTech	Not Provided	10~100 ppm	Not Provided	Not Provided	$1–50
	iAQ-100 C/110-802 [160]	SPEC	±2 ppm	0~100 ppm	12 ± 2 VDC	20 s	$1–50
	SP3_AQ2 [161]	Nissha FIS	Not Provided	0~100 ppm	5 v ± 4%	Not Provided	$1–50
	TGS2602 [162]	FIGARO	Not Provided	1~30 ppm	5 ± 0.2 v	30 s	$1–50
	MICS-VZ-87 [163]	SGX SensorTech	Not Provided	400–2000 ppm equivalent CO_2	5.0 v	30 s	$1–50

Table 2. Common air quality guidelines and standards.

Measured Parameter	NAAQS/EPA (U.S. Enforceable) [164–168]	OSHA (U.S. Enforceable) [169]	WHO/Europe (Christopher et al., 2017; WHO, 2016b, WHO, 2010) [170,171]	ACGIH [172]	ANSI/ ASHRAE 62.1 [173]	NIOSH [173]	CAAQS (SCAQMD) [174]
O_3	0.07 ppm (8-h mean) 0.12 ppm (1 h mean) 0.08 ppm	0.1 ppm	120 μg/m^3 (8-h mean)	0.3 ppm (15 min) 0.05 ppm (heavy work) 0.08 ppm (moderate work) 0.1 ppm (light work) 0.2 ppm (work ≤ 2 h)	100 μg/m^3; 50 ppb (8-h mean)	0.1 ppm (0.2 mg/m^3)	0.07 ppm (8-h) 0.09 ppm (1-h)
CO	9 ppm (8-h mean) 35 ppm (1 h mean)	50 ppm	100 mg/m^3 (15-min mean) 35 mg/m^3 (1-h mean) 10 mg/m^3 (8-h mean) 7 mg/m^3 (24-h mean)	25 ppm (8-h)	9 ppm (8-h mean)	35 ppm 40 mg/m^3 (8-h mean) 200 ppm (229 mg/m^3) ceiling	20 ppm, (1-H mean) 9.0 ppm, (8-H mean)
CO_2	N/A	5000 ppm	N/A	5000 ppm (8-h) 30,000 ppm (15 min mean)	5000 ppm 300~500 ppm (outdoor suggest) 1000 ppm (indoor suggest)	5000 ppm (9000 mg/m^3) 30,000 ppm (15 min) (54,000 mg/m^3)	N/A
SO_2	75 ppb (1-h mean)	5 ppm	20 μg/m^3 (24-h mean) 500 μg/m^3 (10-min mean)	0.25 ppm (15 min)	80 μg/m^3 (Annual mean)	2 ppm (5 mg/m^3) 5 ppm (10 mg/m^3)	0.25 ppm 1-H mean 0.04 ppm (24-h mean)
NO_2	100 ppb (1-h) 53 ppb (Annual mean)	0.1 ppm	200 μg/m^3 (0.1 ppm) (1-h mean) 40 μg/m^3 (0.02 ppm) (1-yr average)	0.02 (15 min)	200 μg/m^3 (Annual mean) 470 μg/m^3 (24-h mean)	1 ppm (1.8 mg/m^3)	0.18 ppm, (1-H mean) 0.030 ppm, (Annual mean)

Table 2. *Cont.*

Measured Parameter	NAAQS/EPA (U.S. Enforceable) [164–168]	OSHA (U.S. Enforceable) [169]	WHO/Europe (Christopher et al., 2017; WHO, 2016b, WHO, 2010) [170,171]	ACGIH [172]	ANSI/ ASHRAE 62.1 [173]	NIOSH [173]	CAAQS (SCAQMD) [174]
$PM_{2.5}$	35 μg/m^3 (24-h mean) 12 μg/m^3 (Annual mean)	5 mg/m^3	25 μg/m^3 (24-h mean) 10 μg/m^3 (Annual mean)	3 mg/m^3(8-h)	15 μg/m^3	N/A	12 μg/m^3, Annual mean
PM_{10}	155 μg/m^3 (24-h mean) (Not to be exceeded more than once per year on average over 3 years)	N/A	50 μg/m^3 (24-h mean) 20 μg/m^3 (Annual mean)	10 mg/m^3(8-h)	50 μg/m^3	N/A	50 μg/m^3 (24-H mean) 20 μg/m^3 (Annual mean)
t-VOCs	200 μg/m^3 AQI INDEX: 0~50 GOOD 51~100 Moderate 101~150 Unhealthy for Sensitive Group 151~200 Unhealthy 201~300 Very Unhealthy 301~500 Hazardous	N/A	300 μg/m^3 (8-h mean)	N/A	See full list on: ASHRAE Standard 62.1 TVOC guidance	N/A	N/A

4. Air Quality Guidelines

Table 2 presents a series of common air quality guidelines and standards for industrial and non-industrial environments. The majority of these guidelines are being improved constantly by implementing different criteria and procedures. The ambient air quality standards set by NAAQS and CAAQs are used for outdoor environments, and those set by OSHA, NIOSH, and ACGIH are used for industrial environments. The guidelines set by ASHRAE are designed for indoor environments, especially where building HVAC systems are used, and the WHO air quality standards are designed for the general environment. The following are the descriptions of these individual guidelines, which can provide criteria information for the decision-maker in adopting these values.

