Indoor Air Quality Management

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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 entry 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.

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][3][4][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][6][7][8]. On the other hand, SBS is a collection of symptoms for which the cause is unclear [10][11][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][16][17][18][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][23][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][27][28]. The indoor thermal comfort criteria were recommended by the ASHRAE Standard 55-2017, which specifies an indoor operative temperature between 68.5^{o}F and 75^{o}F in the winter, and between 75^{o}F and 80.5^{o}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].

2. 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][36][37][38][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].

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 [48][49][50]. 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 [51][52]. Studies have shown that modern LCAQS provide useful qualitative information for scientific research, as well as for end-users [50][53][54]. 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 [52][55][56][57]. 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 [48]. 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 [58]	BW Technologies/ Honeywell	±5%	0~1 ppm	Not Provided	Not Provided	≈$500
	uHoo-O_3 [59]	uHoo	±10 ppb or 5% of reading	0~1000 ppb	5.0 V	Not Provided	$300–500
	ME3-O_3 [60]	Winsen	<2% (/Month)	0~20 ppm	Not Provided	≤120 s	$100–300
	DGS-O_3 968-042 [61]	SPEC	±15%	0~5 ppm	3.3 v	<30 s	$50–100
	ULPSM-O3 968-005 [62]	SPEC	±2%	0~20 ppm	2.7 V~3.3 V	<30 s	$1–50

	ZE25-O_3 [63]	Winsen	Not Provided	0~10 ppm	3.7 V~5.5 V	≤90 s	$1–50
	MQ131 [64]	Winsen	Not Provided	10~1000 ppm	≤24 V DC	Not Provided	$1–50
	MiCS-2610 [65]	SGX SensorTech	Not Provided	10~1000 ppb	5.0 v	Not Provided	$1–50
CO	uHoo-CO [66]	uHoo	±10 ppm	0~1000 ppm	5.0 v	Not Provided	$300–500
	CO-B4 [67][68]	Alphasense	±1 ppm	0~1000 ppm	Not Provided	1 s	$100–300
	MNS-9-W2-GS-C1[69]	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 [70]	SPEC	< ±3% of reading or 2 ppm	0 to 1000 ppm	3.3 v	<30 s	$50–100
	MiCS-4514/ CJMCU4541 [71]	SGX SensorTech	Not Provided	1~1000 ppm	5.0 v	Not Provided	$1–50
	TGS 5342 [72]	FIGARO	±10 ppm	0~10,000 ppm	5.0 v	60 s	$1–50
	TGS 2442 [73]	FIGARO	Not SProvided	30~1000 ppm	5.0 v	1 s	$1–50
	HS-134 [74]	Sencera	Not Provided	20~1000 ppm	5.0 v	<2 s	$1–50
	MiCS-5524 [75]	SGX SensorTech	Not Provided	1~1000 ppm	5.0 v	<25 s	$1–50

	TGS5042 [76]	FIGARO	< ± 10 ppm	0~10,000 ppm	5.0 v	5.0 v	$1–50
	MQ-7 [77]	HANWEI	Not Provided	20~2000 ppm	5.0 v	≤150 s	$1–50
CO_2	uHoo-CO_2 [66]	uHoo	±50 ppm or 3% of reading	400~10,000 ppm	5.0 v	Not Provided	$300–500
	GC0028/ CM-40301 [78]	The SprintIR®-6S	±70 ppm ± 5% of reading	0–5%	3.25~5.5 v	Flow Rate Dependent	$100–300
	AW6404 [79]	AWAIR	±75 ppm (400 to 6000 ppm)	0~4000 ppm	5.0 v	3 min	$100–300
	B-530 [80]	ELT SENSOR	±30 ppm ±3% reading	0~50,000 ppm	9~15 v	120 s	$100–300
	FBT0002100 [81]	Foobot (Airboxlab)	±1.0 ppm (400 to 6000 ppm)	400~6000 ppm	Not Provided	Not Provided	$100–300
	8096-AP [82]	Air Mentor Pro	± 5%	400~2000 ppm	3.7 v	Not Provided	$100–300
	Yocto-CO2 [83]	Yoctopuce	± 30 ppm ± 55%	0–10,000 ppm	4.75~5.25	2 s @ 0.5 l/min	$100–300
	NWS01-EU [84]	Netatmo	± 5% (1000 to 5000 ppm)	0~5000 ppm	5.0 v	Not Provided	$100–300
	CozIR®-LP2[85]	GSS	± 30 ppm ± 3% reading	0–5000 ppm	3.25–5.5 v	30 s	$100–300
	K-30 [86]	CO2Meter	±30 ppm/ ±3% of reading	0~5000 ppm	4.5–14 v	2 s @ 0.5 l/min	$50–100

