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Review article

Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone?

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ABSTRACT

Over the past decade, a range of sensor technologies became available on the market, enabling a revolutionary shift in air pollution monitoring and assessment. With their cost of up to three orders of magnitude lower than standard/reference instruments, many avenues for applications have opened up. In particular, broader participation in air quality discussion and utilisation of information on air pollution by communities has become possible. However, many questions have been also asked about the actual benefits of these technologies. To address this issue, we conducted a comprehensive literature search including both the scientific and grey literature. We focused upon two questions: (1) *Are these technologies fit for the various purposes envisaged*? and (2) *How far have these technologies and their applications progressed to provide answers and solutions*? Regarding the former, we concluded that there is no clear answer to the question, due to a lack of: sensor/monitor manufacturers' quantitative specifications of performance, consensus regarding recommended end-use and associated minimal performance targets of these technologies, and the ability of the prospective users to formulate the requirements for their applications, or conditions of the intended use. Numerous studies have assessed and reported sensor/monitor performance under a range of specific conditions, and in many cases the performance was concluded to be satisfactory. The specific use cases for sensors/monitors included outdoor in a stationary mode, outdoor in a mobile mode, indoor environments and personal monitoring. Under certain conditions of application, project goals, and monitoring environments, some *sensors/monitors were fit for a specific purpose*. Based on analysis of 17 large projects, which reached applied outcome stage, and typically conducted by consortia of organizations, we observed that a sizable fraction of them (~ 30%) were commercial and/or crowd-funded. This fact by itself signals a paradigm change in air quality monitoring, which previously had been primarily implemented by government organizations. An additional paradigm-shift indicator is the growing use of machine learning or other advanced data processing approaches to improve sensor/monitor agreement with

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reference monitors. There is still some way to go in enhancing application of the technologies for source apportionment, which is of particular necessity and urgency in developing countries. Also, there has been somewhat less progress in wide-scale monitoring of personal exposures. However, it can be argued that with a significant future expansion of monitoring networks, including indoor environments, there may be less need for wearable or portable sensors/monitors to assess personal exposure. Traditional personal monitoring would still be valuable where spatial variability of pollutants of interest is at a finer resolution than the monitoring network can resolve.

1. Introduction

Low-cost air pollutant sensors/monitors are 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. It is therefore not surprising that most of the research groups with interest in air quality, and government organizations with responsibility for it, focus to develop their own programs to assess and utilize low-cost sensors/monitors. Some report disappointing outcomes, others varying degrees of success. Scientific papers on the topic are multiplying, as are grey literature and web-based sources. The complexity and multi-dimensionality of the topic make it difficult to comprehensively track all projects being undertaken.

The paradigm shift of air pollution monitoring from being based on standardized government-operated networks, consisting of reference instruments, to mixed networks involving both reference-grade monitors as well as emerging sensor/monitor technologies was recognised several years ago by the U.S. EPA (Snyder et al., 2013; White et al., 2012). The emergence of low-cost air monitoring technologies was also recognised in Europe and was recommended to be included in the next Air Quality Directive (Borrego et al., 2015). In its Draft Roadmap for Next Generation Air Monitoring, the U.S. EPA proposed a five-Tier system for general consideration that includes low-cost technologies (USEPA, 2013). Each Tier corresponded to a group of specific applications and their anticipated users (Table S1). Both the U.S. and the European Union (EU) have funded projects to evaluate low-cost air quality monitoring technologies and establish networks for trial purposes (CITI-SENSE, 2016; USEPA, 2016). There is a consensus that the low-cost air quality monitoring equipment should be characterised carefully to meet the expectations for their specific applications, be it ambient air or indoor monitoring (Castell et al., 2013; Lewis and Edwards, 2016).

Since the publication of Snyder et al. (2013), which recognised the role of low-cost sensors/monitors in the future of air quality monitoring, there have been a number of reviews on the development and applications of low-cost monitors and their networks (Borghi et al., 2017; Castell et al., 2013; Clements et al., 2017; Jovasevic-Stojanovic et al., 2015; Kumar et al., 2015; Kumar et al., 2016; McKercher et al., 2017; Rai et al., 2017; Spinelle et al., 2017a; Thompson, 2016; Wang and Brauer, 2014; Woodall et al., 2017). These reviews either focused on characterizations and descriptions of one group of sensors/monitors, such as for monitoring of particulate matter - PM (Borghi et al., 2017; Jovasevic-Stojanovic et al., 2015); for gaseous pollutants (Baron and Saffell, 2017; McKercher et al., 2017; Spinelle et al., 2017a); crowd-sourced monitors (Thompson, 2016); or offer a general overview of the state-of-the-art and the relevant applications (Castell et al., 2013; Clements et al., 2017; Kumar et al., 2015; Kumar et al., 2016; Wang and Brauer, 2014; Yi et al., 2015).

