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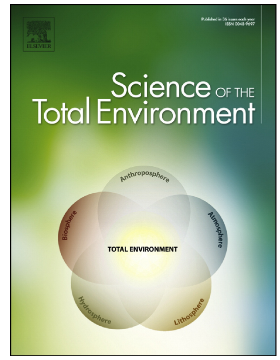

Development of low-cost indoor air quality monitoring devices: Recent advancements

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Development of low-cost Indoor Air Quality monitoring devices: Recent advancements

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Abstract

The use of low-cost sensor technology to monitor air pollution has made remarkable strides in the last decade. The development of low-cost devices to monitor air quality in indoor environments can be used to understand the behaviour of indoor air pollutants and potentially impact on the reduction of related health impacts. These user-friendly devices are portable, require low-maintenance, and can enable near real-time, continuous monitoring. They can also contribute to citizen science projects and community-driven science. However, low-cost sensors have often been associated with design compromises that hamper data reliability. Moreover, with the rapidly increasing number of studies, projects, and grey literature based on low-cost sensors, information got scattered. Intending to identify and review scientifically validated literature on this topic, this study critically summarizes the recent research pertinent to the development of indoor air quality monitoring devices using low-cost sensors. The method employed for this review was a thorough search of three scientific databases, namely: ScienceDirect, IEEE, and Scopus. A total of 891 titles published since 2012 were found and scanned for relevance. Finally, 41 research articles consisting of 35 unique device development projects were reviewed with a particular emphasis on device development: calibration and performance of sensors, the processor used, data storage and communication, and the availability of real-time remote access of sensor data. The most prominent finding of the study showed a lack of studies consisting of sensor performance as only 16 out of 35 projects performed calibration/validation of sensors. An even fewer number of studies conducted these tests with a reference instrument. Hence, a need for more studies with calibration, credible validation, and standardization of sensor performance and assessment is recommended for subsequent research.

Keywords: low-cost sensors, sensor development, sensor specifications, indoor air quality, air quality monitoring

1. Introduction

The right to breathe healthy air is a fundamental right for all. This right is violated every day as 90% of the world's population breathes polluted air, causing 7 million deaths annually (WHO 2018b). While there are a high number of studies focusing on outdoor air pollution and its adverse impacts on human health (Ostro et al. 2018, WHO 2018a), poor indoor air quality (IAQ) may be equally damaging, if not more, as humans spend nearly 90% of their time indoors (Klepeis et al. 2001). Therefore, monitoring air pollutants is of high significance in indoor environments like homes, hospitals, offices, museums, among others (David and Seter 2019, Dzullkiflli et al. 2018, Sánchez-Barroso and García Sanz-Calcedo 2019). WHO guidelines of selected pollutants for IAQ include: benzene, carbon monoxide (CO), formaldehyde, naphthalene, nitrogen dioxide (NO_2), polycyclic aromatic hydrocarbons (PAHs) (specifically, benzo[a]pyrene), radon, trichloroethylene, tetrachloroethylene, $PM_{2.5}$ and PM_{10}. Although not mentioned by WHO in the list of selected pollutants, ozone is considered as a pollutant at ground-level atmosphere (troposphere), whose high concentrations in indoor environments like schools and offices have been reported in the literature (Salonen et al. 2018, Lee et al. 2004). Carbon dioxide (CO_2), while also not included in the list of selected indoor pollutants by WHO, has been used as a surrogate of air ventilation where high CO_2 concentrations imply poor ventilation, which might indicate accumulation of indoor pollutants (Salthammer et al. 2016, Branco et al. 2019, Griffiths and Eftekhari 2008).

Due to the plethora of potential pollutants that might arise in high concentrations in indoor environments, air quality monitoring becomes indispensable. Traditional approaches to air pollution monitoring use high cost, complex, stationary devices, which puts a limit on the data access, application flexibility, and overall budget. In the last decade, low-cost sensor technology has made remarkable strides to monitor air pollution, giving the opportunity of changing this status quo (Snyder et al. 2013).

As an emerging technology, it is essential to define what exactly is meant by low-cost air sensors firstly. The review article by Rai et al. (2017) acknowledged the lack of any universally agreed definition. It stated, “anything costing less than the instrumentation cost required for demonstrating compliance with the air quality regulations can be termed as low-cost”. They ended up using the term low-cost for sensors costing a few 10’s of US dollars in their article. Morawska et al. (2018) defined low-cost air pollutant sensors as “technologies which promise a revolutionary advance in air quality monitoring, through massive increases in spatial and temporal data resolution, thus providing answers to scientific questions and applications for end users” and used the term low-cost sensor for sensors costing less than 100 US dollars. This definition is in-line with the paradigm shift vision described by the United States Environmental Protection Agency (U. S. EPA) (Snyder et al. 2013). It can be achieved if sensors of lower-cost are deployed in abundance.

Low-cost air quality sensors can be used to economically analyse air quality in near real time. User-friendly interface and low maintenance requirement makes them an easy-to-use and convenient device (Castell et al. 2013). Scalability of pollutant detection is also an advantage and can supplement the already existing air quality monitoring networks (Castell et al. 2013, Thompson 2016, Santos et al. 2018). Their portability allows personal pollutant monitoring and, subsequently, one can choose less polluted routes while commuting (Castell et al. 2013). The use of low-cost sensors also makes room for citizens to engage in community-driven science, i.e., people can contribute by collecting air quality data (Snyder et al. 2013, White et al. 2012, Thompson 2016).

Low-cost sensors have associated weaknesses. Cheap devices can be accompanied by flaws in their design, which can lead to a lack of reliability of data. Sensors based on electrochemical cell (EC) and metal oxide semiconductor (MOS), which are the two most prevalent technologies used to make low-cost gas sensors, usually suffer from high cross-sensitivity, interference from other pollutants, require frequent recalibration and short lifetime (White et al. 2012). They are also sensitive to changes in ambient conditions and suffer from a drift in calibration over some time (Peterson et al. 2017, White et al. 2012, Morawska et al. 2018). The manufacturing process of the MOS sensors result in differences in the reactivity of the metal oxide substrate of individual sensors. Thus, they have weak reproducibility and are prone to inter-sensor variability (Zhang et al. 2014, Peterson et al. 2017). The low-cost PM sensors that are based on light-scattering technology have two major challenges associated: i) they are not a direct mass measurement technology; and ii) they cannot detect ultrafine particles, i.e., their limit of detection are particles with approximately 0.3 μm diameter, below which particles do not scatter enough light (White et al. 2012, Koehler and Peters 2015).

With the rapidly increasing number of studies, projects and grey literature based on low-cost sensors, information got scattered. Although there were some review publications related to low-cost sensors and IAQ (Kumar et al. 2016a, Kumar et al. 2016b, Thompson 2016, Morawska et al. 2018), as far as the authors' knowledge goes, there was no review study published focusing on the studies that specified the characteristics of low-cost IAQ monitoring device development, such as: i) integration of relevant low-cost sensors; ii) processor for data acquisition; iii) analogue to digital convertor for the measurements; iv) data logging and transmission; v) software layer; vi) hardware enclosure; and vii) device performance assessment. It is a crucial but overlooked gap in the literature and this study aims to review the components used by various studies while developing a novel IAQ monitoring device and evaluate which components (especially sensors) perform the best. Therefore, the present systematic review intended to identify scientifically-validated literature on the development of low-cost IAQ monitoring devices with emphasis on the above-referred characteristics, as well as on sensor specifications.

This study is organized as follows. Section 1 provides an introduction and discusses the background of the study. Section 2 describes the review methodology. Section 3 presents the results and discussion along with the review table of the study, which is further divided into two parts: Section 3.1 device development results, and Section 3.2 sensor performance results. Finally, Section 4 consists of the discussion on critical conclusions and future outlook.

2. Methodology

The present review includes studies published from 2012 to May 2019 in the following databases: ScienceDirect, IEEE *Xplore*, and Scopus. Although there were no language restrictions imposed during the search, all publications obtained from the search were in English. With no previous review articles on this topic, an exhaustive search was done, and published research and conference articles were both included.

The keywords used were: i) low-cost "Indoor Air Quality" monitoring device, ii) low-cost "Indoor Environmental Quality" monitoring device, and iii) low-cost "Indoor Air Pollution" monitoring device. A total of 891 publications were found with potential interest from the initial search and their titles were screened based on their context of research. As an example, the publications not delving into device development were eliminated. From those, 99 publications remained and their abstracts were appropriately reviewed. After this, exclusions were performed based on the following criteria: i) devices measuring only temperature and relative humidity were excluded; ii) devices measuring only a single pollutant were excluded; iii) IAQ monitoring of indoor environments such as offices, homes, classrooms, hotels were included, but for mines, quarries, subway stations, greenhouses, etc. were excluded; and iv) publications that did not develop their monitoring device were excluded. Multiple publications of the same device (same project and authors) were clubbed together, or only one of them with the complete information regarding device development was included. Using these criteria, 59 abstracts were excluded. Four additional relevant articles were found while reading the selected 40 publications. After rejecting three publications that didn't have enough information regarding device development and clubbing the articles of the same project, 35 total projects were reviewed in detail, corresponding to 41 publications. Figure 1 shows the flowchart with the number of studies identified and included/excluded.