	D-400 [87]	ELT SENSOR	±30 ppm ±3% of Reading	0~2000 ppm	4.75~12 v	30 s	$100–300
	GC-0015 [88]	MinIR™	±70 ppm ± 5% of reading	0–5%	3.3 ± 0.1 v	4~2 min	$100–300
	ELT T110 [89]	ELT SENSOR	± 50 ppm ±3% reading	400~2000 ppm	3.2 v~3.55 v	90 s	$50–100
	MT-100 [90]	ELT SENSOR	±70 ppm ±3% of reading	0~10,000 ppm	3.5~5.2 V	120 s	$50–100
	S-300 [91]	ELT SENSOR	±30 ppm, ±3% measure	0~2000 ppm	5.0 V ± 5%	60 s	$50–100
	T6713 [92]	Telaire	±3%	0~5000 ppm	4.5–5.5 v	3 min	$50–100
	T6615 [93]	Telaire	± 10% of reading	0~50,000 ppm	5 v	2 min	$50–100
	MG811 [94]	Winsen	±75 ppm	350~10,000 ppm	7.5–12 v	Not Provided	$1–50
	TGS4161 [95]	FIGARO	±20% at 1000 pm	350~10,000 ppm	5.0 ± 0.2 v	1.5 min	$1–50
	MH-Z16 NDIR CO_2 [96]	Winsen	±50 ppm ± 5% of reading	0~5000 ppm	3.3 v	30 s	$1–50
	MH-Z19 [97]	Winsen	± 50 ppm ±5% reading	0~5000 ppm	3.3 v	60 s	$1–50
SO_2	B4 SO_2 [98]	Alphasense	±5 ppb	0~100 ppm	3 v	30 s	$100–300

	ME4-SO_2 [99]	Winsen	±2%	200 ppm	Not Provided	30 s	$100–300
	DGS-SO_2 968-038 [100]	SPEC	±15%	0~20 ppm	3.0 v	30 s	$50–100
	EC-4SO2-2000 [101]	Qingdao Scienoc Chemical	±2%	0~2000 ppm	Not Provided	60 s	$50–100
	MQ-136 [102]	HANWEI	±2%	1–100 ppm	5 v ± 0.1	60 s	$1–50
	FECS43-20 [103]	FIGARO	±2%	0~20 ppm	Not Provided	25 s	Not Provided
NO_2	uHoo-NO_2 [66]	uHoo	± 10 ppb ±5% of reading	0~1000 ppb	5.0 v	Not Provided	$300–500
	DGS-NO_2 968-043 [104]	SPEC Sensors	±15%	0~10 ppm	3 v	30 s	$50–100
	Mics-6814 [105]	SGX SensorTech	±10 ppb	0.05–10 ppm	5.0 v	30 s	$1–50
	MiCS-4514/ CJMCU4541 [71]	SGX SensorTech	Not Provided	1~1000 ppm	5.0 v	Not Provided	$1–50
	MiCS-2714 [106]	SGX SensorTech	Not Provided	0.05~10 ppm	4.9~5.1 v	30 s	$1–50
	B4 NO_2 [107]	Alphasense	±12 ppb	0~50 ppm	3.5~6.4 v	25 s	$1–50
PM	uHoo-$PM_{2.5}$ [66]	uHoo	±20 μg/m^3	0~200 μg/m^3	5.0 v	Not Provided	$300–500