The NAAQS (40 CFR part 50) are the criteria for the air pollutant standards enforced by the US EPA under the authority of the Clean Air Act (42 U.S.C.) [164,165]. The purpose of the primary standards of the NAAQS (2016) is to determine the acceptable range of seven principal pollutants (CO, NO_2, Ozone, $PM_{2.5}$, PM_{10}, Lead, and SO_2) for public health protection, including the high-risk populations [164,166]. In 2019, up to 1131 counties in the US published their ambient air quality data under the NAAQs in the national platform [167]. Multiple studies indicate that NAAQS are applicable to outdoor conditions, rather than indoors, due to the technical difficulties and specific properties of indoor pollutant concentrations [166,167,170].

In 2006, the WHO published an air quality guideline, which was a global update edition based on the previous versions (WHO/Europe, 1987 and 2000) [164,165]. This guideline targeted five specific pollutants (NO_2, Ozone, $PM_{2.5}$, PM_{10}, and SO_2) for application to the general environment [167,173,175]. In 2010, the WHO's regional office in Europe released the book 'The Guidelines for Indoor Air Quality: Selected Pollutants', according to a review of the overall WHO guidelines and the related indoor air quality studies [176]. The book provided threshold concentrations of selected indoor pollutants, such as CO, NO_2, benzene, formaldehyde, naphthalene, radon, and polycyclic aromatic hydrocarbons. However, a few of biases and limitations of the current WHO air quality guidelines were retained [177–179]. The meeting of the WHO Expert Consultation (2016) recommended a systematic re-evaluation of the health-related evidence, the interactions among pollutants, and the risk assessment of the biases, which are required to be performed for the new version of the WHO air pollutants guideline, which is expected to be published in 2020 (WHO, 2020) [178,180].

The ANSI/ASHRAE 62.1 and 62.2 standards of ventilation for acceptable indoor air quality are a non-judicial enforcement established by ASHRAE in 1973 [181]. The 2016 version of ANSI/ASHRAE 62.1 include contaminant concentration targets for ten types of indoor pollutants: CO, NO_2, SO_2, Ozone, $PM_{2.5}$, PM_{10}, Odors, Radon, Lead, and TVOCs [74,181–183]. The new version of the ANSI/ASHRAE 62.1-2019 standards puts more emphasis on the consideration of the interaction of the outdoor air quality with the HVAC system. Meanwhile, it prohibits any air-cleaning equipment that generates ozone [178,180,184].

The NIOSH is the federal agency under the US CDC [173]. NIOSH and the US EPA have worked jointly on the guidance for the development, evaluation, and validation of the protocols for indoor air quality sampling since the early nineties [179]. NIOSH recommended a non-enforcement guideline for industrial environments, which includes Maximum Exposure Limits (MEL) for CO, NO_2, SO_2, ozone, lead, and formaldehyde [74,173,179]. These are based on industry and workplace settings, and are not applicable to the high-risk populations [174].

The OSHA is a national public health agency which is separate from the U.S. DOL [180]. The OSHA developed enforceable guidelines for maximum exposure limits, which currently contain over 600 types of hazardous substances; some of these were adopted by the NIOSH and ACGIH [181,185,186]. The OSHA Permissible Exposure Limits (PELs), which were primarily designed for commercial and institutional buildings, have not been updated since 1970 [169,180,181]. Therefore, the OHSA and its related organizations recommend that employers and participants consider referencing the alternative guidelines for the uncovered scenarios, and OSHA PELs are not suggested to protect the high-risk populations [74,169,173].

The ACGIH TLVs® Committee has provided maximum permissible exposures for industrial workplaces since 1962 [172,187]. The current TLVs® guidelines (ACGIH, 2019) include more than 700 chemical substances [172]. The ACGIH's TLVs® developed time-weighted average concentration limits both for periods of 15 min (short-term) and for 8 h workdays (40-h a week) [187]. The ACGIH air quality guidelines are unenforced in the United States; they are intended to protect industrial workers, and should not be applied for sensitive or high-risk populations [181,187,188].

The CAAQS is part of the regional Air Quality Management Plans (AQMPs) developed by the CARB, and they have been updated jointly with the SCAQMD and the U.S. EPA [189]. According to the 2016 AQMP review (2016), the design value of seven principle pollutants (ozone, CO, NO_2, SO_2, $PM_{2.5}$, PM_{10}, and lead) and additional three VOCs (SO_4^{2-}, H_2S, and C_2H_3Cl) are set by CAAQS, which are enacted in a manner that is often more stringent than the NAAQS [190–192]. Under the authority of the Clean Air Act (CAA), the CAAQS were established to prevent adverse health and welfare effects for high-risk populations, but currently, the values are not enforceable [174,192–194].

5. Air Quality Measurements and Data Analysis

In recent years, the field measurement study of indoor and outdoor air quality has accelerated, and now includes numerous monitoring strategies. In Tables 3–5, we summarize studies that analyzed critical factors regarding the assessment of both indoor and outdoor air quality for occupant satisfaction. A total of 33 original papers, published from 2015 to 2019, are included for this narrative review; among these, 13 measurement studies were conducted in school buildings, six were focused on residential buildings, and 14 focused on other types of building (offices, hospitals, shopping malls, museums, metro stations, etc.). As the table presents, $PM_{2.5}$, PM_{10}, CO_2, VOCs, CO, ozone, NO_2, and SO_2 are the commonly measured pollutants across the studies. Tables 3–5 contains the list of the studies, in which most of them analyzed the correlation between indoor and outdoor concentrations, as well as the I/O ratio. They indicate that LQAS is rapidly being applied in practical applications and air quality research, but conventional and expensive quality monitors are still the mainstream equipment that is applied to IAQ research. Additionally, studies have been conducted using various equipment in different environments, and most choose their respective sampling protocols along with the approach of analyzing the output data. This shows that there is a lack of a uniform method for data quality and uncertainties control. Few of these studies considered the multicollinearity and cross-sensitivity between each of the sensors. The literature search was carried out based on the electronic databases Web of Science and Science Direct, using the keywords "Indoor air quality", "Indoor and outdoor concentrations", and "Field monitoring", and "Field measurement".