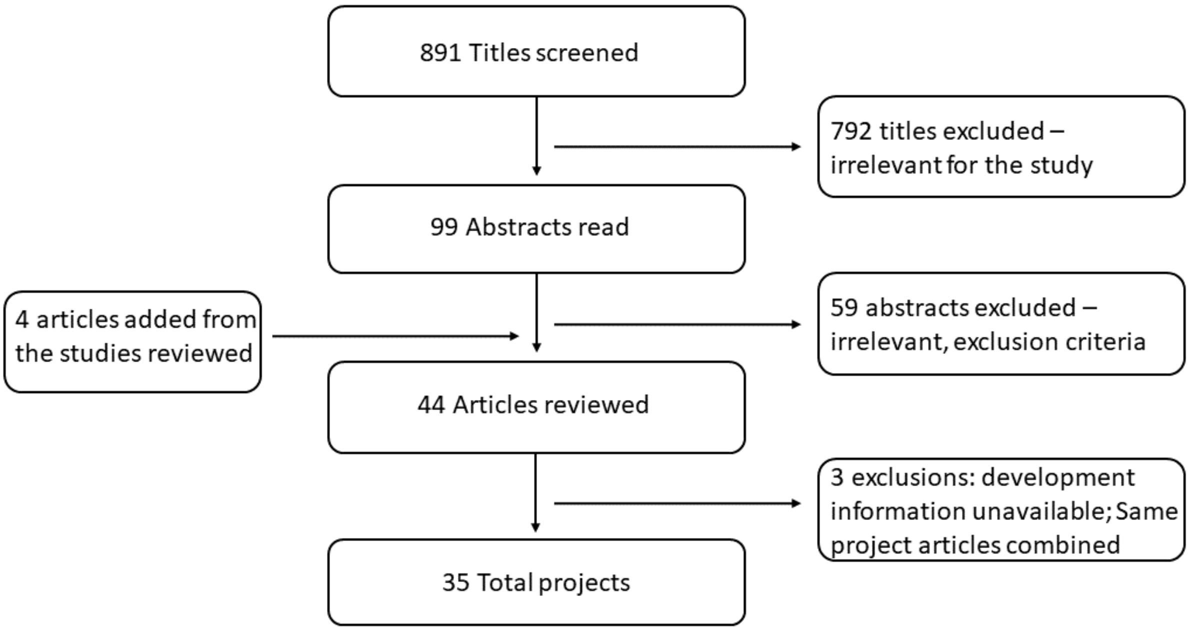

Figure 1. Systematic review flowchart.

3. Results and discussion

The review of the 35 projects was divided into two major parts: i) the first part focusing on device development phase, which included description of sensors, hardware and software details of the device including data communication protocol and total cost of the device (Table *1*); and ii) the second part focusing on sensor performance, which included calibration and/or validation outcomes of the sensors. The latter was performed by 16 out of 35 projects (Table *2*).

3.1 Device development

The reviewed studies were globally distributed and not concentrated in a specific region. Figure *2* shows the geographical distribution of the reviewed projects. Although there were more studies from U.S.A (8) than from any other country, there were a total of 13 studies from Asia, 8 from Europe (including U.K.), 3 from Oceania, 2 from the Middle East, and 1 from South Africa.

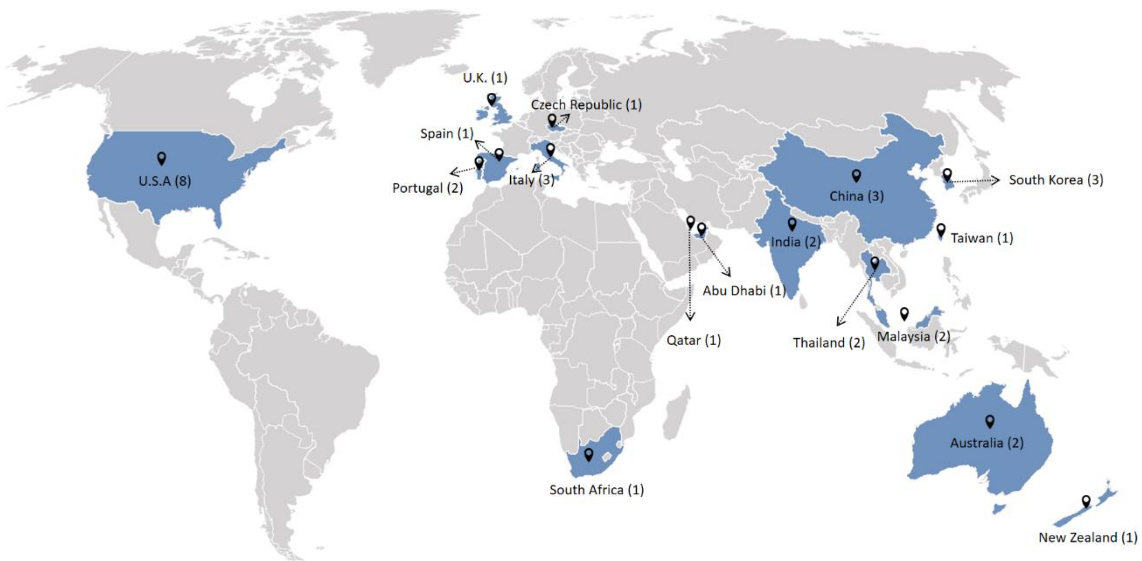

Figure 2. Geographical distribution of the reviewed projects on the world map.

The relevant projects identified were only from 2014 onwards, although the year-range of the present study was 2012-2019, as mentioned in the methodology section. The majority of projects, i.e., 26 out of 35, were published in the last three years (2017-2019).

Most of the projects mentioned buildings or general indoor environment monitoring as their intended application, but there were studies that aimed for specific applications, namely: IAQ monitoring of classrooms (Wang et al. 2017, Sharma et al. 2017), hospitals (Yang et al. 2014, Lasomsri et al. 2018), personal monitoring (Smith and Li 2016, Cho 2016), smart cars (Peng et al. 2017), and for asthma trigger assessments (Teixeira and Postolache 2014). A lack of other relevant IAQ applications such as households in low-income countries, museums or airports was observed. However, the above-referred environments have been mentioned in the literature as potential sites of high indoor air pollutants (David and Seter 2019, Dzullkiflli et al. 2018, Sánchez-Barroso and García Sanz-Calcedo 2019).

The indoor air parameters monitored varied from study to study. The number of projects considering each monitoring parameter is represented in Figure *3*. The majority of projects included only sensors to monitor temperature, relative humidity (RH) and CO_2. Although not a pollutant per se, CO_2 is an important parameter to measure indoors, especially in spaces like offices and classrooms (Branco et al. 2015). CO was the next most frequent indoor air parameter evaluated (in 43% of the devices), followed closely by Volatile Organic Compounds (VOC) (37%). Despite being an important indoor air pollutant and widely studied (WHO 2006, Sousa et al. 2012, Nunes et al. 2015), the inclusion of PM sensors was surprisingly lower, as only 20 projects included them, having less than 10 projects included a $PM_{2.5}$ sensor and even fewer studies (6) included a PM_{10} sensor. The other 5 studies added a PM sensor but did not define the PM size fraction being measured ($PM_{unspecified}$ in Figure *3*). Emphasis on formaldehyde monitoring was even scarcer as only 4 projects had a formaldehyde sensor in their device. Ozone and NO_2 measurements were also sporadic with less than 10 projects, including the pertinent sensors. The remaining studies measured ammonia (3 projects), and benzene, toluene, and NO_x (1 project each). None of the projects included a sensor for naphthalene, PAHs, trichloroethylene, tetrachloroethylene, and radon even though they are relevant pollutant described by WHO. Kumar et al. (2016b) also mentioned the significance of these parameters in their review article on real-time indoor air monitoring sensors for urban buildings that were found to be left out by all the projects covered in this review.

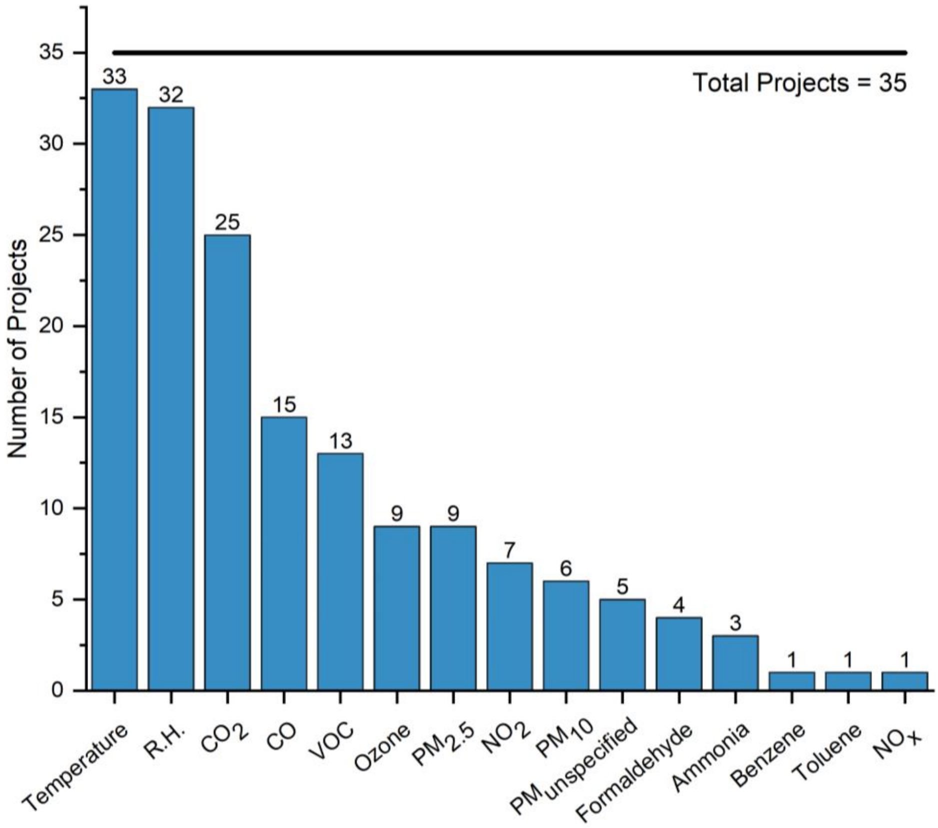

Figure 3. Monitoring parameters included in the 35 reviewed projects.

