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A Review of State-of-the-Art Low-Cost Sensors for Detection of Indoor Air Pollutants that Correlate with Health

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Abstract: Indoor air quality and public health have always been an area of prime interest across the globe. The significance of low-cost air quality sensing and indoor public health practices spikes during the time of pandemic and epidemics when indoor air pollution becomes a threat to living beings especially human beings. Indoor diseases are hard to diagnose if they are due to the indoor environmental conditions. A major challenge was observed in establishing a baseline between the indoor air quality sensors and associated diseases. In this work, 10,000+ articles from top literature databases were reviewed using bibliometric analysis to formulate indoor air quality sensors and diseases correlation rubrics to critically review 500+ articles. A set of 200+ articles were selected based on for detailed study based on seven bibliometric indices for publications that used WHO, NIH, US EPA, CDC, and FDA defined principles. This review has been conducted to assist end-users, public health facilities, state agencies, researchers, scientists and air quality protection agencies.

Keywords: indoor epidemiology (IE); respiratory diseases; low-cost air quality sensors; air quality assessment; sensing technologies (STs); fabrication; measurement; configurations; sensor assemblies; gas sensors calibration systems (GSCS)

1. Introduction

It is widely accepted that air pollution leads to major health problems, costing economies billions of dollars per year in terms of health care costs and loss of productivity. Various studies around the world have linked many chronic diseases to air pollution. Indoor air quality (IAQ) is affected by ventilation rates, temperature and humidity, indoor activities, building materials through degassing, kind of devices and chemicals used indoor, occupant's activities within the closed space, poorly designed air conditioning and ventilation systems, and indoor air pollutants. Specifically, IAQ depends on several parameters which may be separated into two categories: (1) Comfort (Temperature, relative humidity, noise and vibration, and the three V's-velocity/volume/ventilation) and (2) health (indoor air pollutants like CO2, NOx, SOx, Radon, cigarette smoke, cleaners, Viruses, bacteria, fungi, an dust mites PM10/PM2.5). Health problems associated with IAQ are very serious as people, particularly vulnerable population including ill and elderly and young children, tend to spend most of their time indoor. While most people think IAQ is better than indoor, IAQ is typically twice to five-times worse than indoors.

According to the United States Environmental Protection Agency (EPA), throat irritation, dizziness and headaches constitute immediate symptoms of exposure to polluted air. Long-term health risks may include respiratory problems and disease, heart disease and even cancer. From the classroom to the cubicle, the benefits of maintaining good indoor air quality extend beyond protecting the occupant's health. According to a US White House Summit on Sustainable Buildings, healthy air improves students' information retention and teachers have fewer sick days. For employers, improving indoor air quality directly correlates with higher productivity and a more satisfied and pleasant workforce.

The quality of indoor has been perceived in terms of temperature, humidity and carbon dioxide (CO2). Unfortunately, improving indoor air quality has been to dilute the amount of CO2 and other contaminants through HVAC (heating, ventilation and air conditioning) systems or air filtration systems. The detection of the presence of volatile organic compounds (VOCs) has now become possible by virtue of the advancement in detection technology and techniques. VOCs are such as acetone, formaldehyde, cooking odors, indoor pollutants, paints and lacquers, cleaning supplies, and toxins. According to the EPA, VOCs are two to five times more likely to be found inside the home than outside.

In 2020, it was anticipated that household air pollution caused 3.2 million fatalities annually, including approximately 237000 deaths of children under the age of 5 [1]. Each year, 6.7 million premature deaths are attributed to the consequences of ambient and home air pollution. Living with chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease, stroke, and other non-communicable illnesses is made worse by household air pollution [2]. The term "Air Quality" refers to a gas assessment mechanism that can be used as a standard unit variable to govern acceptable pollution in a reciprocal manner as defined per the worldwide health organization (WHO), the U.S. Environmental Protection Agency (US-EPA), and the United Nations Environment Programme (UNEP) [3].

Monitoring of air quality are made using sensors and instrumentation, which face many challenges. An air quality gas sensor is an electronic or electro-chemical instrument that can measure the ratio of gas particles in a given volume of air, usually in units of part per million (ppm), through some sensing element. The air quality gas sensor may also have a variety of other applications [3–5]. Detection threshold or resolution, range, and linearity are critical challenges in sensors' systems. The sensor's resolution becomes critical when detecting low concentration pollutants like VOCs and Radon. In 1815, the first gas detector system known as Davy lamp was invented by Sir Humphry Davy (of England) to detect the presence of methane (firedamp) in underground coal mines [6]. The first gas sensor was invented by Dr. Oliver Johnson that originated from the catalytic combustion (LEL) sensor [7]. Clark and Lyons utilized the strategy of electrochemical detection of oxygen or hydrogen peroxide to measure glucose in biological samples [8]. The ubiquity of impedance mainly leveraged to realize the gas transducers [9]. The optical sensors are passive, i.e. require external field excitation source to inject some energy into the observation specimen for measurement [10–12]. The feedback of this energy can have many numerical relationships with the induced signal termed as working response (refractive coupling) [13].

In this work, we focus on surveying sensors and instrumentation used in air quality measurement as well as associated diseases. The research hierarchy of this work is presented in Figure 1.

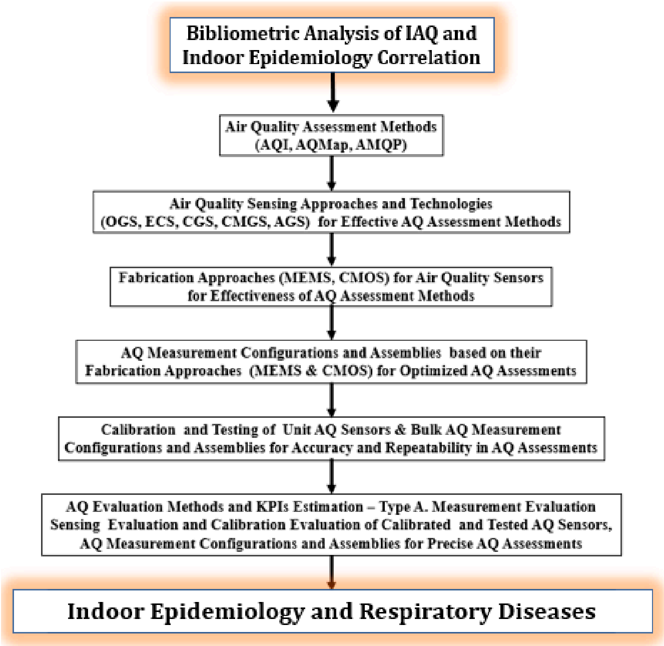


Figure 1. Indoor Epidemiology and Practical Hierarchy of Air Quality Assessment, Sensors, Configurations, Fabrication, and Calibration [1–210].

The existing practices lead to lack of transparency and conceptual challenges that can make it difficult to recognize the similarities and differences between indoor diseases and existing gas sensing systems and the contributions of new techniques. The contributions of this paper are chronologically comprehended as indoor epidemiology-focused: 1) Bibliometric Analysis of IAQ and Indoor Epidemiology Correlation; 2) Air quality assessment (AQA) frameworks; 3) AQ sensor types and technologies; 4) state-of-the-art AQ sensors fabrication approaches and technologies; 5) AQ sensors, configurations, and topologies; 6) AQ sensors calibration and testing systems; 7) AQ measurement systems; 8) Indoor Epidemiology and Diseases; 9) Indoor Epidemiological Merits in Operational and Lifecycle Cost Evaluation of IAQ Sensors. Since low-cost AQ is a huge domain and has a plethora of terminologies, Table 1 presents the key acronyms and abbreviations used in this research.

Table 1. Key Terms used in the Work.

Acronyms	Description	References
AQ	Air Quality	[1–178]
WHO	World Health Organization	[1–178]
NIH	National Institute of Health	[1–178]
FDA	Food and Drug Administration	[1–178]
CDC	Centers for Disease Control and Prevention	[1–178]
AQA	Air Quality Assessment	[14–44]
AQMap	Air Quality Mapping	[29–33,132,133]
AQMP	Air Quality Management Plan	[30–41]
AQI	Air Quality Index	[14–44,55–108]
API	Air Polution Index	[21,27]
EPA	Environmental Protection Agency	[1–41]
AQ-GS	Air Quality Gas Sensors	[6–13,18–153]
OGS	Optical Gas Sensors	[44,49–51]
ECS	Electro-chemical Gas Sensors	[44,52–55]
AGS	Acoustic Gas Sensors	[44,64–67]
CGS	Capacitive Gas Sensors	[44,56,57]
NDIR	Non-dispersion Infra-red	[49–51]

CMGS	Calorie-meter Gas Sensors	[44,58].
CMOS	Complementary Metal-oxide Semiconductors	[86–100]
MEMS	Micro Electro-Mechanical Systems	[44,74–85]
RIE	Reactive Ion Etching	[77–94]
SOI	Silicon on Insulator	[86–94,109–111]
SoM	System on Module	[35,56,80–86,101–112]
LoC	Electrode on Chip	[35,56–58,80–95]
GSAs	Gas Sensing Arrays	[102–113]
GSGs	Gas Sensing Grids	[106–111]
MFCs	Mass-Flow Controllers	[109–127]

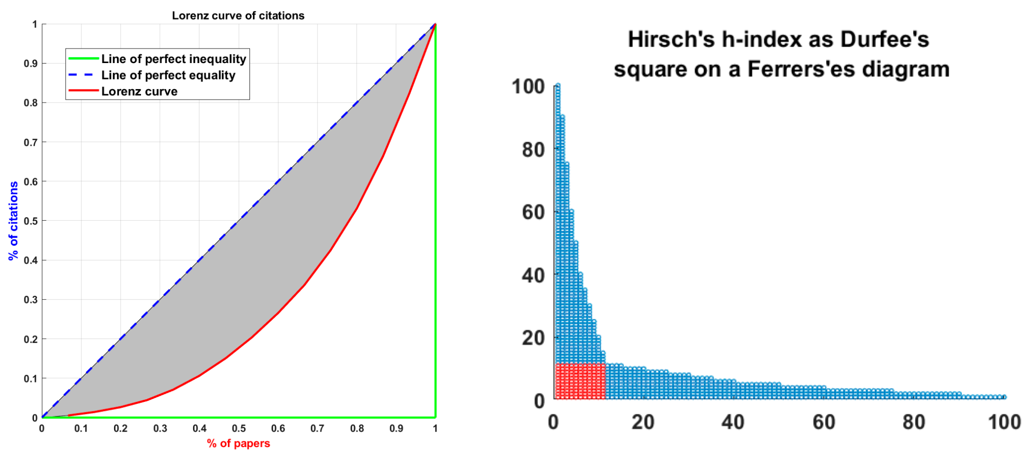
2. Bibliometric Analysis of IAQ and Indoor Epidemiology Correlation

For this analysis, the past 50 years 10,000+ articles were selected from Web of Science (WoS), Google Scholar, SCOPUS, CrossRef and Dimensions research databases. The bibliometric analysis was performed in MATLAB using six statistical indices as: a) Lorenz Curve of Citations; b) Hirch's H-Index; c) Kosmulski's H2-Index; d) Harzing's Hl-Norm-Index; e) Sidoropolous's HC-Index; and f) Schrieber's HM-index. The biblio-statistical parameter settings are presented in Table 2 below.