Table 3. Air quality measurements and data analysis for school buildings.

Study	Location	Subject	Indicators	Measuring Tool	Standard	Analysis/Program	Main Results
Ehsan et al., 2019 [195]	Mid-Atlantic region, the United States	16 urban public schools	CO; NO_2; CO_2; $PM_{2.5}$	Sampler: Personal DataRam, model pDR-1200 monitor for PM; AdvancedSense Pro indoor air quality meter	WHO	Wilcoxon rank-sum, Kruskal-Wallis tests, Spearman rank correlation coefficient (I/O correlation).	Outdoor Condition, school, and room level found to contribute significantly to indoor pollutant concentration.
Julie et al., 2019 [196]	Wellington, New Zealand	primary school	NO_2: CO_2; $PM_{2.5}$; PM_{10}	TSI Dusttrak II Aerosol Monitors., Model 8530; TSI Q-Trak IAQ monitor Model 8552; low-cost metal oxide type sensor e2v MiCS-5525 (Air Quality Egg); E-BAM	ISO 12103-1 AI Test Dust; ASHRAE	Positive matrix factorizat, ion	$PM_{2.5}$ associated with infiltration of TRAP; PM_{10} was significantly higher than the outdoor level; Natural ventilation as a key role dropped IAQ of the aquatic center.
Nkosi et al., 2017 [197]	Gauteng and North West provinces, South Africa	Schools	PM_{10} and SO_2	AEROQUAL mobile air monitoring station	South African Air Quality Standard	Univariate and multiple backward hierarchical regression analysis; Spearman's correlation coefficients;	A significant correlation between PM_{10} and indoor dust; Indoor coal or fossil fuel contributes to levels of SO_2; pulmonary function and respiratory symptom are very sensitive to SO_2
Raysoni et al., 2017 [198]	El Paso, the United States	School Building	VOCs;	Local central ambient monitoring site (CAMS 37); Passive badge samplers 3 M 3500 Organic Vapor Monitor	EPA; NAAQS	Spearman's Rho correlations	All Indoor VOCs concentrations are impacted by traffic emissions; Toluene concentrations were the highest among the BTEX group;
Kalimeri et al., 2016 [199]	Kozani, Greece	School Buildings	CO_2; CO; O_3 SO_2; VOCs; PM_{10}, $PM_{2.5}$; VOCs; Radon	Radiello passive samplers; Gammadata RAPIDOS samplers; Telair 7001; aeroQUAL CO sensors; Derenda LVS3.1/PMS3.1-15; Grimm 1.108	ENV 13419, 2003, ASTM 5116, 1997, ISO 16000–3, 2001, ISO 16000–6, 2004; ASTM D6245-07; SINPHONIE; EPA	The Limit of Detection	The ventilation effect is the major parameter affect IAQ. Cleaning products, do-it-yourself products might increase indoor Formaldehyde and benzene; Strong/positive correlation between indoor and outdoor NO_2 and O_3; pupils' activities and outdoor source effect PM value;

Table 3. *Cont.*

Study	Location	Subject	Indicators	Measuring Tool	Standard	Analysis/Program	Main Results
Madureira et al., 2016 [200]	Portugal	School Buildings (73 primary classrooms)	VOCs, aldehydes, $PM_{2.5}$, PM_{10}, bacteria and fungi, CO_2, CO	Thermally desorbed adsorbents; Dani STD 33.50; gas chromatography; Radiello® passive devices; TSI DustTrak DRX photometers; single-stage microbiological air impactor	WHO; ISO 16000-1, (2004).	PCA; Multilevel linear regression;	Ventilation, Building location, Occupant behavior, maintenance/cleaning activities associated with IAQ
Madureira et al., 2016 [201]	Porto, Portugal	School Buildings 20 primary schools	CO_2, PM_{10}, VOCs	Low-drift NDIR sensors; light-scattering laser photometers	EPA ASHRAE	PCA; Multilevel linear regression;	Activities or building features as major sources of indoor CO_2, PM_{10} and VOCs; PM_{10} levels increased by the mixed source from indoor activities
Oliveira et al., 2016 [202]	Oporto, Portugal	School Buildings (Preschool)	TVOCs; CO_2; Ozone; $PM_{2.5}$; PM_{10}, CO; HCHO	Samplers; polytetrafluoroethylene membrane disks; multiparametric probe (model TG 502; GrayWolf Sensing Solutions);	EPA; NIOSH	Non-parametric Mann–Whitney U analysis;	Indoor CO_2 and TVOCs are significant than outdoor; Ozone is formed by electronic equipment (old printers and photocopy machines; air humidifier) and infiltration of outdoor air;
Verriele et al., 2016 [203]	France	School buildings	CO_2; TVOC; Ozone; NO_2; Formaldehyde	Radial-type diffusion samplers; Radiello® 145 samplers	Radial-type diffusion samplers; Radiello® 145 samplers	Multiple regression analysis	Energy-efficient building and the standard building has similar IAQ conditions; acetone, 2-butanone, formaldehyde, acetaldehyde, hexaldehyde, toluene, heptane, and pentanal are the highest concentrations been found of VOCs; Strongly correlation between acetone, butanone, alkanes with occupants activities.