There has been significant focus on the *fitness-for-purpose* of the monitors/networks, acknowledging that applications are many and varied, and therefore differing in the requirements for the type and quality of the data to be obtained. For example, McKercher et al. (2017) discussed the fit-for-purpose question of monitors of gaseous pollutants. Recently, Rai et al. (2017) discussed the advancement in sensor/monitor technology from the end-users perspective.

The ultimate vision is that when the technology matures, there will be ubiquitous networks of sensors/monitors present everywhere, someone owning and operating them (governments, municipalities – or individuals), and many end user applications will be available. Also, anyone, not necessarily an expert in air pollution monitoring, will be able to purchase the right type of sensors/monitors for their intended application, install them and obtain data which will address their questions although there could be issues concerning data interpretation by non-experts. To test whether this vision is already within the reach, two questions can be formulated: (1) *Are these technologies fit for the various purposes envisaged?* and (2) *How far have these technologies and their applications progressed to provide answers and solutions* (beyond just demonstrations that they can be utilized)?

The aim of this review is to provide answers to the above questions based on systematic search and review of peer reviewed publications, as well as grey literature (e.g. non-peer reviewed industry/government documents and/or web-based sources).

2. Conceptual framework for utilisation of low-cost air quality sensors/monitors

The term “low cost” is relative, depending on the users and the specific purposes, and has been used loosely in the literature. For example, U.S. EPA Tier III instrument (US$2000–US$5000) could be low

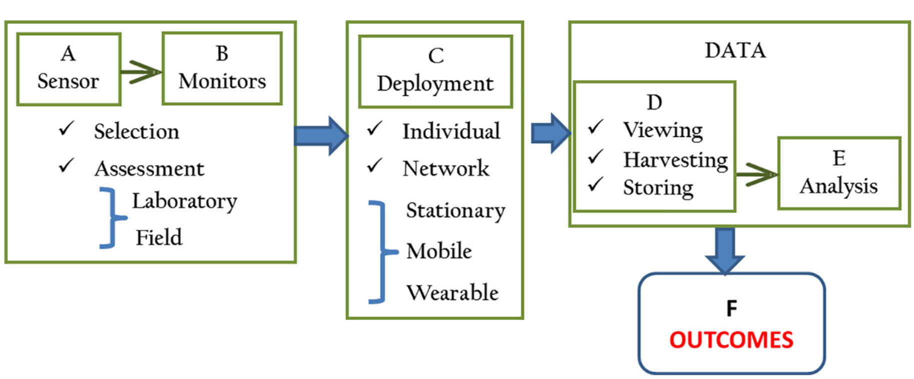


Fig. 1. Conceptual framework for the utilisation of low-cost sensing technologies.

cost for a regulatory authority but unaffordable for community monitoring (USEPA, 2013). The term "low cost" has colloquially been identified by the U.S. EPA as devices costing < $2500 namely because this is the limit often defining capital investment limits by citizen scientists (Air Sensor Toolbox). Additionally, the term "sensor/monitor" was sometimes used to refer to both the measuring component (e.g. the Shinyei PPD42NS sensor by Austin et al. (2015)), as well as the whole monitoring systems, including one or multiple sensors/monitors, enclosure, data display (optional), battery or other power source connection, and varying components for data storage, transmission, and retrieval (e.g. AQMesh and Air-Sensor Box by Borrego et al. (2016)). In this paper, we will use the term "sensor" for the measuring component and the term "monitor" for the whole monitoring system, as per the definition adopted by McKercher et al. (2017). Since the "sensor" alone will be of little use without the supporting components, most of the information reported in the literature is actually about "monitors" and their networks. Therefore, we define hereafter that for the purposes of individual/community applications and/or personal monitoring, a low cost sensor must be < US$100 and a low cost monitor consisting of one or several sensors and communication/data components must be < US $1000.