From the projects that disclosed the sensing principle of the sensors used, thermistors were the most recurrent technology choice for temperature monitoring, and capacitive sensor technology was used most commonly to monitor RH. Most of the CO_2 sensors were based on nondispersive infrared (NDIR) technology. All reported PM sensors were optical particle counters based on light scattering technology. CO sensors were based on either MOS or EC technology. Most of the VOC and formaldehyde sensors were based on MOS technology. Cross-sensitivity is a critical issue associated with these sensors. Still, these studies neither mentioned nor tested the results from their MOS sensors for cross-sensitivity with non-target gases, i.e., gases that the sensor wasn't designed to measure. In long term monitoring campaigns, this disregard for cross-sensitivity tests can lead to increasing inconsistencies in sensor performance (Peterson et al. 2017).

SHARP's GP2Y1010AU0F was mentioned to monitor PM_{10} in some publications and $PM_{2.5}$ in others. Further, some studies just mentioned it to be monitoring PM (unspecified size fraction). It was the most common choice in the reviewed studies for PM monitoring, although Wang et al. (2017) tested the accuracy of this sensor and found that it lacked long term stability and accuracy and chose another sensor for their device – Plantower Technology's PMS3003. There were some discrepancies noticed in the description of sensor nodes: i) MQ-135 was mentioned as a benzene sensor by one study (Zakaria et al. 2018) and as a CO_2 sensor by another (Sharma et al. 2017); and ii) Marques and Pitarma (2019) used a single, highly cross-sensitive MOS sensor to measure 8 gases. Further, they didn't mention any calibration methods used or any reference instrument for validation of the sensor. In contrast, He et al. (2017) used a sensor array of multiple cross-sensitive MOS sensors and developed a pattern recognition algorithm to identify target gases with precision.

Arduino, Raspberry Pi, and ESP8266 were the most frequently opted microcontroller units (MCUs). Wireless networking was commonly implemented using WiFi, ZigBee, Bluetooth, and Global System for Mobile Communications (GSM). Chanthakit and Rattanapoka (2018) implemented Message Queuing Telemetry Transport (MQTT) network protocol for their device and Vcelak et al. (2017) tested LoRa, Sigfox and IQRF technologies for wireless data communication. Quan Pham et al. (2019) developed an Electromagnetic Interference (EMI)-free real-time monitoring system by designing a visible light communication (VLC) system, which is an emerging technology for high-speed data communication system.

Data storage is a quintessential part of a monitoring device. The rapid and consistent growth of cloud servers was evident from the result of this review as 20 projects were equipped with both the ability to remotely access the sensor data in real-time (via mobile or web application) and online historical data storage. Real-time remote access is a feature that can find its use not only in remotely monitoring the air quality post-development, but also to check if the devices are working correctly during the calibration and validation phase. Seven projects had both online and offline (on-board) storage, while merely 5 projects stored data only offline. The remaining 10 projects didn't mention any specific details about data communication or storage. Morawska et al. (2018) studied the applications of low-cost sensing technologies and mentioned that data protection criteria could lead to the exclusion of cloud-based wireless networks if they don't comply with data security legislation. But neither can the significance of historical data storage be neglected. Striking the right balance between data storage and data security needs to be found. An emphasis on offline data storage is crucial in cases where data security can be a potential concern.

Eleven projects estimated the total cost of their device excluding the labour cost (values are shown in Table 1; currencies were converted to euros; conversion rates on 19th January 2020). Any cost-based comparison should be made with caution, because the studies used a various number of sensors, implemented different communication networks, monitored different IAQ parameters, and used sensors from different sensor manufacturers for most parts. For these reasons, the total costs varied from as little as around 54 € (Marques and Pitarma 2019) to as high as almost 2700 € (Gillooly et al. 2019).

The reviewed projects had heterogeneous development focus and design phase outcomes. Benammar et al. (2018) used an algorithm to resubmit unsuccessfully transmitted data packets in their wireless communication system. This helps avoid any packet loss and, consequently, any sensor data loss. Salamone et al. (2017b) used thermal analysis to detect temperature distribution near the device. This can help avoid errors in working conditions by providing an idea of how far the sensors should be placed from the device electronics to avoid elevated temperature and decreased humidity as the sensors can give unrepresentative values of the surroundings due to the equipment heat. Wang et al. (2017) developed their prototypes named SKOMOBO, whose level of noise generation was stated to be lower than that of a computer, which is an essential aspect in IAQ monitoring, especially in environments such as offices, classrooms, hospitals, etc. Tran et al. (2017) developed a battery-free device that was based on ultra-low-power sensors and MCU, and a radio frequency energy harvester. This was the only study analyzed in the present review that developed a device that could work without any direct source of power or battery. Cho (2016) created interesting device designs: i) a wall-clock like Personal Environmental Monitoring System (PEMS) and ii) a wrist-watch like Wearable Environment Monitoring System (WEMS). Teixeira and Postolache (2014) developed a web-based information system *Enviogis* capable of importing indoor or outdoor air quality data and "breath parameters" of the room occupants. Their goal was to assess asthma trigger factors and this system helped them correlate air quality conditions and respiration activity. Hence, several projects showcased uniqueness in design during the development phase.

An explanation of the vast diversity of technologies observed can paradoxically be the question posed by Morawska et al. (2018): "Are these technologies fit for the various purposes envisaged?" Several projects do justify their choice of technologies and device designs. For example, SKOMOBO prototypes were designed to be used in school classrooms and can monitor with minimal noise (Wang et al. 2017). The sleek design of SAMBA prototypes can be attributed to its end-use as an office monitoring device (Parkinson et al. 2019a), and Cho (2016) used micro-sensors for their very small watch-like WEMS.

Table 1. Summary of the device design characteristics and main conclusions of the reviewed research studies.

Study	Location	Objectives	Intended Application	Monitoring Parameters	Sensor Description	Sensing Principle	Processor and Data Acquisition & Communication	Estimated Device Cost‡	Design outcomes
(Gillooly et al. 2019)	Boston, MA, USA	To develop a comparatively lower-cost, portable, in-home air sampling platform and a guiding development and maintenance workflow to characterize key indoor pollutants	To characterize key indoor pollutants with high sensitivity and reasonable accuracy.	CO NO NO_2 $PM_{2.5}$ $PM_{2.5}$ Temperature Temperature RH Noise CO_2	Alphasense COB4 Alphasense NOB4 Alphasense NO2B43F Alphasense OPC-N2 Harvard miniPEM Onset Temperature Sensor Netatmo Weather Station Netatmo Weather Station Netatmo Weather Station Netatmo Weather Station	EC[a] EC EC Optical† N/A N/A[b] N/A N/A N/A N/A	**Processor**: Not mentioned **Data**: Not mentioned (Cloud based wireless networks not chosen because of data security issues)	Around 2700 €	• More money was spent on maintaining the sensors than on buying them • Power consumption of the device: 0.35 kWh in one week • Lack of built-in power supply was identified as a shortcoming in case there is unavailability of outlets, or power interruption episodes
(Marques and Pitarma 2019)	Guarda, Portugal	To develop iAir system: an IAQ monitoring solution based on the Internet of Things (IoT) composed of a hardware prototype for environment sensing and web/smartphone interface for data access	Indoor Air Quality (IAQ) monitoring in home in real time.	CO NO_2 Ethanol H_2 Ammonia CH_4 C_3H_8 C_4H_{10}	MICS 6814 MICS 6814 MICS 6814 MICS 6814 MICS 6814 MICS 6814 MICS 6814 MICS 6814	MOS[c] MOS MOS MOS MOS MOS MOS MOS	**Microcontroller**: ESP8266 **Data**: Cloud storage and real-time remote access, via Thingspeak (server and cloud platform)	54 €	• iAir has low cost, easy installation, configuration, and full compatibility with homes with internet access and a phone • It needs experimental validation to improve system calibration and accuracy
(Parkinson et al. 2019a, Parkinson et al. 2019b)	Sydney, Australia	• To review relevant industry standards and guidelines regarding instrument specifications and measurement protocols	IEQ monitoring of offices with major focus on hardware design and testing the device performance.	Temperature RH Globe Temperature Air Speed CO_2	N/A N/A N/A N/A N/A	Thermistor Capacitive Thermistor Anemometer NDIR[d]	**Microprocessor:** ARM Cortex **Data:** On-board storage, Cloud storage and	Total sensors cost only: 198 €	• This study recognized a lack of guidance on sampling procedures or measurement protocols to ensure fair and reliable representation of measured IEQ