Table 3. *Cont.*

Study	Location	Subject	Indicators	Measuring Tool	Standard	Analysis/Program	Main Results
Mainka et al., 2015 [204]	Gliwice, Poland (Urban and Rural Regions)	Nursery schools; Education Buildings	PM_1, $PM_{2.5}$, PM_{10}; CO_2	5 mm Nuclepore membranes;Teflon filters; Whatman QMA filters; automatic portable monitors	WHO and EU Legislation; ASHRAE; PN-EN 13779	The Wilcoxon paired sign rank test	Low efficiency of ventilation systems caused high CO_2 and PM concentration; older children's classrooms have higher PM concentration than younger's classroom. Teaching hours have the highest IAQ concentrations;
Mainka et al., 2015 [205]	Gliwice, Poland	Nursery schools	PM_1, $PM_{2.5}$, PM_{10}; CO_2; VOCs	Thermal desorber TurboMatrix 100 connected to a gas chromatograph Clarus 500 with a flame ionization detector	WHO and EU Legislation; ASHRAE; PN-EN 13779,12341; US EPA TO-17 method	The Wilcoxon paired sign rank test, Statistical package	Indoor sources are the main contributors of IAQ in investigated schools; CO_2 concentration reaches highest after slept during the afternoon; mitigation method included: Improving ventilation, decreasing the occupancy per room, modifying every-day vacuum cleaning into wet cleaning;
Vassura et al., 2015 [206]	Bologna, Italy	School Building (educational institute, preschool and elementary Schools)	VOC; CO_2; CO; NO_2	Sensors: Photoionization detector (PID); (Q-Track) non-dispersive infrared; Electrochemical; conductibility detector (Metrohom, 761 Compact IC)	WHO	Pearson correlation analysis	CO_2 comes mainly from indoor; CO_2 and TVOC have similar daily trend;
Sunyer et al., 2015 [207]	Catalonia, Spain	Primary School	EC, NO_2, and ultrafine particle number	MicroAeth AE51 (AethLabs) and DiSCmini (Matter Aerosol) meters; high-volume sampler (MCV); passive tube (Gradko)	WHO	Spearman Regression Analysis	Traffic-related air pollution is associated with a smaller increase in cognitive development; Brain development might be affected by TRAP

Table 4. Air quality measurements and data analysis for residential buildings.

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/ Program	Main Results
Huang et al., 2018 [208]	Shenyang and Fushun Northeast China	Six residential buildings; 21 households	HCHO; VOCs; $PM_{2.5}$; CO_2	Spectrophotometer based on phenol reagent(HCHO); Gas Chromatography-Mass Spectrometry (VOCs); Telaire 7001 CO_2 testers (CO_2); The TSI particle tester($PM_{2.5}$);	Chinese national standard GB/T 18204.2–2014	Pearson correlation analysis (SPSS Ver.22); Crystal Ball software_ Monte Carlo simulation (The health risk analysis);	Indoor $PM_{2.5}$ is closely correlated with outdoor contamination; HCHO and CO_2 were significantly and correlated with the window-opening duration; TVOC had a positive correlation with indoor RH&T, the surface area of furniture; Outdoor $PM_{2.5}$ was significantly correlated with the building heating load
Zhao et al., 2018 [209]	Tianjin, China	Residential dwelling	PM_{10}; CO_2;	$PM_{2.5}$, sensor; CO_2, sensor; power sensor behavior recording sensors(Xiaomi)	Chinese National Standard GB/T 18883–2002; WHO	Data batch processing	Outdoor particle concentration and indoor activities affected IAQ; Natural ventilation with a portable air cleaner can remove mass particle and create good IAQ;
Liu et al., 2018 [210]	Baoding, China	85 residential buildings	Fungi; $PM_{2.5}$, PM_{10}; CO_2	TIS 7515; TIS 8520; six-stage Anderson impactor	N/A	Single hidden layer ANN models with a back-propagation algorithm; The	The ANN model for airborne culturable fungi reached 83.33% in the testing with 30% tolerance
Quang et al., 2017 [211]	Hanoi, Vietnam	Residential Houses	Particle number (PN); $PM_{2.5}$	Aerasense NanoTracers (NTs); TSI model 3787 Air quality monitoring station	WHO	Descriptive statistics with t-test and ANOVA test	$PM_{2.5}$ concentrations are not indicative of the PN concentrations; combustion (traffic emission) sources are the main contributor to PN value; PN concentrations lower in dry weather;

Table 4. *Cont.*

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/ Program	Main Results
Du et al., 2015 [212]	Finland and Lithuania	Multi-family buildings	CO_2; CO; $PM_{2.5}$; PM_{10}; NO_2; VOCs; radon; Formaldehyde	HD21AB/HD21AB17, Sensors; OPCs, Handheld 3016 IAQ; Difram100 Rapid air monitor; Radiello™ Cartridge Adsorbents	WHO; EC; Ministry of Social Affairs and health, “Finnish Housing Health Guide”; Lietuvos higienos norma HN 35:2007	Spearman correlation Analysis;	Different insulation and ventilation system could be the primary reasons for the IAQ Concentrations; mechanical ventilation provides lower IAQ concentrations and infiltration of outdoor source;
Meier et al., 2015 [213]	Basel, Geneva, Lugano, Switzerland	Residential, House	UFP, PM_{10}, $PM_{2.5}$, PMabsorbance, and NO_2.	37 mm Teflon filters (Pall Corporation); One MEDO vacuum pump VP0125 (MEDO USA); passive diffusion samplers (Passam AG);	EPA;	Pearson, STATA	The site allowed tobacco smoke had higher I/O value; Outdoor Concentrations associated with traffic conditions; PNC levels showed highest during lunchtime; PMabsorbance, the lowest for PNC and PMcoarse showed the highest correlation;

Table 5. Air quality measurements and data analysis for other types of buildings.