To be able to answer the set questions, we first need to encompass all the elements, which constitute the entire pathway from the sensor(s) to the answer. Fig. 1 presents the conceptual framework with the progressive phases A to F, with A being a sensor, and F, an outcome of the application of low-cost sensors for air quality monitoring and/or exposure assessment. The outcomes may be pollutant concentration values (current, averaged over time); live air quality maps; apportionment of personal exposure; and citizen/community science information, which can be accessible from websites or via mobile phone applications, etc.

Which phases are implemented, and by which projects, depends to a larger extent who is undertaking them and for what purpose. For example, a multidisciplinary research team may go from A to F, with the outcome being a live air quality map, while an individual may buy a monitor (Phase B), view the readings (Phase D: viewing), and compare them to the national standards (Phase F: outcome). Our review will consider each of these phases separately first, before addressing the overall state-of-the-art of the air sensor technology field.

3. Method for review

This review follows the "state-of-the-art review" approach, which addresses current matters using the grey literature (as explained below) in addition to the scientific literature (Grant and Booth, 2009). The air sensors field is progressing rapidly, with new developments and information often published outside of traditional peer-reviewed literature, therefore this broader search was necessary to fully grasp the state of the field. The search was conducted using the scientific databases, including Scopus, Web of Science, IEEE Xplore Digital Library and via a general Google (Scholar), with publication date until August 2017. The separate keywords employed in the search were general to include as many documents as possible, and included:

- "low-cost sensor" and "air quality" in Scopus, Web of Science.
- "sensor network" and "air quality network" for IEEE Xplore Digital Library, Google.

The search was limited to the English language. We note that the search could have missed some publications, because other terms such as sensing network, sensor system, and air pollution could have been used as an alternative for "low-cost", "sensor" and "air quality" in different publications. The search outcomes were screened to identify relevant papers and websites to be used in this review. Relevant returns (based on queries of Title and Abstract fields) were collected and organized in EndNote (version ×7.5, Web of Science).

In addition to the peer-reviewed papers, we also screened "grey literature" using the Google search engine with the same set of keywords. Due to a large number of results from each Google search (usually > 1 million), only the first 100 results of each search were scanned for relevance and those related to applications of the low-cost sensor were recorded.

4. Sensors and monitors

4.1. Existing sensors and monitors

Tables S2 and S3 (Supplementary Information Section 1) summarize, respectively, all the identified particulate matter (PM) and gaseous sensors and monitors reported in the peer-reviewed literature up to November 2017. The Google search for non-peer-reviewed publications identified a range of low-cost sensor projects and networks, which are presented in later sections.

A general conclusion, based on the peer-reviewed literature, is that there is a limited number of companies that presently manufacture air quality sensors. These include six companies that manufacture PM sensors and four that manufacture gas sensors. It was also noted that some of these manufacturers provide a number of different models of the same sensor. There are many more companies utilizing combinations of sensors, as well as ancillary components to build different types of monitors.

The operation of all the identified PM sensors is based on the light scattering principle. The, aerosols are carried in the air flow across a focused beam of visible or infra-red light and the intensity of the scattered light in a selected direction ismonitored by a photodetector. PM sensors are classified into two types – volume scattering devices and optical particle counters (OPCs). In the former the light is scattered from the ensemble of particles and the photodetector provides a single digital or analog output. The output reading is usually converted to a particle mass concentration by comparison to a reference monitor using some test aerosol. The Shinyei PPD42 is an example of such a sensor. On the other hand, OPCs count and estimate the sizes of individual particles, following which the readings are converted to a particle mass concentration, based on the assumption that the particles are spherical and of consistent bulk density and refractive index. An example of such a sensor is the Plantower particle sensor).

Unlike PM sensors, the principles of operation of gaseous sensors involve measuring changes in specific properties of a sensing material (e.g. electrical conductivity, capacitance, mass) upon exposure to a gas species (Comini et al., 2009; Kalantar-Zadeh and Fry, 2008; Liu et al., 2012). These changes can be measured directly or indirectly. A typical gas sensor consists of a sensing layer, deposited on a transducing platform, which is in contact with the environment, together with a transducer that produces a measurable output signal. The performance of a gas sensor is evaluated by considering several indicators: sensitivity, selectivity, speed, stability, power consumption, and reversibility. Details of different gas sensing principles are discussed in Supplementary Information Section 2.