		of building Indoor Environmental Quality IEQ performance assessment • To build and test the performance of a low-cost IEQ monitoring system (100 devices developed and tested)		CO PM_{10} Formaldehyde TVOC[e] Sound Pressure Illuminance	N/A N/A N/A N/A N/A N/A	EC N/A EC Photoionization Microphone Photodiode	real-time remote access; WPAN for remote access Data transmission using LTE to cloud server		parameters
(Quan Pham et al. 2019)	Busan, South Korea	To design a bidirectional visible light communication (VLC) system prototype to serve as a remote sensing data acquisition for indoor environments.	General IAQ monitoring with major focus on developing an Electromagnetic Interference (EMI) free device by replacing radio frequency with VLC technology for wireless communication.	Temperature RH O_2 CO_2 VOC[f]	HDC1080 HDC1080 Grove-Gas sensor CCS811 CCS811	N/A N/A N/A N/A N/A	**Microcontroller:** STM32F4 Discovery **Data:** Cloud storage and real-time remote access: Wireless communication via VLC *SpeakThing* platform	N/A	• The implemented VLC technology could successfully communicate sensor data acquired from indoor environments
(Yang et al. 2019, Yang et al. 2014)	Taiwan	To develop the prototype for real time access in OpenStack as cloud computing application, and a distributed computing environment based on Hadoop. To develop the service to connect back-end and front-end HBase data.	General IAQ monitoring device with a focus on system architecture and implementation on cloud (data collection and storage) Their 2014 research was for IAQ monitoring of hospitals.	Temperature RH Formaldehyde VOCs CO CO_2 Temperature RH CO_2 (in 2014)	Series WHT Series WHT CTX300 OLCT 100XP OLCT 20D ZGw08VRC N/A	N/A N/A N/A N/A N/A N/A N/A	**Processor:** not mentioned **Data:** Cloud storage and Real-time remote access Data stored via Zigbee WSN technology into Hbase database system	N/A	• This study implemented cloud storage with real-time data collection, built a platform iDEMS for data processing, and used Thrift to connect back-end and front-end for information monitoring • Time effectiveness comparison in Linux showed Hbase has better performance than MySQL

(Wang et al. 2017, Wang et al. 2018)	New Zealand	To develop and test a low-cost, low power consumption indoor environment monitoring instrument, called SKOMOBO (school monitoring box)	IAQ monitoring box for schools with a focus on developing prototypes and validating against reference instrument in controlled and uncontrolled environments.	Temperature RH CO_2 $PM_{2.5}$ PM_{10} Occupancy	TELAiRE T9602 TELAiRE T9602 SenseAir K30 PMS3003 PMS3003 TB-XC4444	Capacitive Polymer Capacitive Polymer SenseAir K30 Optical (Laser light) Optical Passive Infrared	**Microcontroller:** Arduino Pro Mini **Data:** On-board storage, Real-time remote access Arduino Pro Mini was connected to a Node.js server via a wireless module	266 €	• Choice of CO_2 and PM sensors was based on a prior shortlisting and testing of different sensors. The sensors showing high consistencies were selected. • The enclosure for the prototype was a 3mm thick clear acrylic and was built using software SOLIDWORKS
(Benammar et al. 2018)	Doha, Qatar	To develop a distributed modular IAQ monitoring system using sensors nodes for air quality parameters, a WSN, and an IoT server; Gateways to ensure that data is transmitted without packet loss.	General IAQ monitoring with major development focus on IoT functionality.	SO_2 NO_2 O_3 CO_2 CO Cl_2 Temperature RH	4-SO2-20 4-NO2-20 OX-A431 INE20-CO2P-NCVSP 4-CO-500 4-Cl2-50 BME280 BME280	EC EC EC NDIR EC EC N/A N/A	**Microcontroller:** Raspberry Pi 2 model B **Data:** On-board storage, Cloud Storage and real-time remote access; On-board network: Ethernet Port Radio gateway: XBee Pro	N/A	• The radio communication reliability between sensors, gateways, and internet communication between the gateways and servers was found • The system modularity allows a large number of sensors to be added to the system
(Martín-Garín et al. 2018)	San Sebastian, Spain	To build a monitoring prototype to track the environmental conditions of buildings and to make it applicable to other smart environments, and to provide implementation in a real case	IAQ monitoring of buildings with major focus on developing a device prototype, calibrating sensors, and using it in a building as a case study.	Temperature RH Temperature RH Temperature Pressure Temperature	DHT22 SHT21 BMP180	Thermistor Capacitive Band Gap Capacitive N/A	**Microcontroller**: ESP8266 **Data**: On-board storage, cloud storage and real-time remote access;	90 €	• The prototype developed can be quickly deployed, can record data and is fully compatible with tools like google data studio for real-time graphical representation dashboards • The prototype overcomes the

		study – air quality monitoring of an apartment.		Pressure RH CO_2	 BME280 MH-Z19	 N/A NDIR	Wi-Fi communication		shortcomings of currently commercially available devices that have limited number of detection parameters, lack data transmission via WiFi network, or they are not economical
(Karami et al. 2018)	Wyoming, USA	To develop Arduino-based IEQ monitoring toolbox, integrated with ZigBee communication protocol incorporating a software platform VOLTTRON.	IEQ monitoring of buildings with major development focus on toolbox calibration, i.e., data acquisition device	Temperature RH Air Velocity Globe Temperature CO_2 Illuminance Occupancy $PM_{2.5}$ VOCs	HMP60 HMP60 TSI 8475 Type K thermocouple K-30 LI-210SA & amplifier Sensky Infrared Sensor SHARP GP2Y1010AU0F IAQ-2000	N/A N/A N/A Thermocouple NDIR Photometric PIR[g] Optical N/A	**Microcontroller**: Arduino Uno, **Data**: Cloud storage and real-time remote access; ZigBee platform for wireless communication, *VOLTRRON* Software	N/A	• The accuracy of data improved by calibrating Arduino Uno with a reference data acquisition card • No missing data was found during the data collection, which implies the robustness of toolbox for long-term applications
(Carre and Williamson 2018)	Australia	To integrate occupant satisfaction data and IEQ data with a low-cost logger and to identify empirical connections between measurable environment and resident behaviour and residential perceptions of the indoor environment.	To create an integrated platform to log the indoor environment data and the resident satisfaction level and their behaviour with a low-cost logger	Temperature Globe Temperature RH Light Intensity Sound level Air Velocity PM CO_2 Occupancy	DS18B20 DS18B20 SHT21 Broadcom-APDS 9930 Condensor microphone Wind Sensor rev P SHARP GP2Y1010AU0F GC0010 Unbranded	Semiconductor Semiconductor Capacitive Photodiodes Waveform Anemometer Optical NDIR Infrared (IR) Sensor	**Microcontroller**: Arduino Mega 2560 **Data**: On-board storage, cloud storage and real-time remote access; 3G cellular modem	342 €	• Dynamic and heterogeneous parameters like illuminance, sound level and air-speed make comparison difficult. • Results showed that useful information can be obtained from the sensors to model relationships between occupant perceptions and environmental parameters that will likely enhance our understanding of the factors that contribute to IEQ.

(Zakaria et al. 2018)	Melaka, Malaysia	To develop a wireless and affordable IoT-based device that can monitor air quality, to integrate the monitoring system with a cloud storage and to generate an alert notification e-mail when the air quality is in unhealthy condition.	General IAQ monitoring with a major focus on the connectivity and cloud storage.	Temperature RH Benzene Ammonia NO_x	DHT 22 DHT 22 MQ-135 MQ-135 MQ-135	N/A N/A N/A N/A N/A	**Microcontroller:** Raspberry Pi 2 Model B **Data:** Cloud storage and real-time remote access; A Web page is created on open source platform *ThingSpeak*,	N/A	• Real-time monitoring works only where wireless network access is available.
(Tiele et al. 2018)	Warwick, UK	To design a system able to operate as a rechargeable and portable unit that measures indoor air pollutants via low-cost sensor modules.	IAQ monitoring device for research purposes with a special attention to workplace parameters.	Temperature RH PM_{10} & $PM_{2.5}$ TVOC TVOC TVOC CO_2 CO IAQ Illuminance Sound	SHT31 SHT31 HPMA115S0 CCS811 iAQ-Core C MiCS-VZ-89TE T6713 LLC 110-102 LLC 110-801 TSL2561 T6613	CMOS[j] CMOS Optical MOS MOS MOS NDIR EC EC IR based Photodiode Electret Microphone	**Microcontroller:** Feather M0 **Data:** On-board storage	235 €	• The IAQ sensor was not sensitive enough for indoor monitoring
(Chanthakit and Rattanapoka 2018)	Bangkok, Thailand	To implement a low-cost air quality monitoring system that measures temperature, humidity, CO, O_3, and $PM_{2.5}$ and communicates data via Message Queuing Telemetry Transport (MQTT) protocol, and to implement an air quality monitoring	General IAQ monitoring device with major focus on implementing the MQTT protocol.	Temperature RH CO O_3 $PM_{2.5}$	DHT 22 DHT 22 MQ-7 MQ-131 SHARP PPD42NJ	Thermistor Capacitive MOS MOS N/A	**Microcontroller:** ESP8266 **Data:** Communication via MQTT protocol Mobile and web application for real-time remote monitoring	56 €	• The equation used to convert signal of PM sensor to concentration was non-linear (cubic equation) • They implemented an air quality monitoring dashboard which can be used as both web and mobile application.