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/Program	Main Results
Kim et al., 2019 [214]	Seoul, Korea	Commercial office	CO_2; $PM_{2.5}$; PM_{10}	Wireless sensor: Wiseairsense (Wifi-Sensor) BR-Smart-126 (micro-SD Sensor)	ASHRAE A.N.S.I 55-2004; 62.1; EPA-Air Quality Criteria for Particulate Matter; Standardized EPA Protocol for Characterizing Indoor Air Quality in Large Office Buildings	Multivariate analysis of variance (MANOVA) Pearson correlation analysis	A non-woven fabric filter resulted in poor indoor air quality due to high resistance to flow (room A) and an electrostatic filter improved indoor air quality (room B)
Roshan et al., 2019 [215]	Tehran, Iran	Children’s Medical Center	Fungal bio-aerosols	Sampler	NIOSH	One-way ANOVA followed by post hoc Scheffe’s test.	The indoor fungal bio-aerosols may have originated from the outdoor environment

Table 5. *Cont.*

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/Program	Main Results
Tolis et al., 2019 [216]	Kozani, Greece	An aquatic center	$PM_{2.5}$; NO_2; O_3; VOCs	47-mm quartz fiber filters; Low Volume Air Sampling Systems (Derenda LVS3.1/PMS3.1-15 and Teccora with a $PM_{2.5}$ inlet); AEROQUAL (Series 500 IAQ)	WHO	TD-GC-MS analysis	Indoor $PM_{2.5}$ in the aquatic center is mainly influenced by outdoor climatic conditions and pollutant concentrations; Indoor NO_2 value is higher than outdoor due to indoor transport phenomena and combustion sources; Outdoor O_3 higher than Indoor.
Hwang et al., 2018 [217]	Seoul, Korea	82 indoor-facilities (hospitals, geriatric hospitals, elderly care facilities, and postnatal care centers)	PM_{10}; CO_2; airborne bacteria (AB); TVOCs; Formaldehyde	Sampler SARA-4100; Microbial one-stage Buck Bio-Culture sampler; 2,4-dinitrophenylhydrazine cartridge and an MP-Σ100 pump; UV-VIS detector; Tenax-TA tubes; MP-Σ30	Korean IAQ standard	Spearman's correlation; Whitney analyses;	A significant correlation between indoor temperature and AB concentration, TVOCs, Formaldehyde. Indoor PM_{10} was higher than Outdoor concentration in all facilities.
Deng et al., 2017 [218]	Beijing, China	Public buildings (basketball stadium, hotel, a shopping center, research center and commercial office and two residential homes)	$PM_{2.5}$	TSI 8530 instrument	Chinese standard, "Indoor-air-quality standard (GB/T18883-2002)	Linear regression analysis	Indoor $PM_{2.5}$ mainly associated with the outdoor source; the natural Ventilation is more effective to reduce the $PM_{2.5}$ Concentration; Ventilation system with fan-coil air cleaning system can remove approximately 90% of outdoor particles;
Saraga et al., 2017 [219]	Doha, Qatar	An office building	$PM_{2.5}$, PM_{10}	Samplers (LVS16 by WB Engineering GmbH)	WHO; EN 12341:2014	Pearson correlation analysis; IBM SPSS	Outdoor and Indoor PM concentrations were significantly lower when reduced indoor activities; traffic-related sources and re-suspended dust were associated with OC/EC value; a positive correlation between indoor and outdoor pm and PM concentrations when HVAC in operation;

Table 5. *Cont.*

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/Program	Main Results
Loupa et al., 2016 [220]	Kavala, Greece	Hospital	$PM_{2.5}$; CO_2, BC;	Sampler (90 mm diameter Dichotomous Stack Filter Units); Gas Card II, infrared gas monitor; Particle Soot Absorption Photometer; LASAIR Model 5295	EN 13779, 2007; EN 779, 2012; WHO	Pearson correlation analysis	Indoor concentrations of $PM_{2.5}$, BC, and CO_2 were showed positively correlated; The average I/O $PM_{2.5}$ ratios are less than one; $PM_{2.5}$ and BC were strongly related to the outdoor value; PM increased in all particle sizes
He et al., 2016 [221]	Guangdong, China	Hotel buildings	CO_2; CO; PM_{10}, $PM_{2.5}$; VOCs	HP 6890 gas chromatograph/5973 mass selective detector; samples (Air-Check-52, (DC-LITE), portable analyzers, portable Q-Trak monitors (Model 8551 and 8520)	EPA method To-17; Chinese indoor air quality standard (IAQS); ASHRAE	Regression Analysis; PCA;	Occupants' activities were the main source of PM_{10}, $PM_{2.5}$ concentrations; building materials, outdoor sources, human activities, cleaning products, and human respiration are the main source of indoor pollutants;
Irga et al., 2016 [222]	Sydney, Australia	Office buildings	CO_2; CO; SO_2; VOCs; PM_{10}, $PM_{2.5}$; Total suspended particulate matter; VOCs; Airborne fungi	Yessair 8-channel IAQ Monitor (Critical Environment Technologies); DustTrack II Aerosol Monitor 8532 laser densitometer. a GasAlert Extreme T2A-7X9; a Reuter Centrifugal air sampler(RGS).	WHO; ISIAQ; ACGIH; AIHA	Univariate data analysis multivariate analysis; General linear model ANOVA; analyses of similarities (ANOSIM) using a 4th root transformation and the construction of a Euclidean distance similarity matrix; Similarity percentages analysis (SIMPER)	MVS buildings recorded the lowest PM and Airborne fungi; NV buildings and CVS buildings observed highest NO_2; MVS showing higher CO_2 than others;