In the future, nanotechnology is expected to have a significant impact on the field of gas sensing. In particular, this includes potentially enabling the development of portable and inexpensive sensors that exhibit operational advantages such as enhanced sensitivity and responsivity, selectivity, and low operation power, as well as high integration flexibility with respect to their conventional counterparts. Nanostructured materials have shown a great potential for use as sensing layers due to their unique properties including high surface to volume ratio, greater surface active sites, high specific surface area as well as the effect of crystal facets with high surface reactivity (Comini, 2016; Comini et al., 2009; Kalantar-Zadeh and Fry, 2008; Zhang et al., 2016). However, developing portable gas sensors with high performance, operating at room temperature, still presents a challenge.

4.2. Assessment of sensors and monitors

4.2.1. Testing protocols

Currently, manufacturer's specifications of low-cost sensors/monitors are of limited use in many cases, as they do not normally conduct sufficient testing that cover the range of desired applications. To address this gap, a number of researchers or government organizations have undertaken evaluation of real-world sensor/monitor performance for a specific use mode and environment of application. Tables S1 and S2 present information regarding the applications of sensors/monitors in various projects reported in the literature, together with information on any assessments conducted and their outcomes. One issue, however is that there is variability in how the different assessments were conducted and to what degree their findings are comparable. Over the last few years, several testing protocols have been proposed and utilized. In particular, the European Metrology Research Programme of EURAMET proposed and applied a protocol to evaluate the performances of single commercial gas sensor (Spinelle et al., 2013), (Spinelle et al., 2015, 2017b). Also, the U.S. EPA initiated its own sensor evaluation efforts in the laboratory and field (Jiao et al., 2016; Long et al., 2014; Williams et al., 2014b) and issued a general guideline for evaluation and use of low-cost air quality sensors, including suggested performance goals for the sensors (Williams et al., 2014a). Other U.S-based groups saw value in the systematic evaluation of sensors and began developing performance research protocols (SC-AQMD, 2017).

Of the 57 studies on sensor/monitor evaluation found in the peer reviewed literature, only 5 studies reported use of or made references to available protocols in the literature. In particular (Jiao et al., 2016; Zikova et al., 2017) made reference to U.S. EPA protocol; and (Castell et al., 2017; Spinelle et al., 2015, 2017b) used the European protocol. The majority of the studies, however, developed their own, study specific protocols. Given the current wide variety of approaches to evaluating sensors/monitors – including varying duration of testing, measurement environments, number of replicate technologies, and benchmark reference monitors utilized – there are limitations to how the outcomes of testing can be combined across studies or utilized for applications or environments that differ from the original testing setups.

Performance criteria to assess sensors/monitors, based on reviewing the testing protocols, have been developed and utilized by individual studies. A comprehensive list of such criteria includes: (1) linearity; (2) accuracy; (3) precision; (4) response time; (5) detection limit; (6) detection range; (7) impact of temperature and relative humidity (RH); and (8) co-pollutant interference. The definitions of these terms are provided in Table S4.

It is important that the sensors/monitors are tested under both laboratory and field conditions. While all of the criteria listed above are important for laboratory testing, such testing typically includes linearity (against reference instrument); accuracy and the impact of temperature and RH (Williams et al., 2014c). On the other hand, field evaluation exposes the sensor/monitor to the actual air pollution and environmental conditions under which it is expected to operate, and it usually involves collocation of the sensor/monitor with the relevant reference instruments. Field evaluation tests are easier and less costly to conduct, especially when the existing air quality monitoring stations can be utilized with their sets of reference instrumentation for comparison. According to the evaluation protocol proposed by the State of California South Coast Air Quality Management District, the Air Quality Sensor Performance Evaluation Center (AQ-SPEC), sensors are to be tested under field conditions at two different monitoring stations, with subsequent laboratory testing conducted if the field testing results are promising (SC-AQMD, 2017). This method of testing has also been recommended as the first choice for citizen/community groups. Fishbain et al. (2017), with this application in mind, proposed a Sensor Evaluation Toolbox (SET) for evaluating Air Quality Micro Sensing Units (MSU) by a range of criteria, to better assess their performance in varied applications and environments. Of the 57 sensor/monitor testing studies found, 30 performed field tests only, 14 laboratory tests only, while 13 studies conducted both field and laboratory tests. It is not surprising that more than half of the studies performed only field tests, and the outcomes of such testing enable utilisation of the sensors/monitors in the same general area where the tests were performed but not necessarily elsewhere.