		dashboard.					Data are not stored at a database yet (future work)		
(Tijani et al. 2018)	Abu Dhabi, UAE	To design and develop a wireless sensor node for an IAQ monitoring system.	General IAQ monitoring device.	Temperature RH CO CH_4 PM	LM35 HIH-4030 MQ-7 MQ-4 SHARP GP2Y1010AU0F	N/A N/A MOS MOS Optical	**Microcontroller:** Arduino Yun (Atmel ATmega32U4 and an Atheros AR9331 Wi-Fi chipset) **Data:** On-board storage (SD Card)	N/A	N/A
(Lasomsri et al. 2018)	Nakhonnayok, Thailand	To develop low-cost devices to measure IAQ. The developed device was used to monitor IAQ at a large-scale hospital.	IAQ monitoring of hospitals	Temperature RH Pressure TVOC	Adafruit BME680 Adafruit BME680 Adafruit BME680 Adafruit BME680	N/A N/A N/A N/A	**Microcontroller:** Raspberry Pi 3 Model B **Data:** Nothing mentioned about communication or storage of data	N/A	N/A
				Temperature TVOC CO_2e	amsAG CCS811 amsAG CCS811 amsAG CCS811	N/A N/A N/A			
(Scarpa et al. 2017)	Venice, Italy	To present main features and expected applications of a low-budget monitoring platform currently under development.	Indoor environment monitoring and building energy.	Temperature Temperature Temperature RH Illuminance CO_2 PM Movement Distance	DHT 22 Thermocouple RTD[i] DHT22 TSL2561 N/A DYP-ME0010 N/A N/A	N/A N/A N/A N/A N/A NDIR N/A Infrared Sensor Infrared Sensor	**Microcontroller:** Arduino ATmega328P and ESP-8266 WiFi microcontroller **Data:** On-board storage, Online storage and real-time remote access; Wifi,	N/A	N/A
(He et al.	Beijing,	To develop an E-Nose	General IAQ monitoring	Temperature	SHT 10	N/A	**Microprocessor:**	N/A	• The prediction accuracy was

2017)	China	consisting of an array of sensors having multiple cross-sensitive target gases and to develop a pattern recognition algorithm to identify the pollutant gas with precision.	device with major focus on having multiple low-cost MOS gas sensors and using pattern recognition algorithm to precisely estimate IAQ.	RH H_2, CO, CH_4, Ethanol H_2, Ammonia Toluene H_2, CO, Ethanol, Ammonia	SHT 10 TGS2600 TGS2602 QS-01	N/A MOS MOS MOS	STM32 (ARMv7 Cortex) **Data:** Online storage and real-time remote access; Xbee (S6B model) wifi module Web service and Mobile APP		significantly improved by the E-nose and using artificial neural network along with pattern recognition algorithm
(Vcelak et al. 2017)	Prague, Czech Republic	To present examples of smart-structure and environmental monitoring applications developed: An IoT enabled sensor platform	IAQ monitoring in buildings with a focus on smart cities and smart buildings	Temperature RH CO_2 VOC	N/A N/A N/A N/A	N/A N/A N/A N/A	**Processor:** Not mentioned **Data:** Real-time remote access; Cloud storage not mentioned; Wireless: LoRa, Sigfox, IQRF	N/A	• IoT enabled smart IAQ monitoring device was developed • The device was used in a high school in Czech Republic
(Sharma et al. 2017)	Durgapur, India	To use low-cost sensors for checking the air quality of a classroom with varying number of students and class durations	IAQ monitoring in classrooms The major focus was on analysing pollutant levels in the classroom	Temperature RH CO_2 $PM_{2.5}$	DHT 11 SHT 11 MQ-135 SHARP GP2Y1010AU0F	N/A N/A N/A N/A	**Processor:** Not mentioned **Data:** Nothing mentioned about data acquisition, communication or storage.	N/A	N/A
(Kumar et al. 2017)	Roorkee, India	To develop an IAQ monitoring device in conformity with ISO/IEEE/IEC 21451	IAQ monitoring device for smart buildings	$PM_{2.5}$ CO_2 O_3 CO	Developed in-house N/A N/A N/A	Optical MOS MOS MOS	**Microcontroller:** PIC18F4550 **Data:** On-board storage	451 €	• Future work: They will further work to improve on the PM sensor and implement IoT for the sensor modules

		standards.		Formaldehyde	MQ-138	MOS	(MicroSD card module)		
(Jiang and Huacon 2017)	New York, USA	To design a low-cost, cloud-based smart device named Cloud-based Environment Monitoring Smart Device (CEMSD) that monitors different environmental parameters such as air quality, noise, temperature and humidity.	General IAQ monitoring device and implementing its data storage on cloud	Temperature RH Sound Level $PM_{2.5}$ & PM_{10} O_3 CO_2	DHT 11 DHT 11 Grove-Loudness Sensor Shinyei PPD42NS MQ 131 COZIR Wide Range 100% CO sensor	Thermistor Capacitive Mic and Amplifier LPO[k] Time Counter N/A NDIR	**Microcontroller:** Raspberry Pi 3 Model B **Data:** Cloud storage and real-time remote access; *Thingspeak* platform	N/A	• The real-time graphical visualization implemented to the device • Notification system implemented for detection of high pollution levels
(Tran et al. 2017)	Busan, South Korea	To develop a novel battery-free sensor module to measure the concentration of VOC, ambient temperature, relative humidity, and atmospheric pressure for monitoring air quality in indoor environment	General IAQ monitoring. The major focus lies in making the device work without any battery or external power. It uses a Radio Frequency energy harvester for receiving power.	Temperature RH Pressure VOC	SHT 15 SHT 15 BMP 180 CCS801	N/A N/A N/A MOS	**Microcontroller:** PIC12F1513 **Data:** Stored in Electronic Product Code (EPC) memory before transmitting to reader; UHF range wireless communication with sensor tags and antenna.	N/A	• There was an exponential decay in the received power of the energy harvester and an exponential increase in the time taken to charge the super-capacitor with increasing distance between the sensor tags and the reader • Beyond 250 cm distance between the sensor tags and the reader, the device cannot work without battery.
(Peng et al. 2017)	Chang Chun, China	To develop a smart movable indoor environment monitoring system based on Arduino control, which uses the tracking, obstacle avoidance sensors to realize autonomous movable, and	IAQ monitoring for smart cars with focus on validating the sensors against reference instrument.	Temperature RH CO $PM_{2.5}$	DHT22 DHT 22 MQ-7 GP2Y1010AU0F	N/A N/A N/A Optical	**Microcontroller:** ATMega328 (Arduino) Data: No on-board or cloud storage mentioned. No real-	N/A	N/A

		applies gas sensors for IAQ monitoring.					time remote access mentioned. PC connection with serial port: LabView was used to visualize data.		
(Salamone et al. 2017a, Salamone et al. 2017b, Salamone et al. 2015)	Lombardy, Italy	To develop a simple, accurate, and easy to use device based on an open hardware/software concept and aimed at evaluating the IEQ. To perform thermographic analysis check during the design phase.	IEQ monitoring device developed for building environment and energy. The three articles focus on: integrating smart ecosystem for IEQ monitoring, the design phase of device development, and validation of the device.	Temperature RH Temperature RH Radiant Temperature Air Velocity Illuminance CO_2	HIH 6130 HIH 6130 DHT 22 DHT 22 Thermistor in a black globe Wind Sensor LDR Sensor K30	N/A N/A N/A N/A N/A Anemometer Resistor N/A	**Microcontroller:** Arduino **Data:** On-board storage, Cloud storage; Real-time remote access WiFi Shield: Web Connection, BlueSmiRF: Bluetooth Connection	N/A	• This study concluded that using a low-cost equipment without a preliminary verification of the performance can lead to errors of measurement due to a faulty calibration or an improper assembly • Through the combined use of additive manufacturing (3D Printing) and thermographic techniques, it was possible to detect anomalies in the distribution of temperature and correcting the causes that generated them
(Smith and Li 2016)	Texas, USA	To develop a smart phone-based sensor system for personal body area micro-climate monitoring applications.	Personal monitoring with a major focus on developing it to work with smartphone via Bluetooth and mobile app.	Temperature RH CO_2	RTH03 RTH03 SenseAir S8	N/A N/A NDIR	**Microcontroller:** Arduino Pro Mini **Data:** Cloud storage and real-time remote access Bluetooth Module, Internet Access, and Mobile Application	N/A	• This study developed a sensor node Printer Circuit Board (PCB) design and, subsequently, the prototype.
(Ali et al.	Chicago,	To design and develop a suite	To use the device in	Temperature	NTC thermistor	Thermistor	**Microcontroller**:	Total Cost	• Manual and tutorials made to