Table 5. *Cont.*

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/Program	Main Results
Shang et al., 2016 [223]	Western China	Shopping mall	CO_2; TVOC; Formaldehyde;	Kanomax 6531; Telaire 7001; PGM-7240 ppb RAE;	China Energy Efficiency Testing of Public Buildings Standard (JGJ.T 177-2009; Formaldehyde™ 400; China Indoor Air Standard (GB/T 18883-2002)	Spearman rank correlation; Multiple Regression Analysis	A strong correlation of customer flow rate with TVOC and CO_2; pre-ventilation rate decreased the first-hour formaldehyde concentrations
Hu et al., 2015 [224]	Yangtze River Region, China	Museums	NO_2; SO_2; O_3 $PM_{2.5}$; PM_{10};	Q-Trak Plus IAQ monitors (Model 7565, 4150, 4240, 4480); mini-vol portable sampler; TSI 8520;	ASHRAE 2011;	N/A	In certain seasons, Investigated buildings are not able to effectively against outdoor air pollutants. Mechanical ventilation equipped system had better perform on IAQ control;
Montgomery et al., 2015 [225]	Vancouver, Canada	OfficeBuilding	PM_{10}, $PM_{2.5}$; PM_1; TVOCs; CO_2	TSI aps 3321; Tsi Velocicalc 8386; PPBrae pgm-7240; Honeywell c7632; Omega px274-05di;	ASHRAE Standard 62.1-2010	Pearson correlations analysis	The mechanical ventilation effectively control the TVOCs and CO_2 regardless of occupant load; natural ventilation difficult to achieve standard flow rate; Ventilation scheduling significantly impact on indoor gas concentrations; The ventilation system should work before occupants arrival and shutdown after room empty and the IAQ reach the standard level;

Table 5. *Cont.*

Study	Location	Subject	Control Factor	Measuring Tool	Standard	Analysis/Program	Main Results
Challoner et al., 2015 [226]	Dublin, Ireland	Commercial Buildings	$PM_{2.5}$; NO_2	(Environmental Devices Corporation, EPAM-5000, Haz-Dust; an M200E model;	WHO	The Personal-exposure Activity Location Model (PALM); Artificial Neural Networks; The Levenberg-Marquardt Algorithm (LMA); the Gauss-Newton Algorithm; "Neural Network Time-series Tool" using a non-linear auto-regression with external input networks (NARX) modeling technique; Pearson correlation Analysis	The ANN modeling showed $PM_{2.5}$ data with a larger range of errors and lower Pearson's R values for regressions. The model had better performance on Indoor NO_2 than $PM_{2.5}$
Kwon et al., 2015 [227]	Seoul, Korea	Metropolitan Subway Stations	PM_{10}; $PM_{2.5}$; PM_1; CO_2	Optical particle sizer (OPS; TSI model 3330)	WHO; ASHRAE	PCA; Non-parametric Kolmogorov–Smirnov test; Self-Organizing Feature Mapping	Seasonal variable was the most significant factor when categorizing the data groups; PM size fraction was highly influenced by the air ventilation rate and depth of the stations; Outdoor PM_{10} if the main source of indoor PM_{10}; Trains volume was associated with Indoor PM platforms;

Analysis of the Sources and Mechanisms Affecting the Concentration Measurements

The identification of the determinant factors and mechanisms affecting the indoor air quality relies on data analysis techniques and quantifiable data, such as the time series concentrations collected from the monitoring equipment, potential building defects, ventilation specifications, and sometimes local meteorological data, occupancy activities, traffic volumes and other information [228]. Descriptive statistics with trends and graphic analysis are commonly used in observational studies. They provide summaries of the initial air quality measures by describing the data's central tendency, dispersion, variability, outliers, typos, and ranges, and the time-weighted average of the concentration levels [229–233]. Correlation analysis is often used for the evaluation of the association of the indoor and outdoor concentrations, as well as other related time-series data [17,220,234,235]. Typically, the linear relationship between two types of air pollutants is obtained by conducting parametric tests, i.e., *t*-tests, ANOVA, and Pearson correlations [219,220]. For the non-parametric studies, Spearman's correlation test has often been applied in order to examine the monotonic relationship between ordinal and binary variables, such as age, sex, health performance, and the degree of building-related defects [195,210,212,217,223]. When dealing with the observational data, which are non-normally distributed, non-parametric tests—such as Mann–Whitney–Wilcoxon and Kruskal-Wallis—can be used to evaluate the difference between the average of the measured exposure variables and ordinal variables [195,202,219,236]. On the other hand, earlier field studies have found significant multicollinearity problems and temporal cross-correlations between the measured ambient air pollutants and the related influence factors [62,237–240]. Very few studies, however, also considered the complex and nonlinear characters of indoor air pollutants [200,221,227]. Kwon et al. [227], using the principal component analysis (PCA) and self-organizing map (SOM) techniques, determined the dominant factors which increase indoor PM concentration by reducing the original set of inter-correlated variables and transforming them into principle component groups that are mutually orthogonal, or uncorrelated. Madureira et al. [200] and He et al. [221], mitigated the multicollinearity problems between the measured IAQ (CO_2, $PM_{2.5}$, PM_{10}, and VOCs), building characteristics, and occupant activities by conducting categorical PCA (dimensionality reduction method) with a varimax rotation approach [200]. Furthermore, the mixed-effect linear regression model with random intercept provides a flexible approach to assess the association between time-series concentrations and building-related categorical variables in field measurement studies. [213,227].