Table 2. Biblio-statistical parameters settings for 10000+ Articles .

#	Description	References
1	Keywords	Indoor air quality, indoor respiratory diseases, indoor pollutants, indoor epidemiolgy, epidemiology-focused sensors, epidemiology-focused air quality methods, epidemiology-focused systems.
2	Citations (50-5000)	[5000 3000 2500 2000 1500 1200 1000 800 500 300 250 200 150 100 50]
3	Years (50)	170 + [10 20 30 40 50 2]
4	Authors per paper (1-20)	[1 3 4 5 6 7 8 9 10 11 12 13 14 15 20]
5	Operators	WHO, NIH, CDC, US EPA, Methods, Policies, Rules, Approaches, Cases, Reports

The BibTex files for each search were segregated as a single file from all four databases and that resulted in 8 unique files from 4 unique databases and 32 files in total with 41093 articles. The repeated articles were filtered using BibTex Script processor and resulting archive contained 23347 articles. The maximum citations selected were 5000 and above and minimum as 50 citations. Figure 1 presented a detailed summary below.



(a) (b)

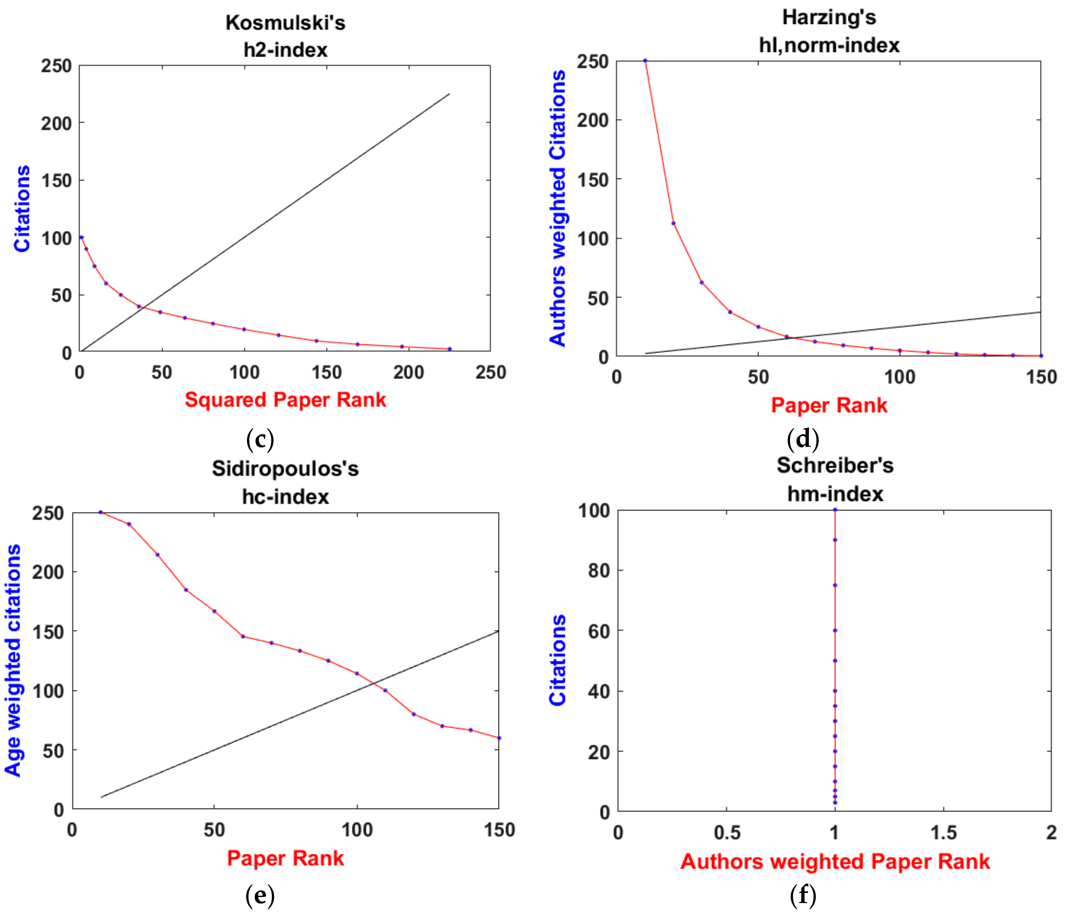


Figure 2. Statistical Bibliometric Indices for IAQ and Indoor Epidemiological relationship and public health baseline: (**a**) Lorenz Curve of Citations; (**b**) Hirch's H-Index; (**c**) Kosmulski's H2-Index; (**d**) Harzing's Hl-Norm-Index; (**e**) Sidoropolous's HC-Index; and (**f**) Schrieber's HM-index.

These indices resolved the 502 article pool for study and out of 210 articles were referred to in this work that defined the indoor epidemiology driven indoor air quality assessments, sensors, and calibration practices.

3. Indoor Air Quality Assessment for Indoor Epidemiology

In the light of indoor epidemiological guidance documented by the core environmental protection agencies, WHO, NIH, CDC, US-EPA, EEA, and UNEP; air quality terminology refers to the entire legislative body of knowledge that involves analysis, methods, and criteria based on air quality [14–17]. The real-time AQA information from AQ sensors is used for environmental health and public safety. The major real-time methods used in this context are:

1. Indoor Air Pollutants
2. Air Quality Index (AQI)
3. Air Quality Mapping (AQMap)
4. Air Quality Management Plan (AQMP)

Air quality assessment and air crisis risk (ACR) mitigation are strictly sequential and systematic processes. Each phase has its clear and precise significance and contribution in the next phase. AQA and ACR involve estimation of bio-tolerable gas threshold [18,19] such as hazardous gas magnitudes and pollutant ratios in atmospheric volume; geospatial AQA to orchestrate regional AQM [19–22], and design a model of regional air volume with effective and contributory variables to provide mitigation plan [23].

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3.1. Indoor Air Pollutants

The international thresholding guidelines for exposure based on WHO and US-EPA are presented in the Table 3 given below adapted from weblink mentioned below.

Table 3. Indoor air quality thresholds and exposure timelines.

Pollutants	Concentration Levels (mg/m^3)	Exposure Time	Organization
CO	100	15 min	WHO
	60	30 min	
	30	1 h	
	10	8 h	
	29	1 h	USEPA
	10	8 h	
CO_2	1800	1 h	WHO
NO_2	0.4	1 h	WHO
	0.15	24 h	
	0.1	1 year	USEPA
PM	0.15	24 h	USEPA
	0.05	1 year	
SO_2	0.5	10 min	WHO
	0.35	1 h	
	0.365	24 h	USEPA
	0.08	1 year	

Source: European Commission DG XVII: https://www.europeansources.info/corporate-author/european-.

3.2. Air Quality Index (AQI)

The indoor air quality depends on the indoor ambient pollutants. Therefore, there is a tight correlation between the indoor air pollutants. AQI refers to a real-time structured chart with a bio-tolerable threshold of specific pollutants and bio-hazardous gases recommended by EPA in the area under a specified border agency [18–24]. The top 10 environmental protection agencies (EPAs) unanimously agreed on the standard of four core gases for indoor air quality [25] i.e. Ozone (O3), Nitrogen Dioxide (NO2), Sulphur Dioxide (SO2), Carbon Monoxide (CO).

In Figure 3 (a), the concentration of the four gases or the air particles part per million (ppm) constitutes the air quality index (AQI) [26,27] is the fundamental design i.e. the quantities of O3, SO2, CO, and NO2 are the standard gases considered in major environmental standards for AQI. The standard AQI evaluation template for a specific region provided by EEA as Common Air Quality Index (CAQI) and US EPA as AQI are presented in Figure 3. The dust pollutants include particulate matter (PM) versions PM-10 and PM-2.5A as standard indoor AQI with distinguishable cross-sensitivities. In Figure 3, the air quality index chart in Figure 3 presents the mandatory thresholds and limit windows for AQI variables that serve as air pollution index (API). Another multi-parametric AQI innovation in assessment is the environmental performance index (EPI) by Yale Center for Environmental Law and Policy [28].

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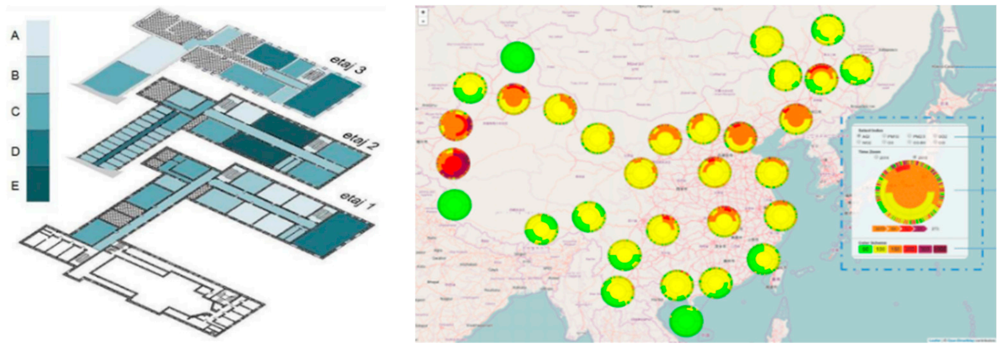
	AQI	PM 2.5 (ug/m3)	PM 10 (ug/m3)	VOC (ppm)	CO2 (ppm)	Formaldehyde (ppm)
Good	0-50	0 - 12	0 - 54	0 - 15	400 - 650	0 - 0.2
Moderate	51 - 100	12.1 - 35.4	55 - 154	16 - 25	651 - 1500	0.21 - 0.4
Unhealthy for sensitive groups	101 - 150	35.5 - 55.4	155 - 254	26 - 50	1501 - 2000	0.41 - 0.6
Unhealthy	151 - 200	55.5 - 150.4	255 - 354	51 - 75	2001 - 2500	0.61 - 0.8
Very Unhealthy	201 - 300	150.5 - 250.4	355 - 424	76 - 100	2501 - 5000	0.81 - 1
Hazardous	301 - 500	250.5 - 500	425 - 600	101 - 150	5001 - 15000	1.01 - 1.2

Figure 3. AQI Charts by EEA and US EPAs [21–27] for Real-time AQI.