2016)	USA	of inexpensive, open source devices based on the Arduino platform for measuring and recording long-term indoor environmental and building operational data. To have more flexibility in synchronizing a large number of measurements with high spatial and temporal resolution in a cost effective manner.	research projects and, eventually, in building automation and control. The focus was on the open source integration and to make tutorials on how to implement it.	RH Surface Temp. Light Intensity CO_2 Occupancy	Sensirion SHT15 NTC thermistor: Modified TAOS TSL2561 SenseAir K-30 1% Parallax PIR	N/A Thermistor Digital Light Sensor NDIR Passive Infrared	Arduino Pro Mini **Data:** On-board storage, Future works to include remote communication	of each individual parameter along with processor was mentioned Total: 469 €	teach how to build air monitoring device • Debugging the circuits of the device can be relatively difficult and time consuming in the event of a problem • Newer SD cards were found to be not compatible with low power mode of their device
(Tapashetti et al. 2016)	Santa Clara, USA	To develop an IoT enabled IAQ monitoring device	IAQ monitoring in offices, schools, homes, etc. with a major focus was on implementing open source sensors with IoT.	Temperature Gas CO_2 Formaldehyde Light Intensity	Grove Sensors Grove Sensors Grove Sensors Grove Sensors Grove Sensors	N/A N/A N/A N/A N/A	**Microcontroller** (WiFi) Marvell 88MW302 **Data:** Cloud Storage (Amazon Web Services) Real-time remote access	153 €	• This study developed an IoT enabled device and implemented cloud-storage and remote access via Amazon Web Services
(Abraham and Li 2014, Abraham and Li 2016)	Texas, USA	To develop a low-cost wireless IAQ monitoring device developed using Arduino, Xbee and micro gas sensor modules. To develop a linear least square-based method for sensor calibration and measurement data conversion.	General IAQ monitoring with a major focus on device development, calibration methods and the choice of sensors	Temperature RH CO_2 VOC CO O_3	RTH03 RTH03 MG811 TGS2602 MQ7 MQ131	N/A N/A EC MOS MOS MOS	**Microcontroller:** Arduino Uno AtMega328 **Data:** XBee module (details not provided)	N/A	This study developed a linear least square estimation-based method for sensor calibration and measurement data conversion
(Du Plessis et	South	To develop a low-cost	Monitoring IAQ in	Temperature	LM35	Thermoresistor	**Microcontroller:**	N/A	• Calibration was found to be

al. 2016)	Africa	Wireless Sensor Network comprised of multiple nodes and powered by a battery.	buildings with a major focus on developing the device with sensor nodes and to transmit the parameters to a sink node where data can be stored and displayed.	RH CO CO_2	HIH-4000 TGS 2442 CO2-D1	Capacitive MOS Potentiometric	ATMega88 **Data:** Online storage and real-time remote access Transciever: Simcom SIM20 (434 MHz) interface with a controller (PC) via UART – Serial communication		essential for obtaining accurate temperature and humidity results • A carbon monoxide sensor (CO-D4) malfunctioned before any measurements. It was then replaced with TGS 2442 MOS sensor • The system sends only 64 bytes every 5 seconds – a lower bitrate is acceptable for the system
(Cho 2016)	Daejeon, South Korea	To develop a personal environmental monitoring system (PEMS) for stationary indoor environment, and wearable environmental monitoring system (WEMS) for outdoor environment.	Personal and wearable environmental monitoring. Major focus was on the platform outlook, sensor calibration and communications.	**PEMS** Proximity VOC Noise **WEMS** O_3 CO NO_2 SO_2 Temperature RH UV, Light	 Camera MiCS 4514 N/A N/A N/A N/A N/A N/A N/A N/A	 N/A N/A N/A N/A N/A N/A N/A N/A N/A N/A	**Processor:** <u>WEMS:</u> Cortex M4 <u>PEMS:</u> ST Microelectronics STM32f4xx (ARM Cortex-M4) and a Freescale KL17 **Data:** <u>PEMS</u>: On-board storage and Cloud storage (via WiFi) <u>WEMS</u>: On-board storage and Cloud storage via Bluetooth	N/A	• Hardware designed for PEMS as a wall clock and for WEMS as a wrist watch • Three modes of operations for WEMS: Standby, Watch and Sensing • Future work: To implement an application of cloud services
(Yang et al. 2015)	Shanghai, China	To implement a low-cost, multi-sensor, sufficiently-sensitive IAQ monitor. To	General IAQ monitoring with a focus on choosing the sensors with suitable	Temperature RH VOC	AMT2001 AMT2001 MQ138	N/A N/A N/A	**Microcontroller:** Arduino Yun (also includes an Atheros	Total device cost not	Experimental results showed that the selected monitoring parameters could be wirelessly

		obtain the sensor data in real-time through Wi-Fi using computers or smart phones, and to store all historical data in the cloud.	detection range and cost.	PM	SHARP GP2Y1010AU0F	Optical	AR9331 Wi-Fi chipset) **Data:** On-board storage Cloud storage and real-time remote access: displayed on website. A smart phone is used to wirelessly plot the data	mentioned Cost of two sensors mentioned: 10.52 €, and 3.29 €	detected in household with acceptable sensitivities up to 50 m away
(Kim et al. 2014)	USA	To examine the issues, infrastructure, information processing, and challenges of designing and implementing an integrated sensing system for real-time IAQ monitoring.	This study discussed the various scenarios in which such a device can be used: Community Health Care, construction/maintenance site, hazardous location, schools or gathering places. The major focus was on development and testing the device.	Temperature RH GAC[h] VOC NO_2 CO O_3 SO_2 PM CO_2	DHT 11 DHT 11 TGS2600 TGS2602 GSNT11 TGS5042 MiCS-2610 SO2-AF SHARP GP2Y1010AUF T6613	Thermistor Capacitive MOS MOS MOS MOS EC EC Optical NDIR	Processor, SD Card or any communication of data was not mentioned.	N/A	• Sensor characteristics and environmental settings such as temperature and humidity may result in measuring errors; thus, pre-calibration and continual auto-calibration are necessary for the sensors • Using gas sensors consumes a lot of power; thus, how to properly select sensor type and improve energy efficiency during design and implementation stages are critical
(Saad et al. 2014)	Malaysia	To develop an IAQ index based on the excellence ratio method which has been applied in the outdoor Air Quality Index (AQI) worldwide.	IAQ monitoring in buildings with a major focus on developing AQI for indoor air by implementing it with their developed device.	Temperature RH PM_{10} CO_2 CO VOC	HSM20G HSM20G SHARP GP2Y1010AUF CDM 4161 TGS 5342 TGS 2602	Analog Sensor N/A Optical N/A N/A N/A	**Microcontroller**: Eight-bit STC microcontroller **Data:** Online storage and Real-time remote	N/A	The indoor AQI was implemented based on outdoor AQI formula but based on indoor air pollutants; It was integrated with their developed device.

				O_3 NO_2 O_2	MiCS-2610 MiCS-2710 KE-25	N/A N/A N/A	access IRIS Mote as the wireless module, programmed using TinyOS		
(Brunelli et al. 2014)	Trento, Italy	To develop an ad-hoc wireless sensor network and to deploy it in Trento, Italy	IAQ monitoring in buildings. The focus was on the aspect of providing long and continuous monitoring in the most inhabited areas of the building and collect comprehensive sensory datasets inferring indoor ecology and people comfort level over a long period of time (different seasons of the year)	Temperature RH Illumination CO_2 CH_4	SHT21 SHT21 BH17 N/A N/A	N/A N/A N/A N/A N/A	**Microcontroller:** Jennic NXP JN5148 SoC; includes a 2.4 GHz IEEE802.15.4/ZigBee PRO complaint module **Data:** Online storage and real-time remote access The ad-hoc WSN relays the data to sink node which stores the data in SQL.	N/A	• The developed device operated for four months delivering high data reliability • The predicted network lifetime is 520 days (excluding gas sensors contribution) that is confirmed by real-life experiments and simulations
(Teixeira and Postolache 2014)	Lisbon, Portugal	To develop a flexible system with low-cost sensor nodes for continuous monitoring of air conditions in order to prevent asthma attacks.	Asthma trigger factors assessment was the intended application with a major focus on the development of communication protocol from Wireless Sensor Network WSN to the internet.	Temperature RH NO_2 O_3 PM_{10}	SHT11 SHT11 N/A N/A N/A	N/A N/A N/A N/A N/A	**Microcontroller**: Raspberry Pi **Data:** Cloud storage and real-time remote access Data communicated with and without Ethernet bus (using ZigBee)	N/A	• The system was developed to establish correlations between air quality parameters and the appearance of respiratory diseases such as asthma • Future Work: The extension of the wireless sensor network and implementing the web based information system for tablets and smartphones

† Optical Sensor: Based on light scattering technology; ‡ Costs converted to Euros and rounded up to nearest integer;

[a] Electrochemical Sensor (EC); [b] Not Mentioned (N/A); [c] Metal Oxide Semiconductor (MOS); [d] Non-Dispersive Infrared (NDIR); [e] Total Organic Volatile Compounds (TVOC); [f] Volatile Organic Compounds (VOC); [g] Passive Infrared (PIR); [h] General Air Contaminants (GAC); [i] Resistance Temperature Detector (RTD); [j] Complementary Metal Oxide Semiconductor; [k] Low Pulse Occupancy (LPO)

3.2 Sensor calibration and performance

The majority of projects did not calibrate or validate the sensors used in their devices. Table *2* summarizes the sensor performance of the 12 projects that presented a calibration and/or quantitative validation of the sensors.

All projects had sensors whose detection range includes the typical concentration levels of the indoor pollutants (WHO 2010), except for Kumar et al. (2017) where CO_2 detection was out of range for average indoor levels as the upper detection limit of their sensor was only 1000 ppm. Several studies did not mention the detection range of some or all of their sensors (Martín-Garín et al. 2018, Carre and Williamson 2018, Peng et al. 2017, Salamone et al. 2015, Salamone et al. 2017a, Salamone et al. 2017b).