6. Discussions

6.1. Air Quality Guidelines

At present, there are several guidelines available around the world to prevent IAQ issues for different kinds of management decisions and planning processes. In most of developed or developing countries, they have and follow their respective local guidelines. The main air quality guidelines—which were reviewed in Section 4—are constantly being updated for more precise results in order to protect the target population. In spite of these efforts, the values of the guidelines are still different among each other due to many factors, such as the difference in the standard operating procedures, enforcement levels, and different design principles. Furthermore, there are various misconceptions about the interpretation of these values and guideline principles, which lead to misquotations by researchers and decision-makers. Most of the values which are represented in Table 3 are currently unenforceable because of the limited data availability, challenging deployment, and non-scalability of conventional air pollution tools such as FRM/FEM instruments. This situation is more prominent in indoor environment-related guidelines. There is also a lack of clear evidence on the exposure relevance of a different range of certain concentration values for the improvement of these guidelines, especially for the high-risk population. Log-term cluster randomized control trials and joint health impact assessment should be investigated for the development of future air quality standards.

6.2. *Air Quality Sensors*

In this sub-section, we discuss the critical support of LCAQS in today's world, as well as their low-cost vs. their measurement accuracies. Besides this, we also discuss the technologies used to connect and transfer data from LCAQS.

6.2.1. LCAQS

Air quality sensor technology is an expeditiously growing field that has the key potential to improve the applicability, reliability, and cost-effectiveness of time-resolved air pollution measurements [84,90,241,242]. Many Low-Cost Air Quality Sensors (LCAQS) products are off-the-shelf, open-source, and are becoming increasingly available on the market. Except for technical inconvenience, the information on service life maintenance and durability are insufficient in the datasheet for most of the sensors. In the US, as per the existing literature, the average cost of LCAQS for CO, CO_2, NO_2, SO_2, ozone, TVOC, and PM ranges between $1 and $500, as of April 2020. There are several advantages of LCAQS besides their lower purchase and operation costs compared to regulatory-grade instruments, such as their higher spatial density; their greater number of options in the time-resolution of their data reporting; and their easier field deployment, data collection, and transmissions [90,243,244].

6.2.2. Cost vs. Accuracy of the LCAQS

In most cases, the measurement performance characteristics—such as the typical detection range, measurement tolerance or repeatability, data resolution, linearity, heat resistance, heater current, operating conditions, circuit condition, response time, supply voltage, supply current, and cross-sensitivity to other gases—are contained in the manufacturer's specifications of the LCAQS products. Even so, these performance indicators can vary from sensor to sensor, depending on the laboratory protocol applied, the test chamber set-up, the reference instrument used, the length of the observation period, the range of desired concentrations covered, the efficiency of the calibration algorithm, and the post-processing and data modeling [90,224–248].

6.2.3. Technology of LCAQS

According to the US EPA, LCAQS technology is not considered to be mature enough to be implemented for regulatory or compliance purposes at a mass scale [83], due to their limitations of robustness and repeatability, and the lack a widely-accepted protocol for the testing and utilization of these technologies [83,247–249]. Only limited numbers of the LCAQS developed are integrated with software and operational interface; most of the available program is only applied for a specific OS such as windows, android, and Linux, which increased the limits of openness. Some of LCAQS are designed to interconnect with smart equipment using Internet of Things (IoT) platforms.

6.2.4. Performance Evaluation of LCAQS

Numerous studies have assessed LCAQS, and can provide useful information on ambient gas species and mass particles in the range of specific conditions [79,91,92,245,250]. However, there is still no standard protocol for the evaluation of the performance and effectiveness of LCAQS against traditional monitoring equipment, such as FRM or FEM monitors, at present. In order to address these issues, three notable programs have been launched to quantitatively evaluate the performance of commercially available LCAQS compared to the high-precision equipment under both laboratory and field conditions. These are the AQ-SPEC operated by SCAQMD [251], the US EPA, Air Sensor Toolbox [252], and the EU JRC [253,254]. These platforms created opportunities to assess the data quality and stability of LCAQS by providing state-of-the-art equipment, such as a characterization chamber system, a zero-air generation system, a dynamic dilution calibrator, an air monitoring station, and the best available reference instruments [116,245,251].