3.3. Air Quality Mapping (AQMap)

The geo-locations in the vicinity of AQ measurement using collective averaging and mean estimation procedures derive a real-time air quality map with an additional parameter, that is geographical positioning system (GPS) value [29,30]. The process of collection of all such points and orientating them geo-spatially is called AQMap [25–31]. There are two types of AQMap: (i) indoor air quality mapping (I-AQMap); and (ii) outdoor air quality mapping (O-AQMap) [32] in Figure 4.



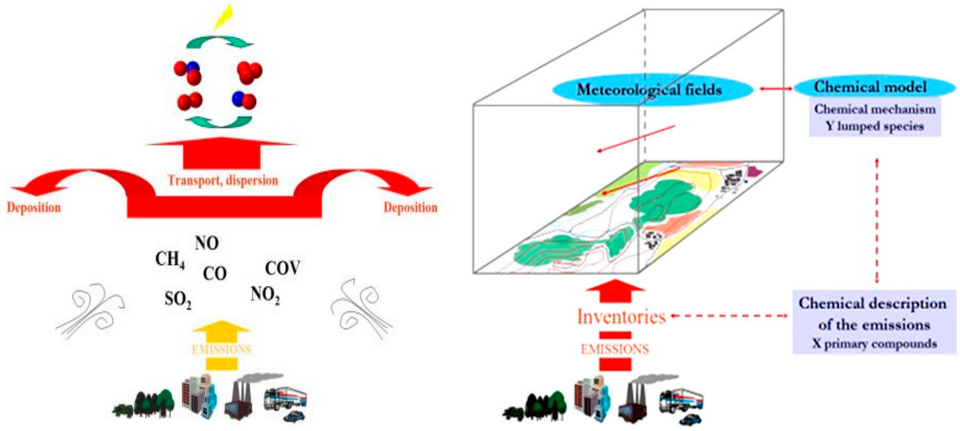
(**a**) (**b**)

Figure 4. Two fundamental approaches in Real-time AQMap[24-33]. (**a**) Real-time Indoor Air Quality Mapping. (**b**) Real-time Outdoor Air Quality Mapping.

Figure 4, shows that I-AQMap is building-wise and O-AQMap is region-wise. There are different sets of gases and ratios of pollutants with molecular sizes [33]. The charting and graphing as well as typo-graphic presentation schemes available, and their standardization process for AQMap based on their relative effectiveness are mentioned in this work [34].

3.4. Air Quality Management Plan (AMQP)

The AQMP is based on the Brownian motion (Robert Brown); and the Brownian motion is defined as the random nature of particle dynamics in the air. In the entire assessment of AQ, the most challenging and attention criteria is AQMP, especially air quality modeling [35]. The key work was accomplished by Dr. Gary Haq and Dr. Dieter Schwela in 2008 while modeling the toughest regions in Asia [36,37].



(**a**) (**b**)

Figure 5. Two Step AQMP Methodology Practices in AQM [18–41] (**a**) Air Quality Modelling [35]. (**b**) Air Quality Management Implementation Scheme [39].

Claudia et al. presented a very appreciable work in virtual pollution modeling using Bayesian network theory [38]. The AQMP (2012) presented by Dr. Bjarne Sivertsen and Alena Bartonova holds a landmark value in regional level AQMP [39]. The INDAIR model and clean energy were focused on bounded value models for a clear interpretation of decision making AQMP parameters [40,41].

4. Indoor Epidemiology-focused Air Quality Gas Sensors (AQ-GS) Technologies.

There are five approaches to sense in air quality measurements and their architectures and presented in Figure 6 [44].

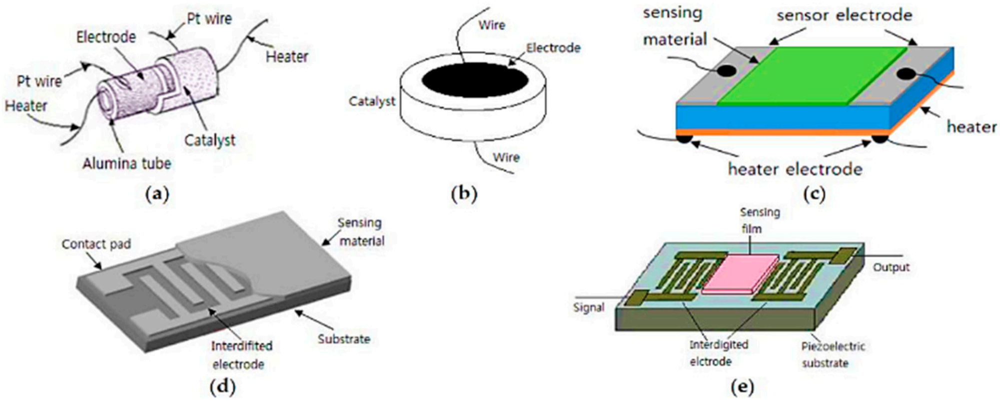


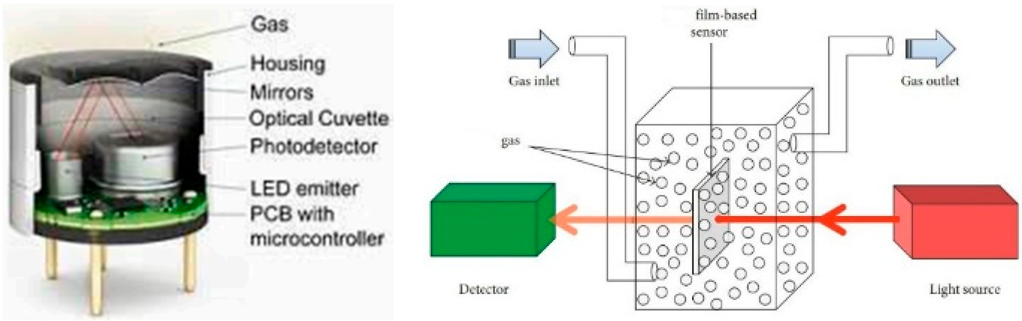
Figure 6. Five Primitive Approaches in AQ Gas Sensors Technologies [44].

Furthermore, there are five unique technologies in low-cost air quality gas sensors (AQGS): a) Optical Gas Sensors (OGS); b) Electrochemical Gas Sensor (ECS); c) Capacitive Gas Sensor (CGS); d) Calorimetric Gas Sensor (CMGS); and e) Acoustic Gas Sensor (AGS) [33–48]. The architectural and working principles are explained in detail in the respective sections.

4.1. Optical Gas Sensors (OGS)

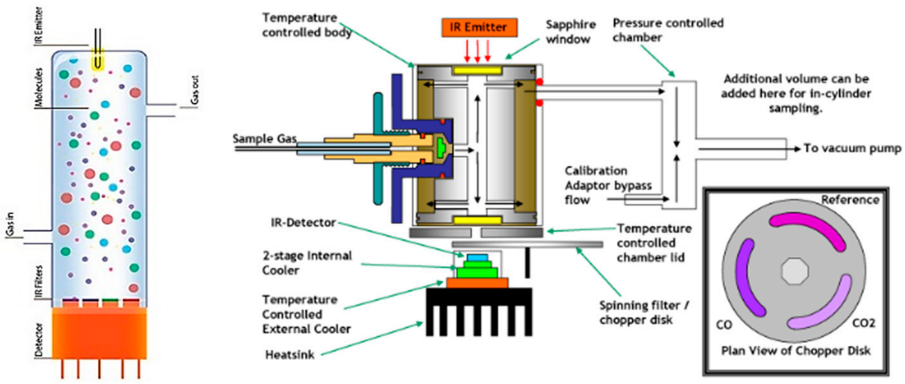
In the entire Identical or isometric coupling by 1:1 Tx/Rx is a combination of transmitting and receiving mode. In this case, a variable dielectric like the human body is introduced as exhibited in Figure 6 [49,50].

In Figure 7, a light source transmits a light array through a file-based sensor that measures the impact of light on air particles and returns an analog voltage value for every unique gas which is cycling through micro-OGS the chamber. The widely used OGS is non-dispersive infra-red (NDIR) gas sensor that has a swift response and long lifetime as this type does not use any consumables. The NDIR-GS is presented in Figure 8 below [49–51].



(a) (b)

Figure 7. Overview of OGS [49,50]. (**a**) Architecture. (**b**) Working Principle.



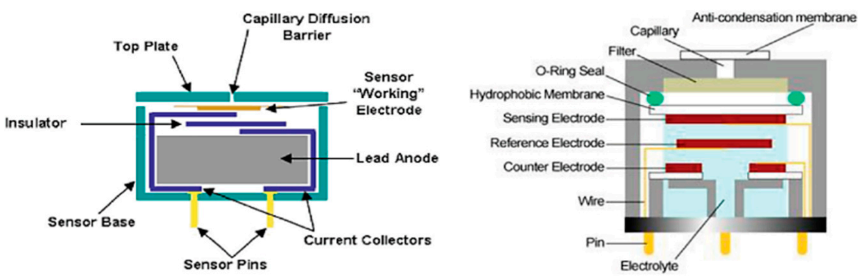
(a) (b)

Figure 8. Overview of NDIR-GS [51] (**a**) Architecture. (**b**) Working Principle.

In NDIR-GS presented in Figure 8, the same principle is used, i.e. light emission and reservation, the only difference is the IR nature of light that can sense up to 0.1"μ" m particles [51].

4.2. Electrochemical Gas Sensors (ECS)

In ECS, the receive mode can possibly be made by making the working electrode as sensing element and counter electrode as an extension of the transmitting electrode to pick transmitted electrons through the electrolyte [52–54]. In this case, a working electrode acts as a multi-channel receiver for multi-variable sensing as exhibited in Figure 9 below [53].



(a) (b)

Figure 9. Overview of ECS [52,54] (**a**) Architecture. (**b**) Working Principle.

The ECS-GS presented in Figure 9 is a generic ECS architecture used by leading vendors in the gas sensors industry, i.e. FIGARO, SGX, and Honeywell. The faster response rates and solid-state architectures are presented in [54,55] needs fabrication tendering to assess their mass production feasibility over existing technologies.