4.2.2. Particulate matter sensor performance

While most of these performance criteria are clearly defined and, therefore, straightforward to incorporate into the testing protocols, the complexity arises when testing PM sensor performance. The complexity is much greater than that when testing gaseous sensors and therefore it is discussed here separately. Since airborne particles vary in size (and encompass a large spectrum of sizes), and in composition, the questions are: (i) what type of aerosol should be used?; (ii) within what concentration range? (iii) how do the composition and concentration of the test aerosol differ from the ambient aerosol in the study area? (iv) if only field intercomparison is conducted, how well does it account for the impact of all the relevant environmental conditions (variation in aerosol composition, concentration, temperature or RH)?. While the AQ-SPEC protocol does have an option for testing particles of different sizes, it does not specify the data analysis that should be conducted in order to conclusively assess the sensor performance (the European protocol was designed only for gas sensors).

Several studies investigated PM sensors under laboratory conditions and considered the above aspects. Different aerosols have been used in those tests, ranging from test particles, such as ammonium sulfate, polystyrene latex, (Austin et al., 2015; Northcross et al., 2013; Wang et al., 2015), sodium chloride, methylene blue, fluorescein sodium (Liu et al., 2017), sucrose, and ammonium nitrate (Wang et al., 2015), to naturally generated aerosols such as wood smoke, cigarette, stick incense, fried foods such as bacon, chicken, and hamburgers (Dacunto et al., 2015; Olivares and Edwards, 2015). A commonly used test aerosol is Arizona road dust (Manikonda et al., 2016; Sousan et al., 2016a, 2017; Sousan et al., 2016b). Such tests allowed the researchers to achieve very high concentrations of PM, of up to 1000 μg/m^3 (Wang et al., 2015) or even several mg/m^3 (Sousan et al., 2016a, 2017, Sousan et al., 2016b) to cover a wide range of occupational conditions.

In general, low cost sensors perform well, with a high degree of linearity, in the laboratory However, they suffer significant response factor changes when used under natural conditions. This is one of the major drawbacks of laboratory-based calibrations. Among the many constraints of laboratory testing compared to field testing is that it is normally difficult to maintain a low concentration of PM, of the level expected in ambient air, for a sufficiently long period of time. Further, the composition and concentration of the test aerosol may not be representative of the ambient aerosol in the study area, or in the area where the sensor/monitor is to be deployed. However, the range of naturally generated aerosols such as wood, cigarette or incense stick smoke could be suitable if the sensors/monitors are to be used indoors. In studies where only field tests were conducted, it was suggested that the sensor/monitor should be deployed in several regions of different ambient PM concentrations and compositions (Jiao et al., 2016; Johnson et al., 2016; Steinle et al., 2015). In conclusion, the general recommendation for users of low-cost sensors/monitors is that they should be pre-tested/calibrated under the condition in which it is intended to be used (Austin et al., 2015). It is interesting to note that there are many studies that did not conduct any sensor/monitor testing, but based their technology selection and expectations on performance solely on the manufacturer's information. This includes studies such as the bicycle-mounted sensors to observe traffic-related air pollution (Liu et al., 2015; Van den Bossche et al., 2015), establishment of urban or school sensor networks (Ali et al., 2015; Arvind et al., 2016), personal exposure estimation (Arvind et al., 2016; Zhang et al., 2017) and indoor air quality monitoring (Plessis et al., 2016).

Table 1
Summary of applied outcomes of selected large low-cost sensor/monitor projects.