Only a minority of the studies checked for response time, which plays a crucial role in real-time monitoring. Gillooly et al. (2019) reported the response time of all of their gas sensors to be below one minute except the Netatmo weather station, which had a temporal resolution of five minutes. Wang et al. (2017) tested the response time of their sensors and found it to be less than 30 seconds for every sensor except the temperature sensor, which had a response time of less than 116 seconds. Ali et al. (2016) mentioned the response time of only two of their sensors: temperature (5-10 seconds) and CO_2 (20 seconds). The response time of the $PM_{2.5}$ sensor developed by Kumar et al. (2017) was 1 minute. At 5 minutes, Netatmo weather station showed the slowest response time but is still quick enough to conduct near real-time monitoring. Therefore, all the studies which reported response time were concluded to have real-time monitoring capability.

Only two studies tested the inter-sensor variability of low-cost gas sensors. Gillooly et al. (2019) did a quantitative analysis of the CO, NO and NO_2 sensors they used (n=16 each) and found the average percentage difference to be 5.28% (SD = 4.02%), 7.17% (SD = 4.90%) and 8.59% (SD = 6.30%) respectively. He et al. (2017) showed a graphical comparison of their test and found inconsistent results between sensors. None of the studies except one performed cross-sensitivity tests (He et al. 2017), which used an array of cross-sensitive MOS sensors with artificial neural network and pattern recognition algorithm to develop an E-nose.

With the lack of a standardization in place, calibration methods varied with each project, and the reference instruments used for validation were different with one exception: The monitoring box SKOMOBO (Wang et al. 2017) and a few sensors of the device SAMBA (Parkinson et al. 2019a, Parkinson et al. 2019b) were both tested with TSI Qtrak (for CO_2) and TSI DustTrak (for PM). Most of the studies did not use professional-grade reference instruments. A few studies calibrated and tested their device by exposing the sensors to a known concentration of pollutant gas (Gillooly et al. 2019, Kumar et al. 2017, He et al. 2017). Parkinson et al. (2019b) calibrated their sensors with reference instruments in a chamber over the anticipated concentration range of the pollutants in an indoor office environment. Abraham and Li (2014) implemented a least-square method for sensor data calibration with a reference instrument – GrayWolf Direct Sense IAQ 610.

Perhaps the most important result of the validation is the lack of it: 25 out of the total 35 projects did not present quantitative results of sensor performance tests. And the absence of any standardization is evident in a closer look at the result outcomes of the projects that did conduct these tests (Table *2*). The validation results ranged from R^2 (Gillooly et al. 2019, Wang et al. 2017, Ali et al. 2016), error difference from the reference instrument (Martín-Garín et al. 2018, Kumar et al. 2017, He et al. 2017, Peng et al. 2017, Du Plessis et al. 2016, Salamone et al. 2015), and average Standard Error Estimate (SEE) (Parkinson et al. 2019b). Peng et al. (2017) mentioned the validation of their device but did not specify any reference instruments except for another low-cost CO device used for validating their low-cost sensor. There is no standardization even for accuracy tests and for the statistical parameters to be used for calculating it. Du Plessis et al. (2016) used *unknown* gas concentration to validate their CO and CO_2 sensors.

Four more projects were not presented in the table but calibrated/qualitatively validated their sensors. They are discussed in this section but not included in the review table because they did not quantify their results in any manner. Benammar et al. (2018) bought pre-calibrated sensors from Libelium and recalibrated them using an in-house developed calibration rig. They mentioned that the results of sensor performance would be included in a future publication, but the authors couldn't find it during their search. Tiele et al. (2018) calibrated their temperature, RH, and CO_2 sensors with a commercially available device – Extech CO210 but did not validate their device with a reference instrument. Yang et al. (2015) performed a qualitative validation of VOC and PM using 75% ± 5% (V/V%) disinfectant alcohol and cigarette, respectively. Kim et al. (2014) also performed a qualitative validation of their device by noting an increase in CO_2 readings with a higher density of people, VOCs, and General Air Contaminants (GACs) with the type of furniture, and temperature with the air conditioning system.

Table 2. Summary of the sensor performance.

Study	Monitoring Parameters	Sensor Description	Sensing Principle	Detection Range	Response Time	Reference Instrument	Calibration Method	Accuracy/Error vs Reference (Outcomes)
(Gillooly et al. 2019)	CO	Alphasense COB4	EC[b]	0-1000 ppm	≤ 1 minute	Only PM sensor was validated in field: with RTI MicroPEM (5-min average)	Known gas concentration TSI SidePak™ AM510 (1-hour average)	Only PM sensor validated against reference: Lab (TSI SidePak™ AM510): R^2 = 0.47, RMSE[d]= 2.94μg/m3 Field (RTI MicroPEM) R^2= 0.83, RMSE = 3.52 μg/m3 EC sensors need frequent calibration (every three months) but do not exhibit inter-sensor variability
	NO	Alphasense NOB4	EC	0-20 ppm	≤ 1 minute			
	NO_2	Alphasense NO2B43F	EC	0-20 ppm	≤ 1 minute			
	$PM_{2.5}$	Alphasense OPC-N2	Optical†	0.38-17 μm	1.4 seconds			
	$PM_{2.5}$	Harvard miniPEM	N/A[c]	N/A	N/A			
	Temperature	Onset Temperature Sensor	N/A	N/A	≤ 1 minute			
	Temperature	Netatmo Weather Station	N/A	0-50°C	≤ 1 minute			
	RH[a]			0-100%	5 minutes			
	Noise			35-120 dB	5 minutes			
	CO_2			0-5000 ppm	5 minutes			
(Parkinson et al. 2019a, Parkinson et al. 2019b)	Temperature	N/A	Thermistor	0-50°C	N/A	VelociCalc 9565-A, TSI 54T21, Dantec Dynamics TSI Q-Trak 7575 Fieldpiece SCM4 TSI DustTrak II 8532 HalTech HFX205 N/A Type 1, NL-52, Rion T10A Konica Minolta	Calibration was done with the reference instruments in a chamber of their Indoor Environmental Quality lab. The test was conducted over the anticipated ranges rather than full range of sensor measurement.	0.26 °C (±0.05)
	RH		Capacitive	5-95%				1.04% (±0.12)
	Globe Temperature		Thermistor	0-50°C				0.16 °C (±0.03)
	Air Speed		Anemometer	0-1 m/s				0.015 m/s (±0.008)
	CO_2		NDIR[f]	0-5,000 ppm				9 ppm (±2)
	CO		EC	0-50 ppm				1.2 ppm (±0.4)
	PM_{10}		N/A	N/A				0.024 mg/m3 (±0.010)
	Formaldehyde		EC	0-2 ppm				0.02 ppm (±0.01)
	TVOC[e]		Photoionization	10-2000 ppb				N/A
	Sound Pressure		Microphone	40-90 dBA				2.4 dBA (±0.4)
	Illuminance		Photodiode	0-20,000 lx				8.9% (±1.5%) Results in Average Standard error of estimate (SEE)

(Martín-Garín et al. 2018)	Temperature	DHT22	Thermistor	-40-80°C	N/A	Temperature, RH, and CO_2: HT-2000 model Atmospheric Pressure: Weather station near the building: Davis Vantage Pro2 Plus	Temperature Calibration: Climate chamber Range: 5-35°C, Reference: AHLBORN 2549 Humidity: Saturated Aqueous Solution Range: 11.30 to 84.6%, Ref: Salt Solutions (1-min sampling interval for both) CO_2: N/A	• Results were shown as an average of all the sensors in their prototype: 0.249°C [Temperature] -3.006% [RH] 68.568 ppm [CO_2] 5.160 hPa [Barometric Pressure] Results as the difference between prototype and commercial sensor (only mean differences shown here) • CO_2 errors were concluded to be higher than expected probably due to the difference in casing protection between the two systems and due to the high sensitivity of these types of sensors (NDIR)
	RH		Capacitive	0-100%				
	Temperature	SHT21	Band Gap	-40-125°C				
	RH		Capacitive	0-100%				
	Temperature	BMP180	N/A	-40-85°C				
	Barometric Pressure			300-1100 hPa				
	Temperature	BME280	N/A	N/A				
	Pressure		N/A	N/A				
	RH		N/A	N/A				
	CO_2	MH-Z19	NDIR	0-5000 ppm				
(Carre and Williamson 2018)	Temperature	DS18B20	Semiconductor	N/A	87-155 seconds	Rotronic HC2-S3	Individual sensors were tested for accuracy against reference before the development of prototype	• Graphical Comparisons for field tests/validation • CO_2 concentration measurements are noisier than the reference sensor, increasing extremes at both the top and the bottom of the measurement range
	Globe Temperature			N/A	N/A	HC2-S3 & 150mm globe		
	RH	SHT21	Capacitive	N/A	N/A	Rotronic HC2-S3		
	Light Intensity	Broadcom-APDS 9930	Photodiodes	0-30,000 lx	N/A	Testo 480		
	Sound	Condensor microphone	Waveform	N/A	1 second	Testo T816-1		
	Air Velocity	Wind Sensor rev P	Anemometer	N/A	1 second	TSI 8475 - Omni		
	PM	SHARP GP2Y1010AU0F	Optical	N/A	N/A	N/A		
	CO_2	GC0010	NDIR	0-2000 ppm	N/A	Vaisala GMP343		
	Occupancy	Unbranded	Infrared (IR) Sensor	N/A	N/A	N/A		
(Wang et al. 2017, Wang et al. 2018)	Temperature	TELAiRE T9602	Capacitive Polymer	-20-70°C	≤ 116 seconds	TSI QTrak	Calibration was not mentioned. The tests were done in two environments: **C.** Controlled (n=6) and **U.** Uncontrolled (n=6)	**C.** $R^2 \geq 0.98$; **U.** $R^2 = 1$
	RH			0-100%	≤ 29 seconds	TSI QTrak		**C.** $R^2 = 0.92\text{-}0.97$; **U.** $R^2 = 0.96\text{-}0.98$
	CO_2	SenseAir K30	SenseAir K30	0-5000 ppm_{vol}	20 seconds	TSI QTrak		**C.** $R^2 = 0.99$; **U.** $R^2 = 0.89\text{-}0.94$
	$PM_{1.0}$	PMS3003	Optical (Laser light)	0.3 to 1 mm	≤ 10 seconds	N/A		N/A
	$PM_{2.5}$			1 to 2.5 mm	≤10 seconds	TSI DustTrak		**C.** $R^2 = 0.82\text{-}0.9$; **U**. Qualitative
	PM_{10}			2.5 to 10 mm	≤ 10 seconds	TSI DustTrak		**C.** $R^2 = 0.68\text{-}0.89$; **U**. Qualitative
	Occupancy	TB-XC4444	Passive Infrared	3 to 7 meters	0.3 to 18 seconds	N/A		N/A