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4.3. Capacitive Gas Sensors (CGS)

In CGS, the transmit mode is made possible by making the sensor body an extension of the transmit electrode (or capacitor) to improvise the nearest transmitter created electric fields [57]. In this case, a gap volume acts as a multi-impedance transmitter for multi-variable sensing receivers as presented in Figure 10 (a) below [58].

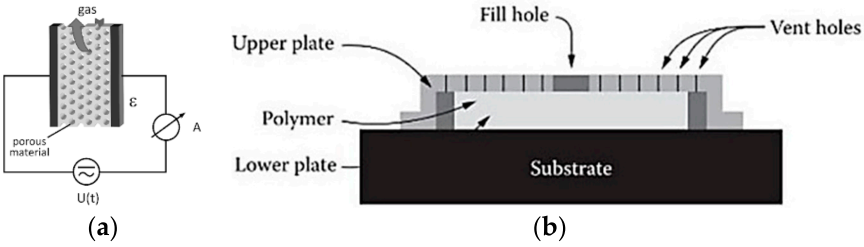

Figure 10. Overview of CGS [58]. (**a**) Architecture. (**b**) Working Principle.

In Figure 10 (b), it is shown that CGS is merely a capacitor in an isolated circuit where the electric flux between the plates is derived from volume for gas measurement. The fill hole allows the air to enter the sensing zone and cycles back to the atmosphere through vents.

4.4. Low-Cost Calorimetric Gas Sensors (CMGS)

In CMGS, a displacement current flows through the body to ground through a catalyst loaded electrode gap [60]. A single electrode is utilized as a transmitter and receiver of flux as exhibited in Figure 11 below [61,62].

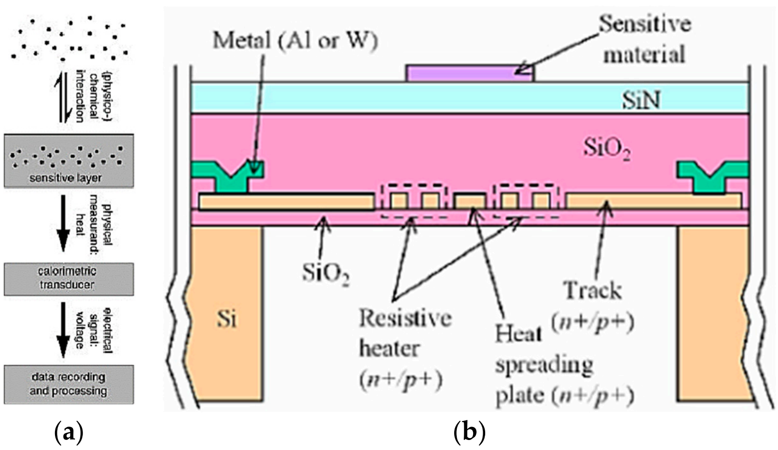

Figure 11. Overview of CMGS [58]. (**a**) Architecture. (**b**) Working Principle.

The finite element methods (FEM) used by Mohamed Serry et al. was a successful demonstration of a unique signal at different heater temperatures which could be increased more than 23 times by increasing the heater voltage from 3.5 to 5.0 V. Selectivity versus acetone vapor was also experimentally verified [63].

4.5. Low-Cost Acoustic Gas Sensors (AGS)

In AGS, a displacement or acoustic wave is transmitted through the gas and the difference in the characteristics of the received wave from the original wave is converted into an equivalent AGS value [64,65]. A single electrode is utilized as a transmitter and receiver of flux as exhibited in Figure 12 below [64–66].

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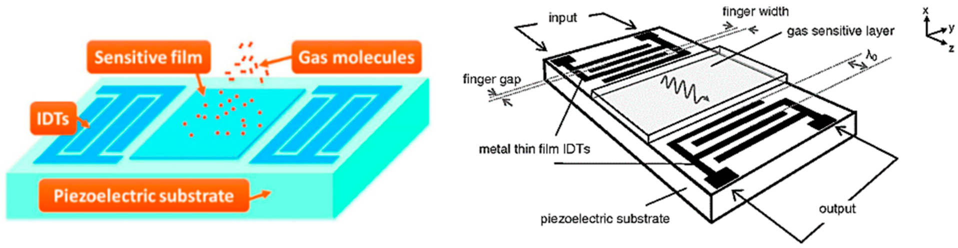

(a) (b)

Figure 12. Overview of CGS [58]. (**A**) Architecture. (**B**) Working Principle.

The new dimension in AGSs was explored in 2018 by Xueli Liu et al [68]. According to Xueli et al, a typical surface acoustic wave (SAW) gas sensor described in Figure 12 has a core element of thin-film coated along the SAW propagation path between the two interdigital transducers (IDTs). The absorption in sensitive thin-film modulates the SAW propagation by a so-called mass loading, viscoelastic or acoustic-electric effect, depending on the physical class of the sensitive thin-film itself.

5. Indoor Epidemiology-Focused Gas Sensors Fabrication Approaches

A comprehensive work in micro-fabrication of gas sensors was accomplished by Jan et al. in [69] where different industries, based on multi-type gas sensors and their effective fabrication methods were elaborated. The acoustic; carbon nano-tube (CNT); electrochemical; fiber-optic; metal oxide semiconductor (MOS); organic-based chemi-resistive; piezoelectric; photonic crystal gas sensors and volatile organic compound (VOC); sensors fabrication was categorically addressed in their works [70–72]. The most recent studies [68–73] highlighted only two state of the art fabrication approaches for the Gas Sensors (GS):

1. Micro-Electro-Mechanical Systems (MEMS) Fabrication Approaches
2. Complementary Metal Oxide Semiconductor (CMOS) Fabrication Approaches

5.1. Micro-Electro-Mechanical Systems (MEMS) Fabrication Approaches

The MEMS was the first of the commercialized approach for CEs fabrication and was composed of 15 core steps as shown in Figure 13 for the first steps in gas sensing as electrode fabrication and placement.

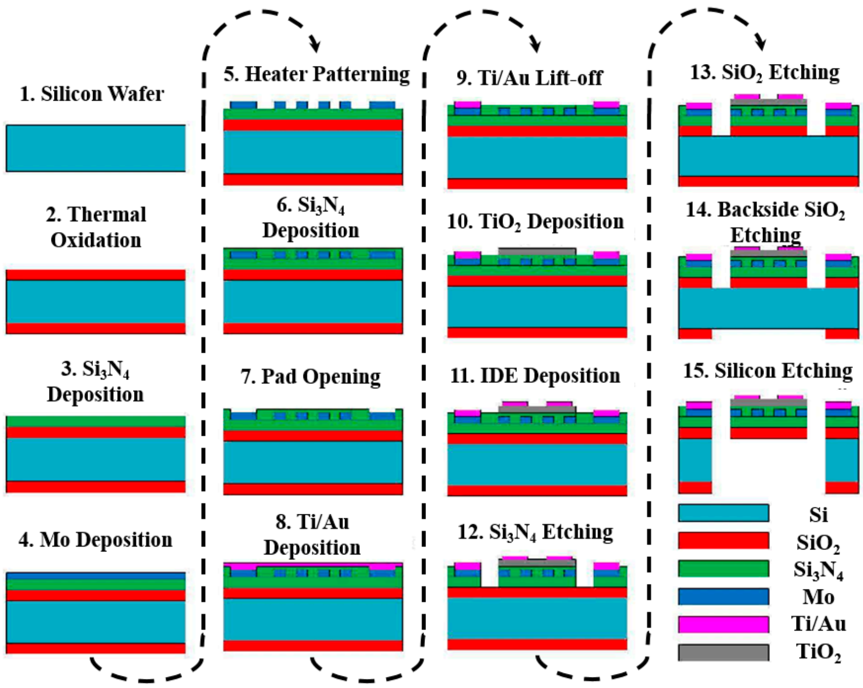

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Figure 13. The Fifteen Step MEMS Fabrication Process for GSs [75].

The molybdenum micro-heaters were prepared in the following steps [74]: a) the membrane micro-heater utilized 104 mW to acquire an 800 °C with a thermal resistance of 7.2 °C/mW; b) FLIR camera was used to acquire thermal distribution patterns overheating area; c) a temperature gradient of 1.18 % to its periphery; d) stabilities of the micro-heated were analyzed (mechanically and chemically as well its membrane failures safety threshold was estimated;) e) the characterization of micro-heater using optical profile-meter was estimated to be 16.25 μm at 800 °C.

In Figure 13 the entire MEMS fabrication process flow of the electrode can be observed. The pulse train and the constant DC voltages were also characterized in [74]. The response time is in the order of 19ms and the recovery time is equal to 34 ms. A stable temperature was exhibited by a micro-heater with a negligible resistance drift (0.96%) for 600 hours. The accuracy of CO was (5000 parts-per-billion (ppb)) measured between 300 to 700 °C. Another MEMS process for ECGS based on micro-heaters are using SiO2 with sputtering of a 10/60 nm were coated with thick Ti/Pt metal layer of 300nm thickness of a 10/60 nm Cr/Au layer [75].

In Figure 14, it can be noticed that the AGS (quartz crystal micro-balance) was manufactured on a 168 μm to 330 μm and a diameter of about 5 mm to 25 mm quartz [77]. Gold (Au) and Platinum (Pt) were used as electrodes. Each quartz was etched using RIE. An anisotropic and inductively-coupled plasma reactive ion etching (ICP RIE) method can be used with etch quartz [78]. Deposition, lift-off, photolithography, beam evaporation, Ni patterning were the major processes employed in these methods [79]. The capacitive micro-machined ultrasonic transducer gas sensor has also been introduced as an exemplary case of MEMS fabrication in 12 sequential steps for AGS given in Figure 15 [80,81].