	DC1100 Pro [108]	Dylos	Not Provided	0~1000 μg/m^3	9 v	Not Provided	$100–300
	OPC-N2 [109]	Alphasense	Not Provided	0.38~17 μm	4.8~5.2 v	Not Provided	$100–300
	FBT0002100 [110]	Foobot (Airboxlab)	±20%	0~1300 μg/m³	Not Provided	Not Provided	$100–300
	AW6404 [111]	AWAIR	±15 μg/m3 15% of reading	0~1000 μg/m^3	5 V/2.0 A	Not Provided	$100–300
	8096-AP [112]	Air Mentor Pro	Not Provided	0~300 μg/m^3	3.7 v	Not Provided	$100–300
	SPS30 [113]	Sensirion	±10 μg/m^3	0~1000 μg/m^3	4.5~5.5 v	60 s	$1–50
	PMS7003 [114]	Plantower	±10 @ 100~500 μg/m^3	0~500 μg/m^3	5.0~5.5 v	10 s	$1–50
	PMS5003 [115]	Plantower	±10 @ 100~500 μg/m^3	0~500 μg/m^3	5.0~5.5 v	10 s	$1–50
	HPMA115S0-XXX [116]	Honeywell	±15 μg/m^3	0~1000 μg/m^3	5 ± 0.2 v	6 s	$1–50
	DN7C3CA006 [117]	Sharp Microelectronics	±0.2	25~500 μg/m3	5 ± 0.1 v	Not Provided	$1–50
	SDS011 [118]	Nova Fitness	15% ±10 μg/m^3	0.0–999.9 μg /m^3	5 V	Not Provided	$1–50
	Shinyei PPD42NS	Shinyei	Not Provided	0~28,000 pcs/liter	5.0~5.5 v	60 s	$1–50

	[119]						
	TIDA-00378 [120]	TI Designs	75% Over Detection Range	12~35 pcs/cm^3	3.3 V	Not Provided	Not Provided
t-VOCs	uHoo-TVOC [66]	uHoo	10 ppb or 5%	0–1000 ppb	5.0 v	Not Provided	$300–500
	8096-AP [82]	Air Mentor Pro	Not Provided	0~300 µg/m^3	3.7 v	Not Provided	$100–300
	AW6404 [111]	AWAIR	±10%	0~60,000 ppb	5.0 v	60 s	$100–300
	FBT0002100 [110]	Foobot (Airboxlab)	±10%	0~1000 ppb	Not Provided	Not Provided	$100–300
	ZMOD4410 [121]	IDT	±10%	0~1000 ppm	1.7~3.6 v	5 s	$50–100
	Yocto-VOC-V3 [122]	Yoctopuce	Not Provided	0~65,000 ppb	Not Provided	Not Provided	$50–100
	uThing::VOC™- [123]	Ohmetech.io	±15%	0–500	5.0 v	3 s	$50–100
	MiCS-5524 [124]	SGX SensorTech	Not Provided	10~100 ppm	Not Provided	Not Provided	$1–50
	iAQ-100 C/ 110-802 [125]	SPEC	±2 ppm	0~100 ppm	12 ± 2 VDC	20 s	$1–50
	SP3_AQ2 [126]	Nissha FIS	Not Provided	0~100 ppm	5 v ± 4%	Not Provided	$1–50

	TGS2602 [127]	FIGARO	Not Provided	1~30 ppm	5 ± 0.2 v	30 s	$1–50
	MICS-VZ-87 [128]	SGX SensorTech	Not Provided	400–2000 ppm equivalent CO2	5.0 v	30 s	$1–50

Table 2. Common air quality guidelines and standards.

Measured Parameter	NAAQS/EPA (U.S. Enforceable) [129][130][131][132][133]	OSHA (U.S. Enforceable) [134]	WHO/ Europe (Christopher et al., 2017; WHO, 2016b, WHO, 2010) [135][136]	ACGIH [137]	ANSI/ ASHRAE 62.1 [138]	NIOSH [138]	CAAQS (SCAQMD) [139]
O_3	0.07 ppm (8-h mean) 0.12 ppm (1 h mean) 0.08 ppm	0.1 ppm	120 µg/m3 (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)	25 ppm (8-h)	9 ppm (8-h mean)	35 ppm 40 mg/m^3 (8-h mean) 200 ppm (229	20 ppm, (1-H mean) 9.0 ppm, (8-H mean)

			7 mg/m^3 (24-h mean)			mg/m^3) ceiling	
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/m3)	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-hoursl mean)	1 ppm (1.8 mg/m^3)	0.18 ppm, (1-H mean) 0.030 ppm, (Annual mean)
$PM_{2.5}$	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	N/A	50 µg/m^3 (24-h mean) 20 µg/m^3	10 mg/m^3 (8-h)	50 µg/m^3	N/A	50 µg/m^3 (24-H mean)

	exceeded more than once per year on average over 3 years)		(Annual 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

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