				100 degrees				Results as Coefficient of Determination (R^2)
(Kumar et al. 2017)	$PM_{2.5}$	Developed in-house	Optical	N/A	1 minute	IAQ-2500	The static chamber method with an incubator was used for calibration: known gas concentrations were inserted in the incubator	±10%
	CO_2	N/A	MOS[g]	100-1000 ppm	N/A	Known Gas concentration inserted in incubator		±4%
	O_3	N/A	MOS	10 ppb-2ppm	N/A			±2%
	CO	N/A	MOS	1-10 ppm	N/A			±4%
	Formaldehyde	MQ-138	MOS	1-10 ppm	N/A			±6%
								Results as Percentage Error from reference
(Peng et al. 2017)	Temperature	DHT22	N/A	N/A	N/A	N/A	Not mentioned	0.15%
	RH		N/A	N/A	N/A	N/A		1.2%
	CO	MQ-7	N/A	N/A	N/A	Hua Chang Sheng CO-110		0.086%
	$PM_{2.5}$	GP2Y1010AU0F	Optical	N/A	N/A	N/A		0.81%
								Results as Percentage Error from reference
(He et al. 2017)	Temperature RH	SHT 10	N/A	N/A		Known amount of pollutant exposure	Calibration method was not mentioned	For ppm <1: 14.18
	H_2, CO, CH_4, Ethanol H_2, Ammonia, Toluene	TGS2600 TGS2602	MOS	1-30 ppm	N/A			For ppm >1: 4.53
	H_2, CO, Ethanol, Ammonia	QS-01	MOS	1-30 ppm				Results as Mean Absolute Percentage Error
			MOS	1-1000 ppm				
(Salamone et al. 2017a, Salamone et al. 2017b, Salamone et al. 2015)	Temperature	HIH 6130	N/A	-40-85°C	5 seconds	4 Wire PT100 sensor	Temperature and RH : Climate Box (**C**) (Results were also compared with commercial sensors)	Graphically represented
	RH		N/A	10-90%	5 seconds	Thin Film		Graphically Represented
	Temperature	DHT 22	N/A	-40-80°C	2 seconds	4 Wire PT100 sensor		**C.** 0.32°C; **U.** <5% (83% of cases)
	RH		N/A	0-100%	2 seconds	Thin Film		**C.** 4%; **U.** <5% (72% of cases)
	Radiant Temperature	Thermistor in a black globe	N/A	-40-60°C	10 seconds	4 Wire PT100 sensor		**U.** <2%
	Air Velocity	Wind Sensor	Anemometer	N/A	N/A	N/A	Air Speed: Test Chamber	**U.** <5% (87% of cases)
	Illuminance	LDR Sensor	Resistor	N/A	N/A	N/A	CO_2: No calibration/validation	**U.** <10% (95% of cases)
	CO_2	K30	N/A	0-10000 ppm	N/A	N/A		N/A

								Results as Percentage Error from reference
(Ali et al. 2016)	Temperature	NTC thermistor	Thermistor	-55-80°C	5-10 seconds	Onset HOBO U12-012	No Calibration mentioned. Controlled and uncontrolled tests were conducted. Commercially available counterparts were used for Controlled Lab Tests **(C)** and Uncontrolled Tests **(U)**	**C.** $R^2 \geq 0.9969$; **U.** $R^2 = 0.9638$
	RH	Sensirion SHT15	N/A	N/A	N/A	Onset HOBO U12-012		**C.** $R^2 \geq 0.9965$; **U.** $R^2 = 0.9907$
	Surface Temperature	NTC thermistor: Modified	Thermistor	-55-80°C	> 5-10 seconds	TMC20-HD		$\mathbf{R^2}$ = 0.9818 (measured in duct)
	Light Intensity	TAOS TSL2561	Digital Light Sensor	0.1 to 40,000 Lux	N/A	Onset HOBO U12-012		**C.** $R^2 = 0.999$; **U.** $R^2 = 0.9884$
	CO_2	SenseAir K-30 1%	NDIR	0-10,000 ppm	20 seconds	SBA-5 & Telaire 7000		**C.** $R^2 = 0.9691$; **U.** $R^2 = 0.8767$
	Occupancy	Parallax PIR	Passive Infrared	3.65 m, 100°	N/A	Onset HOBO UX90-005		R^2 was not calculated Results as Coefficient of Determination (R^2)
(Abraham and Li 2014, Abraham and Li 2016)	Temperature	RTH03	N/A	N/A	N/A	GrayWolf Direct Sense IAQ 610	Linear Least Square Method was used for sensor calibration. The reference instrument used was GrayWolf Direct Sense IAQ 610	Only graphical comparison shown
	RH			N/A				
	CO_2	MG811	EC	350-10000 ppm				
	VOCs	TGS2602	MOS	1-30 ppm				
	CO	MQ7	MOS	20-2000 ppm				
	O_3	MQ131	MOS	10-1000 ppb				
(Du Plessis et al. 2016)	Temperature	LM35	Thermoresistor	0-90°C	N/A	MTD82	RH: EM5510 multimeter with an in-built humidity sensor Others not mentioned	2.6%
	RH	HIH-4000	Capacitive	45.5-98%		EM5510		3.8%
	CO	TGS 2442	MOS	0-29 ppm		Unknown Gas Concentration		N/A
	CO_2	CO2-D1	Potentiometric	0-2000 ppm (self-tested)		Unknown Gas Concentration		N/A Results as Percentage Error from reference

† Optical Sensor;

[a] Relative Humidity (RH), [b] Electrochemical Sensor (EC), [c] Not Mentioned (N/A), [d] Root Mean Square Error (RMSE), [e] Total Volatile Organic Compounds (TVOC), [f] Non-dispersive Infrared (NDIR), [g] Metal Oxide Semiconductor Sensor (MOS)

4. Conclusions

Intending to tackle the growing grey literature and scattered information, this review compiled scientific literature on the development of low-cost IAQ monitoring devices and studied the recent advancements in this field. This work can be especially helpful for researchers who are aiming to develop a novel device.

Although the choice of internal components like microcontroller units and sensors used in the projects exhibited a certain homogeneity, the individuality of the device design lied in how those components were used and encased in the hardware enclosure. It ranged from devices having wrist-watch like hardware design, ultra-low powered battery-free design, low-noise design, electromagnetic interference-free design, and various web-based interfaces for continuous indoor air quality monitoring, among others.

However, the most important challenge associated with low-cost sensor technology is the lack of data reliability. The fact that was disregarded by most of the studies as there was no sensor performance test or even calibration done by the majority of the research projects. The use of low-cost sensors to develop the device without any prior testing was the prevalent practice. To exacerbate the problem, the studies that tested sensor performance showed that the measurement errors could indeed be very high when compared to professional-grade reference equipment. Another important conclusion in this context is that calibration and validation methods varied significantly with each project due to the lack of any standardized practice in place. The reported validation results also lacked any uniformity (R^2, percentage errors, SEE). It puts a significant limitation on the comparison of device performance & design, and a consequent failure to understand the advancements in this field. The abundance of grey literature makes the situation even worse.

With just two studies testing the long-term stability and only one study checking the cross-sensitivity of the sensors, the situation seems very bleak. Now, with this review, the information is gathered, but it still lacks more studies, especially the ones conducted with a thorough check of device performance to ensure data reliability from the low-cost sensors.

While this review generally observed a murky outlook on most aspects discussed, there were several promising results as well. Studies with a high correlation between the reference instrument and low-cost device advocate that this can be the technology of the (near) future. The responsibility to drive this emerging technology forward lies in the scientific community. With a standardized sensor performance assessment and a credible and mandatory validation process, the results can inspire more confidence than they currently do. Hence, the two most prominent future requirements in this field of study would be: i) an increased number of studies with a thorough analysis of sensor calibration/validation and device performance assessment; and ii) a uniform sensor/device validation method.

Conflict of Interest

None

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Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract

Highlights

- Low-cost sensor technology major challenge is the lack of data reliability.
- Calibration and validation methods varied significantly with each project.
- The reported validation results also lacked uniformity.
- Studies on long-term stability and cross-sensitivity of the sensors are lacking.
- High performance indexes advocate low-cost devices as the (near) future technology