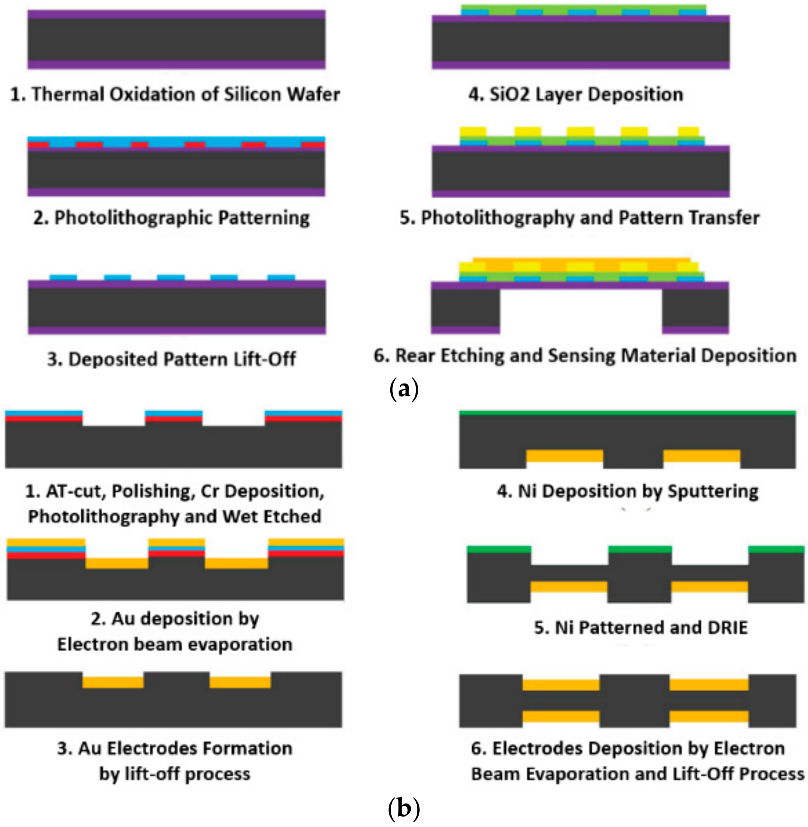


Figure 14. Two Six-Step Electro-chemical gas sensors (ECS) fabrication by MEMS Fabrication Approaches [75–79] (A) RIE Method [74,75]. (B) Au Electrodes [76–79].

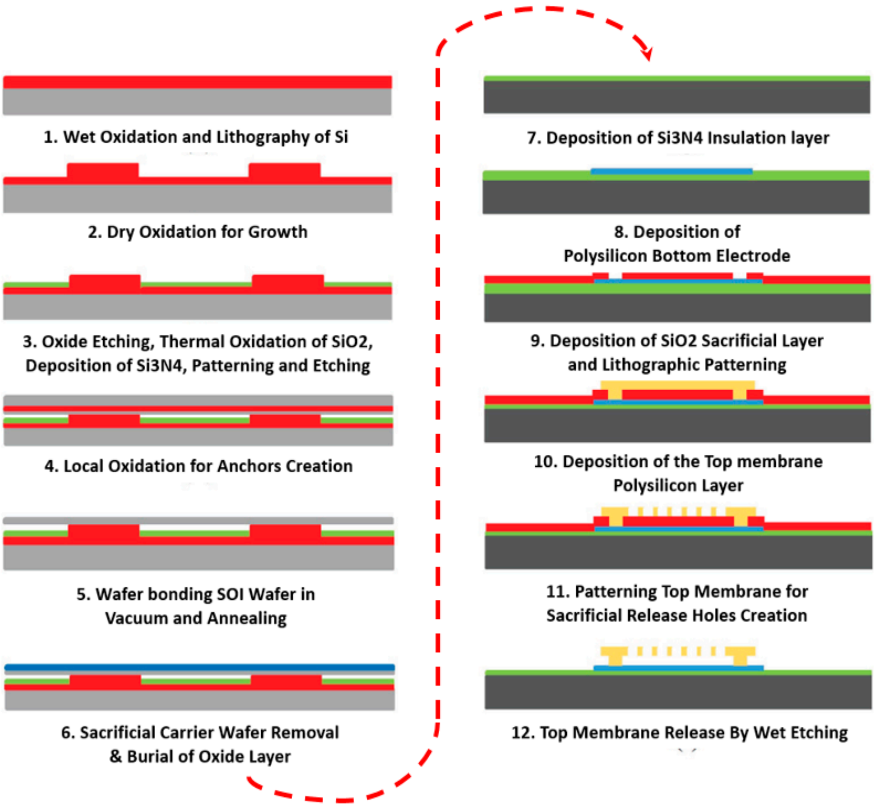
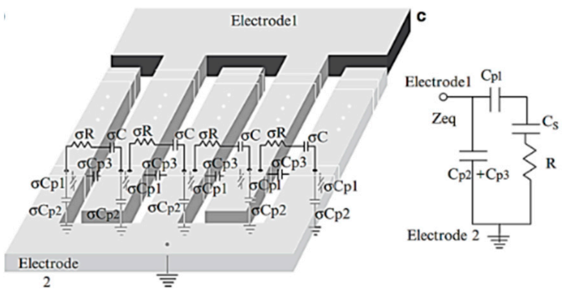


Figure 15. The Twelve Step MEMS Fabrication Process using Si [80–85].

It is eloquent from Figure 15 that in MEMS fabrication is mainly dependent on the coating, sputtering, exposure, electroplating, and photolithography. One of the state-of-the-art methods was the sacrificial method and wafer bonding [80–85], i.e. utilizing the cavity flow for sensing in first and trapping air in second.

5.2. Complementary Metal Oxide Semiconductor (CMOS) Fabrication Approaches

The current CMOS fabrication approaches mainly cover field-effect transistors (FETs) using Silicon on insulator (SOI) technology [86–90] for GSs is CMOS based and its primitive impedance model and assembly are presented in Figure 16 [87].



(a)

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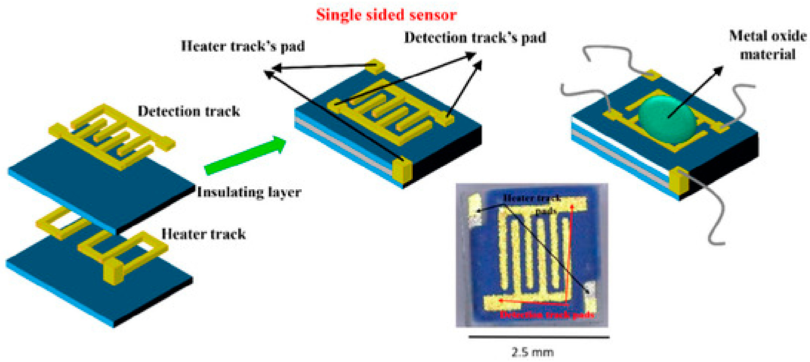
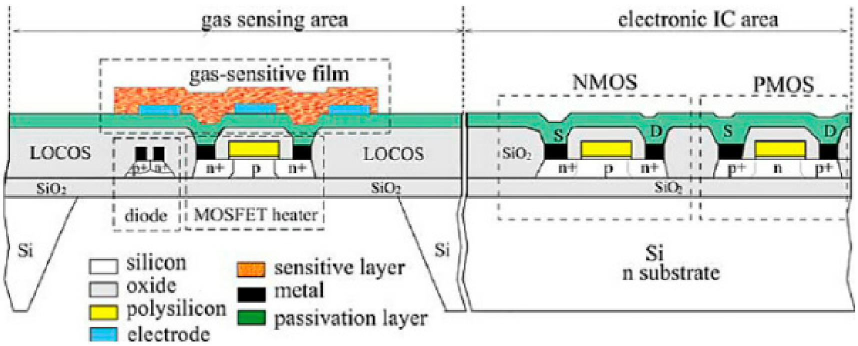


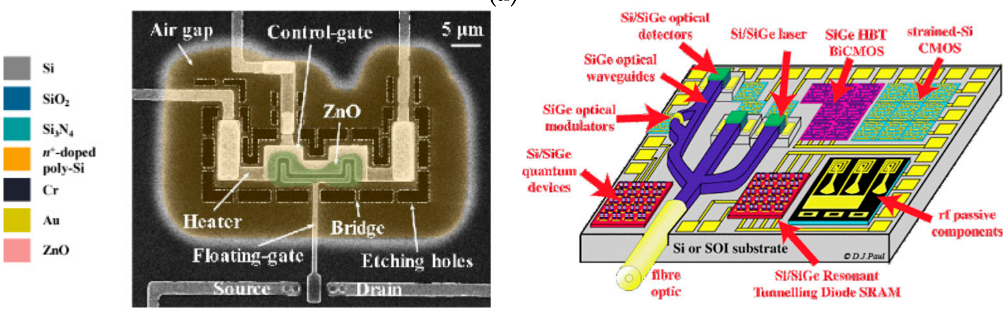
(**b**)

Figure 16. CMOS Realization of GS and its Post Fabrication Assembly (**a**) Impedance Model and Dye Realization [35,56] (**b**) Sensor Assembly (LoC) [35,56–58].

The entire CMOS electrode microchip cluster is resolved into finite elements and is equivalent to a capacitance and a resistance between electrode 1 and electrode 2 [86,87]. The CMOS capacitive electrode-based sensors assembly of manufactured GSs is presented in Figure 16.b. The CMOS fabricated FET sensors are nano-capacitive types in a vast sense and are presented in Figure 17 and Figure 15. The Twelve Step MEMS Fabrication Process for GSs is presented in the following references [80–85].



(**a**)



(**b**) (**c**)

Figure 17. Major FET Gas sensor architectures using CMOS Approach (**a**) Schematic of a Cascaded MOS-FETs coupled with IC area with Si Substrate [87] (**b**) Detailed view of a FET based Gas Sensor [86–88] (**c**) Complete FET Sensor Assembly [86–89].

The three major features of the sensors presented in Figure 17 from [35,56–58,86–90] were able to deliver the response rates of less than 3 seconds and with a resolution of ppb. The SOI technology used in the FETs (from Figure 17) is produced through the CMOS process (Figure 18) detailed in [91].

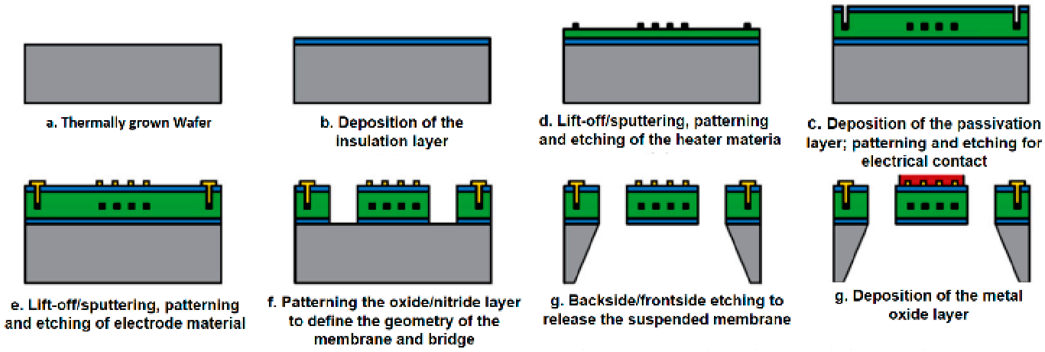


Figure 18. Process of Fabrication of Monolithic GS by CMOS technology [91].