6.2.5. Uncertainties in LCAQS

According to the reported results from the AQ-SPEC and the literature, the measurement uncertainty of all types of LCAQS is observed due to changes in the temperature, the relative humidity, cross-sensitivity, interfering compounds, and electronic component tolerances [89,90,253–256]. There is also uncertainty due to the sensors' calibration and synchronization errors in both the fine particle sensors and gas-phase sensors [90,248,255]. The proper calibration and normalization methods for each sensor need validation through the removal of structure errors between the measured and expected sensor output. Uncertainty and ambiguity can propagate through the description of the sensor data, the sampling of the sensor data, co-location experiments, the placement of the sensor, aerosol concentrations, errors in the running code, data recovery, and inference with the results [255,257–260]. The evaluations found that most $PM_{2.5}$ and PM_{10} sensors showed strong correlations ($0.85 < R^2 < 0.99$) in the laboratory test, and moderate to strong correlations ($0.52 < R^2 < 0.99$) in the field test with the BAM and FEM equipment (at the average range between 0 to 300 $\mu g/m^3$¬). The laboratory results also showed extremely low intra-model variability in data recovery (98% to 100%), and RHT had minimal effects on the sensors' precision [84,90,246,261–265]. In contrast, most low-cost gas sensors (CO, NO_2, and ozone) showed more inter-sensor variability than the fine-partial sensors, especially in the field test. Variations exist from sensor to sensor ($0.1 < R^2 < 0.99$), with a fair to good range of data recovery (85% to 100%). The uncertainty of gas-phase sensors is generally associated with cross-sensitivity to ambient concentrations, out-of-range detection, spatiotemporal variations, and RHT conditions in the field environment [245,260,266–269]. To date, there are limited valid SO_2 sensor evaluation reports available, for which this paper finds a curb on the provision of an overall status of SO_2 conditions. According to the DQOs defined by the European Air Quality Directive, a maximum measurement uncertainty of 15% should not be exceeded for O_3, NO_2, NOx, and CO sensors [191,221,222].

6.2.6. QA/QC Control

Quality Assessment/Quality Control (QA/QC) protocols must systematically be conducted in order to validate the data quality by considering the elimination of obvious outliers, negative values, and invalid data points [90,259,266]. In addition, the following methods should also be taken into account when performing the field measurement. These are: (a) repeated field calibration along with the combination of different sources in a multi-sensor data fusion algorithm [270–273] (b): sensitivity analysis [274,275] (c): Monte Carlo simulation methods [276–279] (d): the mathematical modeling of the error propagation. In concert, it is not mandatory to test the existing LCAQS in these evaluating platforms as well as both the sensor and testing enterprises executed through the optional registration system. This has caused these platforms to selectively recognize a sensor type or its particular parts, resulting in the production of an incomplete evaluation of the products' features and characterizations for the end-users. Currently, these sensor testing programs are being amended on their evaluation system, along with their testing protocols being improved, in order to provide more desired results. However, several of these sensor companies prefer to choose self-evaluation or the general international organization for product standardization. Finally, this study is an extensive review of the integrated sensor system which analysed the characteristics based on various factors, in order to examine indoor and outdoor air quality for the built environment. Therefore, such examinations elaborate on the importance of sensing systems to the monitoring of holistic air quality and the mitigation of pollution levels by impacting the occupants' health levels.

7. Conclusions

Human health is adversely impacted by indoor air pollutants. Various international agencies have incessantly developed quantitative air quality guidelines and standards to meet the requirements for proper indoor air quality management. This paper set out to gain a better understanding of the existing major standards and guidelines related to indoor air pollutants and their health impacts. The different limiting range for the identified pollutants, enforcement levels, applicable people, and operating procedures of each was reviewed. For the large-scale implementation of air quality management, this study indicates that the importance of monitoring air quality, in real-time, at spatial and temporal data resolutions cannot be understated. Furthermore, this paper also reviewed the existing LCAQS technologies, and discussed the corresponding specifications, such as the typical detection range, measurement tolerance or repeatability, data resolution, response time, supply current, and market price. LCAQS have changed the paradigm of indoor air pollution monitoring, and can provide beneficial information. This technology is not considered advanced enough to be implemented for regulatory purposes ata large scale, due to the limitations of their robustness, repeatability, and lack of a widely-accepted protocol for testing and utilization. Compared to the fine particulate matter sensors, gaseous sensors generally perform with added uncertainties and data variation. There is a need for unified industry-standard QA/QC protocols to analyze and validate overall LCAQS performance. Conclusively, this systematic review addressed the requirements of future research and design practices in order to protect occupants' health and achieve optimal indoor environmental quality.

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Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ALA	American Lung Association
AQ-SPEC	Air Quality Sensor Performance Evaluation Center
ASHRAE	American Society of Heating, Refrigerating and Air–Conditioning Engineers
BASE	Building Assessment Survey and Evaluation
CARB	California Air Resources Board
CAAQS	California ambient air quality standards
SCAQMD	South Coast Air Quality Management District
COPD	chronic obstructive pulmonary disease
CDC	Centers for Disease Control and Prevention
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DOL	Department of Labor
DQOS	Data Quality Objectives
EC	Electrochemical
EU JRC	European Union Joint Research Centre
FEM	Federal Equivalent Methods
FRM	Federal Reference
HVAC	heating, ventilating and air-conditioning
IAQ	indoor air quality
LCAQS	Low-cost air quality sensors
MOS	Metal Oxide Semiconductor Sensors
MPI	Mass Psychogenic Illness
NAAQS	Ambient Air Quality Standards
NDIR	Non-dispersive Infrared Sensors
NIOSH	National Institute for Occupational Safety and Health
NO_2	Nitrogen Dioxide
O_3	Ozone
OPC	Optical Particle Counters
OSHA	Occupational Safety and Health Administration
PCA	Principal components analysis
PID	Photo-ionization Detection Sensors

PM	Particulate Matter
SBS	Sick Building Syndrome
SO_2	Sulfur Dioxide
TLVs®	Threshold Limit Values
TVOCs	Total Volatile Organic Compounds
WHO	World Health Organization

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