Project name	Project period	Type of project	Applied outcomes	Operating network	Data access	Location
Government-funded projects						
ARC- LP16	2016–2020	Network development	Low cost sensor/monitor networks in several cities	In progress		Australia
EuNetAir	2012–2016	Network on New Sensing Technologies	Development and evaluation of new sensors/monitors	n.a.	n.a.	Europe
EveryAware	2011–2014	Enhance Environmental Awareness	Games, and temporary personal monitoring campaign	n.a.	n.a.	Europe
CamMobSense	-2010	Small scale deployment of sensor/monitor		n.a.	n.a.	UK
Citi-Sense	2012–2016	Developing technological platforms for distributed monitoring	Multi-country sensor/monitor testing/monitoring network	Commercial products still in development including AQMesh	Data accessible through the Citizens Observatory Toolbox (COT)	Europe
Citi-Sense-MOB	2013–2015	establish mobile air quality measurements	exhaustive evaluation of low-cost platforms	n.a.	n.a.	Norway
OpenSense	2010–2013 2014–2017	investigating community-based sensing using wireless sensor/monitor network	Air pollution map based on mobile sensing platform. Phone-app for route planning	Currently available	Data accessible online over the project's Global Sensor Network (GNS) at http://data.opensense.ethz.ch/	Switzerland
Community Observation Networks for Air (CONA)	2015 ~	Establishing low-cost sensor/monitor network	Monitors developed, network building	In progress	n.a. (provided report for participants)	New Zealand
PiMi Airbox	2013–2016	Indoor Air-quality Monitoring and Large Sensory Data Mining	Monitors developed, network testing	n.a.	n.a.	China
Smart Santander	2010–2013	applications and services for a smart city	Network of internet-based device including air quality	Still available but not very active	Data stored in a repository and can be accessed once authenticated and authorised by using a web service interface	Europe
U.S. EPA CAIRSENSE	2013–2016	Evaluate long-term performance of sensors/monitors and network	Sensors/Monitors tested	n.a.	n.a.	US
U.S. EPA Village Green	2013–2014 2015–2016 2017 ~	Building autonomous monitoring systems	Units built and installed in limited number of sites	Online data for limited sites	Data accessible online	US
U.S. EPA grants Air Pollution Monitoring for Communities	2016–2019	Development and application of low-cost sensor/monitor network	Sensor/Monitor testing facility established	In progress	Data not accessible to the public yet project still ongoing	US
Commercial/crowd funded projects						
AirVisual	2015 ~	Global network of air quality monitors	Map of fixed sites and app developed for all users	Network and monitors available	Data accessible by a free AirVisual app and website	Global (US-based)
Air Quality Egg	2012 ~	community-led air quality sensing network	Map and data function developed for all users	Network and monitors available	Data accessible through an air quality egg, phone app and a website	Global (US-based)
AirCasting (AirBeam monitor)	2012~	a platform for recording, mapping, and sharing health and environmental data using your smartphone	Map of data from AirBeam monitors and app developed for all users	Network and monitors available	Data accessible through an air beam, phone app and a website	US
SMARTCITIZEN	n.a.	a platform to generate participatory processes of people in the cities	Map of data from Smart Citizen monitors and app developed for all users	Network and monitors available	Data accessible through an Smart Citizen kit, phone app and a website	Europe
Purple Air	2015 ~	An air quality monitoring network built on a new generation of "Internet of Things" sensors/monitors	PurpleAir Map displays the points using the U.S. EPA Air Quality Index (AQI) scale	Network and monitors available	Must be a registered user to access data	Global (US-based)

4.2.3. Sensors'/Monitors' fitness for the purpose

The main applications of the sensors/monitors have included outdoor monitoring (Bart et al., 2014; Castell et al., 2017; Gao et al., 2015; Jiao et al., 2016; Olivares and Edwards, 2015; Olivares et al., 2012), indoor monitoring (Dacunto et al., 2015; Jackson-Morris et al., 2016; Semple et al., 2015) or both (Steinle et al., 2015), and personal monitoring (Delgado-Saborit, 2012; Jerrett et al., 2017; Steinle et al., 2015). It can be seen that these applications are diverse, and therefore it is reasonable to expect that they will have different performance requirements. For example, PM sensors/monitors used for traffic-related pollution will need to have the capacity to detect smaller size particles, while sensors/monitors used for construction dust will only need to detect coarser size particles. In other words, the sensors/monitors need to be *fit for the purpose*, with the purpose clearly identified. Therefore, one question is whether it makes sense to discuss 'a standard protocol' for testing or should it be related to the purpose, if there should be different protocols, with fewer criteria to be included. Additionally, the acceptable performance of sensors/monitors for various purposes needs to be delineated. It should be noted that variation in potential acceptability targets have been considered by the U.S. EPA (Williams et al., 2014a).