For wet etching Tetra-methyl-ammonium hydroxide (TMAH) was used being fully compatible with CMOS processes [90–92]. The deep reactive-ion etching (DRIE) in such a case was used for miniaturization of the sensor [91]. The layered deposition of the SOI technique enabled fabrication at 400 to 600C with lowering the leakage current [92–94].

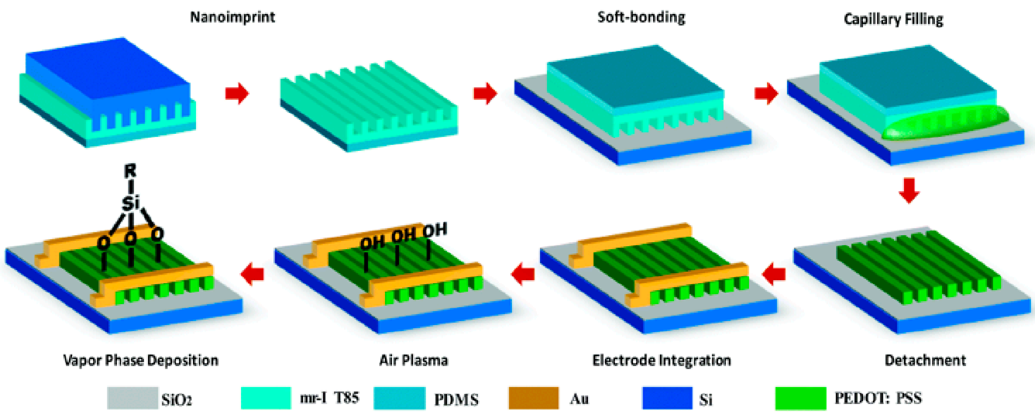


Figure 19. Process of DRIE based SOI Fabrication of Monolithic GS by CMOS technology [92–94].

The most recent work [95] in Mar 2020 by Yiang et al. is the state of the art in the entire generation [96–100] of CMOS nanofabrication based on nano-wires and nano-electrode deposition. The E-Nose term is often used for nano-scale fabrication in CMOS with multi-sensor electrode integration over a single dye [95]. The soft-lithographic technique for chemo-resistive gas sensor array fabrication with ordered sub-100 nm wide conducting polymer nanowires (poly-ethylene-dioxythiophene). The poly (styrene sulfonate) (PEDOT: PSS) functionalized in an assembly of different self-assembled monolayers (SAMs) were able to measure VOCs at ppb.

6. Indoor Epidemiology-Focused AQ Measurement Configurations and Assemblies

Smart methods like machine learning and data analysis for AQA processes require the gas sensors to be in specific format or topology for accuracy, effectiveness, and trustable measurements [101–108]. There are two core multi-gas sensing or sensor topologies (also called electronic nose) arrays and grids, further elaborated as; a) Gas Sensor Arrays and Grids based on System on Module (SoM) Approach; b) Gas Sensors Array on Chip based SOI.

6.1. Gas Sensor Arrays and Grids based on System on Module (SoM) Approach

The term electronic nose board (ENB) was used by various researchers across the world for a specific multi-sensor heterogeneous instrumentation PCB (Figures 20 and 21) from [101–109]. The orientation of ENBs is for a typical sensing application is called gas sensing array (GSA) or GS grid (GSG) [102]. The multiple GSAs send data to a central data acquisition collector or gateway called GSG [104]. Different GSAs and GSGs from novel works were objectively discussed in [103–109].

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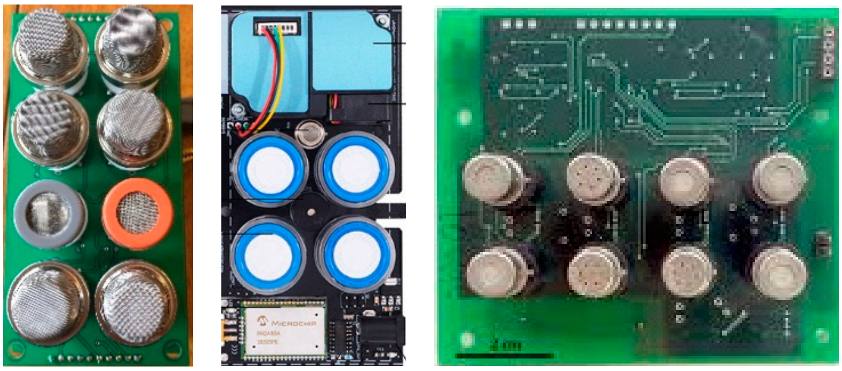
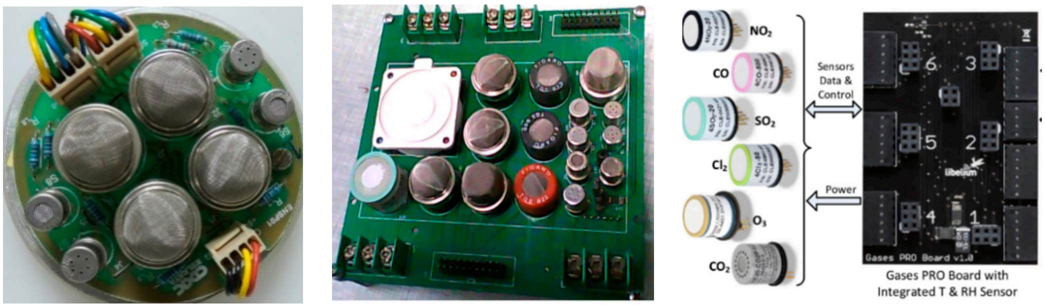


(a) (b) (c)

Figure 20. Major contributions in Applied GSGs and ENBs. (**a**) Trio GSG for I-AQA [107]. (**b**) Wound Infection ENB [108] (**c**) Smart Rig Test ENB [109].

Gradient descent method was used to detect food ripening by GSA interfaced with STM32 in Figure 20 (a) [103]. Later indoor air quality assessment was forecasted by GSA in Figure 20 (b). Similarly, the water filtration assessment was performed using particle swarm optimization (PSO) by 8 MOX GSA boards formed a GSG interfaced with MSP430F247 board as presented in Figure 20 (c) [105,106].



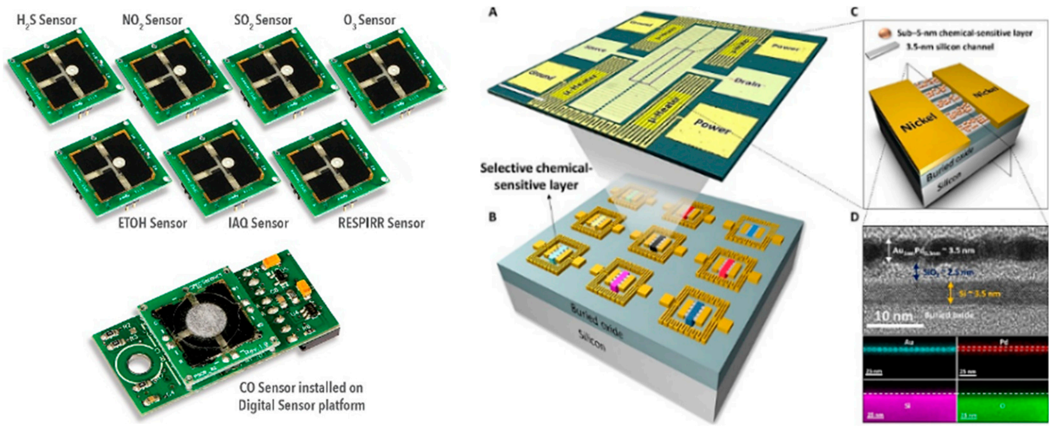
(a) (b) (c)

Figure 21. Major contributions in Applied GSGs and ENBs. (**a**) Trio GSG for I-AQA [107]. (**b**) Wound Infection ENB [108] (**c**) Smart Rig Test ENB [109].

I-AQA was performed in a hospital using least square estimation for HVAC testing using Trio GSG [107], i.e. the 8 indoor gases were assessed from figure 20 (A). In Figure 21 (B), the SVM was used to assess wound infection by ENB based on 4 types of sensors [108]. In April 2020 the most recent ENB was used for assessment of MFCs in a gas sensors calibration test bench [109] presented in Figure 21 (C).

6.2. Gas Sensors Array on Chip based SOI

In 2019-2020, state of the art appeared in the market as GSA on Chip, the next step in Sensor on Chip prepositions [110–113]. These arrays delivered accuracy at details of ppb. In 2016, Screen Printed Electro-chemical (SPEC) sensors shrinked this gas sensing technology down to a size appropriate for consumer devices that can be made at the volumes and costs suitable to the mass market [110] in Figure 22 (a). The multi-sensor chip was proprieted as Digital Sensor Platform on Chip (DSPoC) and the overall ENB was called Open Source DSPoC Kit.



(**a**) (**b**)

Figure 22. Major contributions in GSAoC) based SOI for Applied GSGs and ENBs. (A) SPEC DSPoC with GSA on Chip [110]. (B) Monolithic GSA on Chip with 3.5 nm wires [111].

In 2017, H2S, H2, and NO2 gases were sensed using a novel GSAoC with 3.5nm wires [111]. The most recent work was Single-Chip Gas Sensors Array (SC-GSA) in which a set of four micro-heaters were used to access a single suspended SiO2 diaphragm [112], using thermal proximity and achieved low power consumption (~10 mW for 300 °C). The plasma optimized thin films of ZnO, BaTiO3-CuO doped with 1% Ag, WO3, and V2O5 are employed for selective sensing of CO, CO2, NO2, and SO2. The four sensors were controlled independently and demonstrated CO (~78.3% for 4.75 ppm) at 330 °C, CO2 (~65% for 900 ppm) at 298 °C, NO2 (~1948.8% for 0.9 ppm) at 150 °C, and SO2 (~77% for 3 ppm) at 405 °C operating temperatures. The complete implementation for GSAoC is the current state of the art [113].

7. Indoor Epidemiology-based Calibration and Testing of AQ Gas Sensors

Readings from sensors, especially chemical sensors, shift with temperature and aging, affecting the accuracy of the measured data. Therefore, regular calibration should be conducted. Four major types of automated calibration approaches have been developed and tested till date: a) Uni-Gas Uni-Sensor Calibration; b) Uni-Gas Multi-sensor ENB Calibration; c) IoT-based Networked Multi-Gas ENB Calibration; and d) Climate Smart Heterogeneous ENB Calibration. The recent work realized a plethora of efforts made in gas sensors calibration [114–127] presented in Figures 23–26.

7.1. Uni-Gas Uni-Sensor Calibration

In 2009, the first structured gas sensors calibration system was designed and implemented by a measurement calibration system that was developed by Casey, J.G. et al. [114] presented in the Figure 23 (a).

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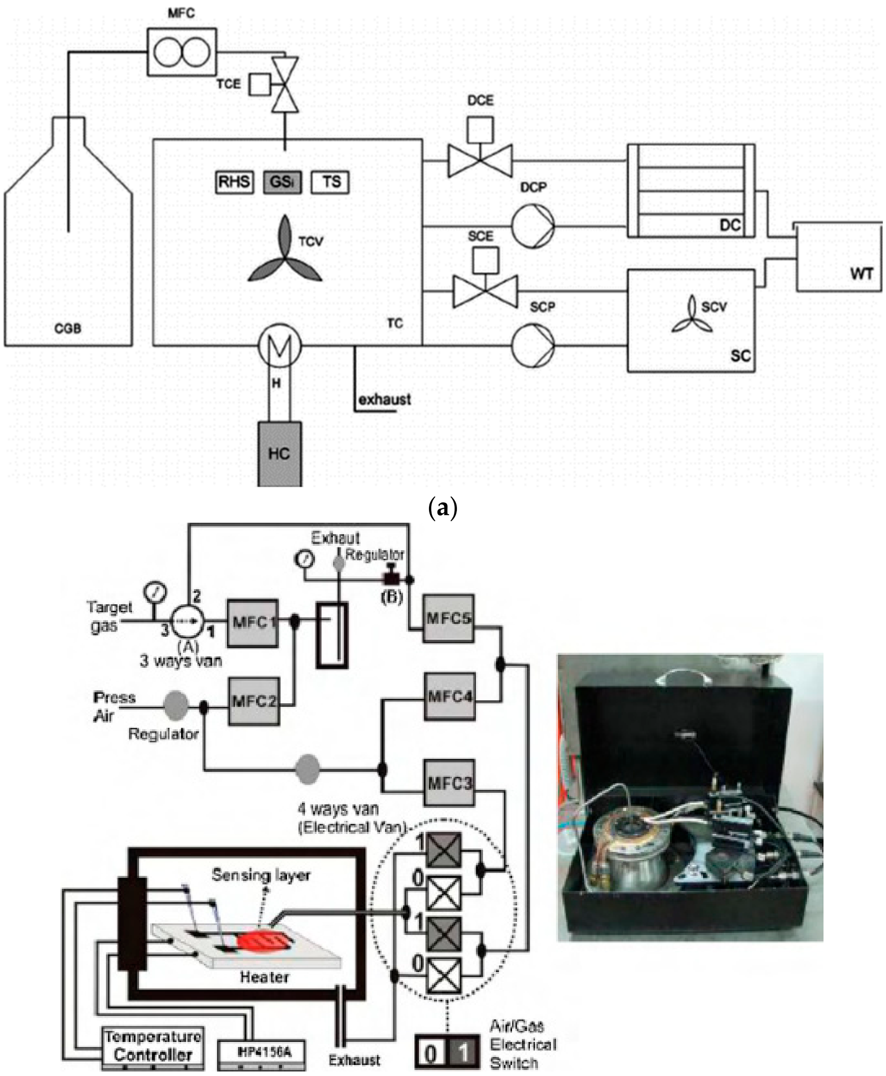

(**a**)

(**b**)

Figure 23. The AQ gas sensor calibration chamber-based system. (**a**) P&ID of a Unit AQGS Testing and Calibration System [114]. (**b**) System Assembly and Architecture [115].

A standard AQS Calibration follows the [114] schematic as: a) An Air-sealed chamber with inflow and outflow valves; b) mass flow controllers (MFCs) for the desired concentration of gas from a cylinder or a PID controller gas flow loop; c) gas cylinders with different concentrations; d) temperature actuator (heater); e) humidity actuator (steam regulator); f) gas collectors for the environmental model; g) measurement instruments other than gas sensors for comparison interfaced with a computer. In Figure 23 (a), an industry-standard instrumentation topology, i.e. piping and instrumentation diagram (P&ID) is presented for AQGS [114]. It consists of 14 components: 1) CGB: Calibration gas bottle; 2) MFC: Mass flow control; 3) TCE: Testing chamber electro-valve; 4) DCE: Drying chamber electro-valve; 5) SC: Saturation chamber electro-valve; 6) DCP: Drying chamber pump; 7) SCP: Saturation chamber pump; 8) DC: Drying chamber; 9) SC: Saturation chamber; 10) HC: Heater control; 11) H: Heater; 12) WT: Water tank; 13) TCV: Testing chamber ventilator and 14) SCV: Saturation chamber ventilator. The chamber ventilator's internal architecture varies with the sensing technology detailed in a survey on gas sensing (Xiao Liu et al. [115]). The two studies in testing performance of field gas sensor calibration techniques were proposed by Joanna et al. [116] for Colorado.

The characterization study conducted by Leidinger et al. led to a new horizon in test gas generation systems [117]. In Figure 23 (b), an experimental gas sensor test, and calibration system by for SnO_2 nanowires-based gas sensors are presented (Le Viet Thong et al. [118]). The test was performed by measuring all the sensors with liquid petroleum gas (LPG, 500–2000 ppm) and NH_3

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(300–1000 ppm) at different temperatures (50–450 ◦C) using a set up with high-speed switching gas flow (from/to air to/from balance gas). Balance gases (0.1% in air) were purchased from Air Liquid Group, Singapore. The system employed a flow-through with a constant rate of 200 sccm.

7.2. Uni-Gas Multi-sensor ENB Calibration

The miniaturized environmental control chambers presented in Figure 24 were introduced by Yi Chen et al. [119] and Jordi Follonosa et al [120].

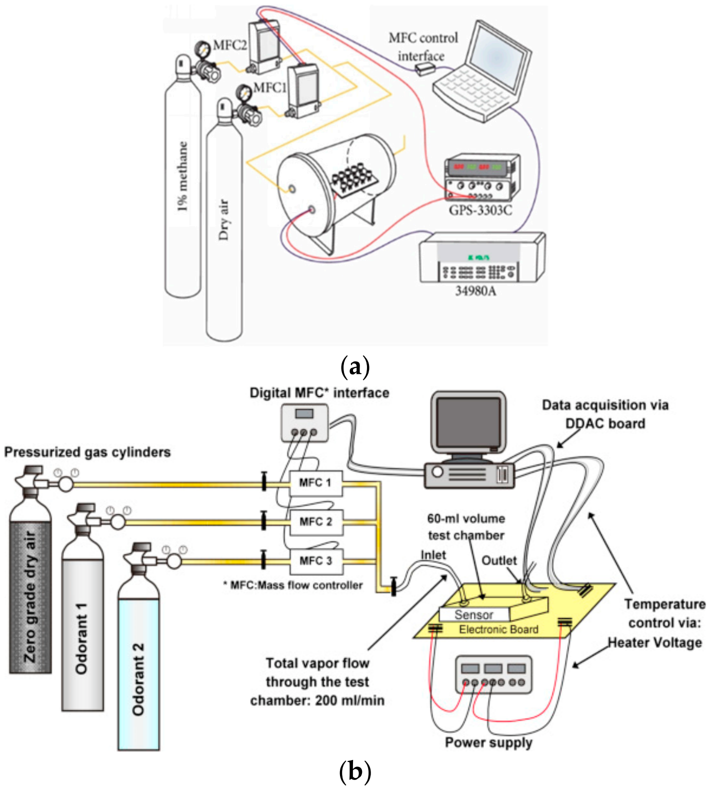

Figure 24. The Computer Supervised AQGS Testing Systems [119,121]. (**a**) AQGS Array Testing and Calibration System [119]. (**b**) The ENB Testing and Calibration System [120].

In Figure 24 (a), the sensor array was placed in a test chamber with a volume of 20 L, composed of ten metal oxide semiconductor gas sensors TGS 2620 by Joanna et al. [119]. The sensor array resistances were acquired by a half-bridge configuration and collected by a multifunction switch/measuring unit 34980A via an electrical interface on the chamber. The gas mixture, based on PID experimented by Jordi et al. [120] and using the dynamic response of each sensor, was recorded at a sample rate of 100 Hz. In this chamber, the RH (0~10%) was varied and captured using a 16-channel ADC. The time-series sequence for entire dataset from 16 channel acquisition system from sensors in the given order, i.e. (CH0-CH15): TGS2602; TGS2602; TGS2600; TGS2600; TGS2610; TGS2610; TGS2620; TGS2620; TGS2602; TGS2602; TGS2600; TGS2600; TGS2610; TGS2610; TGS2620; TGS2620. This discussion will follow a sub-type capacitive bio-sensors (the first type of bio-sensors), further trimmed down to branch bio-sensors based on contactless capacitive electrodes.

7.3. IoT-based Networked Multi-Gas ENB Calibration

In 2020, the most recent state of the smart gas sensors calibration test rig appeared in literature by Mohieddine A. Benammar et al. [122] presented in Figure 25 (a). In Figure 25 (a), Smart TestRig took account of all the major improvements recommended in studies by Maag, B. et al. [123] for gas sensor calibration in air monitoring deployments.

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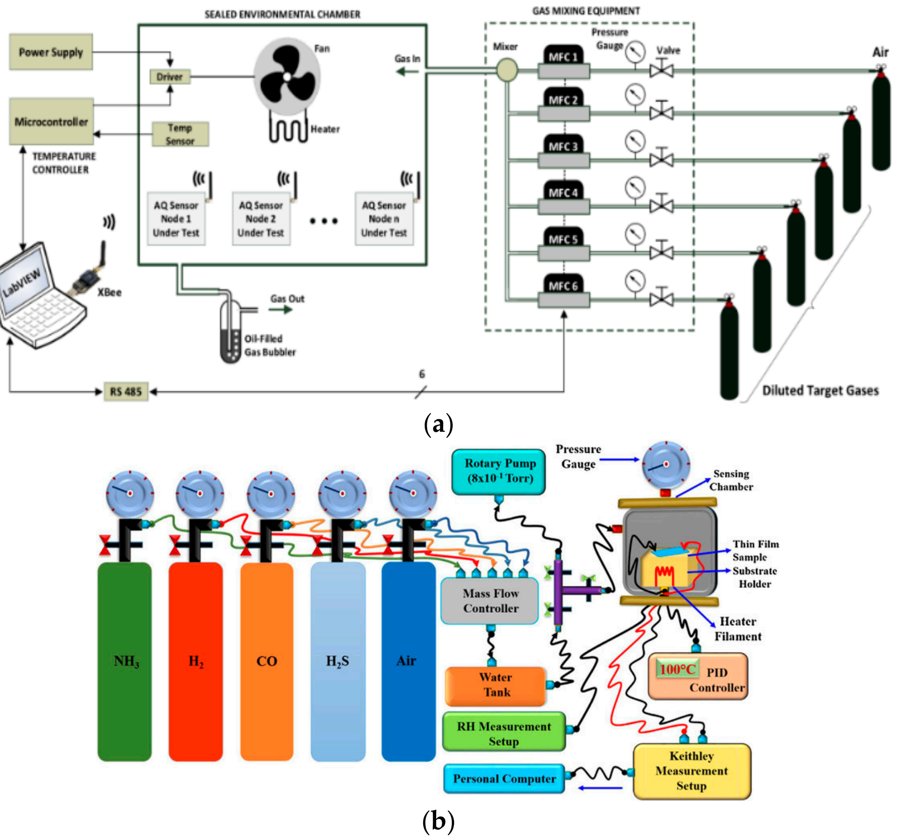

Figure 25. The Controlled Environment Heterogeneous AQGS Testing Systems [119,121]. (**a**) IoT based Smart AQ GSA Testing and Calibration System [121]. (**b**) Air Quality Mesh Network Testing and Calibration System [130].

The Smart AQ GSA test rig by Mohieddine A. Benammar et al. in Figure 25 (a) was developed considering the recommendations in gaps in Spinelle, L. et al. [124] to present field calibration of a cluster of low-cost available sensors for air quality monitoring using O3 and NO2. Mijling, B. et al. [125] worked on field calibration of electrochemical NO2 sensors in a citizen science context. Hagan et al. [126] present calibration and assessment of electrochemical gas sensors by co-location with regulatory-grade instruments; Hasenfratz. D. et al. [127] for on-the-fly calibration of low-cost gas sensors; Yang, F. et al. work [128] introduced dynamic calibration of electrochemical gas sensors for accelerated analytic quantification; Tian, B. et al. [129] proposed an environment-adaptive calibration system for indoor low-cost electrochemical gas sensors.

7.4. Climate Smart Heterogeneous ENB Calibration

In Figure 25 (b), Arvind et al. [130] performed the entire testing and calibration of several gas sensors using a custom sensing chamber (volume ~300 cm3), PID controller electric heater. The gases were individually mixed with dry synthetic air and introduced inside the test chamber at the controlled flow rate of 50 cm3/min. One of the core innovations in this work was an evacuation pump scheme with 8×10−1 Torr using a rotary vacuum pump. In the next generation, testing calibration systems curve fitting and error proportionalities performed for porous silicon filled Pd/SiC nano-cauliflower thin films for high-performance H2 gas sensors as an example by Arvind Kumar et al. [130] presented in Figure 25 (b). The comparison for the four calibration approaches is given in Table 4.

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Table 4. Indoor Epidemiological Scalability of and Calibration Approaches.

Indoor Epidemiological Merits	Uni-Gas Uni-Sensor Calibration	Uni-Gas Multi-Sensor ENB Calibration	IoT-based Networked Multi-Gas ENB Calibration	Climate Smart Heterogeneous ENB Calibration
Calibration Scale (per 24 hours)	1-24	10-120	10-1840	10-144
System Setup Cost (per 10 sensors)	$2~5.1M	$0.4~2M	$1~1.8M	$4~7M
Types of Sensors Supported	4	**4**	**5**	**5**
IoT Support and Remote Calibration	No	**No**	**Yes**	**No**
Calibration Cost (per 10 sensors)	$3-10	**$12-19**	**$2-8**	**$35-120**
Real-time AQI based Climate Focused Calibration	**No**	**No**	**No**	**Yes**
ML/DL Model-in-Loop Support	No	**No**	**Yes**	**No**

8. Indoor Epidemiology and Diseases

Acute respiratory infections, TB, asthma, chronic obstructive pulmonary disease, pneumoconiosis, head and neck malignancies, and lung cancer have all been linked to indoor pollution exposure [131]. The direct relationship presented in the relevant works has been comprehended in the Table 5 given below.

Table 5. Epidemiological Relationship between IAQ and Health Issues [131–147] .

#	Indoor Pollutants	Indoor Diseases and Health Problems
1	PM2.5 and PM10 [131–135]	heart or lung illness, nonfatal heart attacks, irregular heartbeats, worsened asthma, impaired lung function, and a rise in respiratory symptoms including coughing or trouble breathing.
2	NO2 [136–139]	At high quantities, it shortens breath and irritates the mucous membranes of the nose, throat, and eyes. Long-term inhalation of nitrogen dioxide can cause lung damage. It could result in persistent bronchitis. Those who have asthma and chronic obstructive lung disease may experience worsening symptoms from exposure to low levels (COPD). Also, it could make other respiratory illnesses worse.
3	CO [137–141]	Chronic headaches, nauseousness, stomach discomfort, vomiting, weakness, dizziness, fainting, confused mental neural response, exhaustion, loss of consciousness, seizure, and irreversible brain damage are some of the symptoms. In the worst scenarios, death is also conceivable.
4	CO2 [140–143]	respiratory tract infections, chronic obstructive pulmonary disease (COPD), asthma, and rhinosinusitis.
5	VoCs [144–147]	Some VOCs are known or suspected carcinogens. inflammation, including irritation of the eyes, nose, and throat; headaches and lack of coordination; nausea; liver, renal, or central nervous system damage.

The death statistics presented in different global studies and state agencies like WHO and NIH associated with indoor pollutants with their order of instensity are summarized in the Table 6 as:

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Table 6. Annual fatality statistics for indoor pollutants' induced diseases [147–171].

%	Indoor Pollutants	Indoor Diseases and Health Problems
32%	Ischemic heart disease [147–151]	Affects 32% of people. Exposure to home air pollution is responsible for 12% of all fatalities from ischemic heart disease, or more than a million premature deaths yearly.
23%	Stroke [152–156]	Accounts for 23% of deaths, with usage of solid fuels and kerosene in the home contributing to household air pollution on a regular basis, accounting for around 12% of all stroke deaths.
21%	Pneumonia and Low Respiratory Infections (LRI) [157–164]	LRIs account for 21% of fatalities, and exposure to indoor air pollution nearly doubles the risk of childhood LRI and accounts for 44% of all pneumonia-related deaths in children under the age of five. Adults who have acute LRIs are at danger from household air pollution, which also causes 22% of all adult fatalities from pneumonia.
19%	Chronic obstructive pulmonary disease (COPD) [164–168]	Accounts for 19% of cases. In low- and middle-income nations, exposure to home air pollution is to be reason for 23% of all fatalities from COPD in adults.
6%	Lungs Cancer [147–151]	6% of lung cancer-related fatalities in adults are linked to exposure to carcinogens from home air pollution brought on by the use of kerosene or solid fuels like wood, charcoal, or coal. This exposure accounts for around 11% of lung cancer deaths in adults.

9. Indoor Epidemiological Merits in Operational and Lifecycle Cost Evaluation of Low-Cost AQ Sensors

Evaluation of AQ sensors only on basis of costs is not enough. The overall lifecycle cost of entire AQ sensor is the key concern of researchers, manufacturers, AQ and EPA stakeholders. There are five factors to the lifecycle cost assessment of the AQ sensors is presented in Table 7.

Table 7. Real-time Operational Capabilities and Lifecycle Cost Evaluation [172–193].

USD ($)	Rooms Monitored (>100)				GSA/GSG Assemblies (>10X)			
Cost Elements	**OGS**	**ECS**	**CGS**	**MOS**	**OGS ENB**	**ECS ENB**	**CGS ENB**	**MOS ENB**
Lifeline Cost (K) [172–175]	10	1.5	17.1	3.7	3.5	0.7	1.3	0.4
Manufacturing Setup Cost (M) [69–95,176]	23~40	18~29	7~13	33~80	13~17	8~11	9~10	3~5
Calibration Cost (K) [177–180]	17	**12**	**19**	**4**	**29**	**15**	**9.5**	**1.4**
Adaptation Cost (K) [19,181–184]	30	**7**	**5**	**2**	**12**	**3**	**1.1**	**0.3**
Sampling Rate Upgrade Cost (K) [45–58,185–188]	3	**11**	**9**	**1.2**	**0.2**	**0.9**	**0.3**	**0.12**
Networked Sensing Cost (K) [189,193]	1	**1**	**1**	**1**	**1.7**	**0.1**	**0.1**	**0.1**
Real-time AQI Mapping Cost (K) [184–193]	0.7	**2.3**	**3.7**	**1.3**	**0.5**	**1.6**	**9.5**	**0.09**

The key challenges low-cost sensors utilization in the study of air quality measurement, assessment, systems, and their life-cycle were elaborated in this work in a systematic portrait with state-of-the-art contributions by researchers around the world. This research served its purpose

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10. Conclusions

The key challenges of low-cost sensors utilization in the study of air quality measurement, assessment, and their life-cycle were surveyed. The effective assessment techniques at urban and regional level are critical to determine accurate air quality status. Accurate detection of indoor air pollutants, VoCs, and PM2.5 requires the selection of appropriate sensors and sensors' systems. Tactical and strategic orientation of sensors assemblies and arrays could support a great deal in overcoming critical challenges for indoor applications, including sensors-on-chip technology which assisted in meeting cutting edge market needs. In addition, multi-parametric and dedicated sensor testing and calibration systems gave better insights of operational, measurement, and transient anomalies. It was found that the usage of abstract key performance indicators in evaluating sensing and calibration was swift and effective. Moreover, the application of machine learning based signal processing techniques and approaches gives a thrust in improving the accuracy and credibility of air quality measurements. The utilization of higher number of key performance indicators showed to increase the reliability of air quality assessment outcomes and associated mitigation strategies. Nonetheless, this survey revealed the need to investigate the synergy between indoor and ambient indoor air pollutants. Also, further study is needed on modeling of indoor air pollutants (e.g. SO_2, NO_2, O_3, PM) propagation to urban residential areas in correlation with the climatic factors such as wind speed and direction and RH. More efforts targeting measurement accuracy, scalability, and cost-effectiveness using advances hardware and data analysis techniques are further required.

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