Based on the review of sensor/monitor performance and the manner in which they were tested, there is no clear answer to the question stated by this review, namely: *Are these technologies fit for the various purposes envisaged?* This is because neither have the relevant quantitative specifications of the sensors/monitors been provided by the manufacturers (i.e., their performance at different concentrations, particle size, RH), nor have the users formulated the requirements for the applications or conditions under which they intended to apply the monitors. However, as discussed above, numerous studies have assessed and reported sensor/monitor performance under a range of specific conditions. While some of these studies simply reported results without assigning a "pass or fail", in many cases it was concluded that the performance was satisfactory, with the judgment criteria of "good enough' varying between the studies. In other words, *the sensors/monitors were fit for the specific purpose*. The U.S. EPA in their Sensor User Guidebook pointed out that not every sensor need be useful for every type of monitoring (Williams et al., 2014a). The "fit for purpose" approach amplifies that consideration. This points out to the necessity of formulating the requirements for sensors/monitors when intending to apply them for specific purposes and specific locations, and based on this identifying the most suitable sensors/monitors from the published work. The review above and Tables S1 and S2 serve as a useful guide in this respect.

A philosophical comment can be made that it is hardly a novel conclusion that users need to understand the conditions under which they want to use a product. The difference, however, between applications of low cost sensors for air quality monitoring and many other technologies is that many potential users do not have an in-depth background in atmospheric science and consider that no background is necessary. This review suggests that, currently, in-depth expertise is needed to identify appropriate sensor technologies for specific application as well as to understand potential measurement artifacts that could affect data interpretation.

5. Deployment

A sensor network consists of a number of spatially distributed autonomous devices to monitor one or more physical or environmental parameters. The sensor nodes can be interconnected to transmit information and to control operations. This can be achieved by physically wiring the nodes together and to a central processing unit. Although this has some advantages such as superior quality of data, a wireless option offers much easier deployment, flexibility, and troubleshooting in an event that a sensor fails. While there is no doubt that Wireless Sensor Networks (WSNs) will play a major role in the future, it is soon expected to become the key technology for the Internet of Things. There are three main ways in which air quality sensors/monitors may be deployed for use, and they are discussed below.

5.1. Stationary

Here, one or more sensors/monitors are located at a number of fixed sites and monitoring is conducted over a period of time. Provided a sufficiently large number of sensors/monitors are deployed, the results can yield information on spatio-temporal variations, transport rates and sources of pollution. At the same time, it should be noted that a large number of monitors and locations does not necessarily constitute a network unless they are linked together or transmitting information to a central location, generally through wireless connectivity. Currently there are no standardized protocols defining the number of nodes to be placed within a network to achieve sufficient coverage of any environmental pollutant.

The large majority of the studies reviewed (and listed in Tables 1S and 2S) fall into the first category, i.e. stationary deployment. These were mostly conducted in the early days of low cost sensors. In this section, we restrict our analysis to studies involving monitoring at more than one location.

Of the reviewed studies, five monitored particulate matter concentration (Castell et al., 2017; Gao et al., 2015; Jiao et al., 2016; Olivares and Edwards, 2015; Zikova et al., 2017). The total number of sensors/monitors used ranged from 4 to 66 and the duration of the studies ranged from 2 days to 6 months. Three of these studies used either the Sharp or Shinyei low-cost PM sensor. Some stationary networks have been established such as Gao et al. (2015); English et al. (2017) as pilot networks or such as Semple et al. (2015) as part of an epidemiological monitoring campaign. Further, 11 such studies have monitored gaseous pollutants (Al Rasyid et al., 2016; Bart et al., 2014; David et al., 2013; Heimann et al., 2015; Ikram et al., 2012; Masson et al., 2015; Mead et al., 2013; Moltchanov et al., 2015; Sun et al., 2016; Weissert et al., 2017; Wen et al., 2013). The number of sensors/monitors ranged from 3 to 44 and the gases monitored included nitric oxide (NO), nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2), ozone (O_3) and volatile organic compounds (VOCs). Study durations ranged from 3 days covering the marathon route during the Hong Kong marathon, up to a maximum of 1 year.

In general, the purpose of air sensor networks were to produce high resolution pollution maps that could be used for peak event identification, or linking pollution levels to people's exposure. The above studies suggested that sensor networks have the potential to provide a far more complete assessment of the spatio-temporal variability of pollution data of a particular area. This high-granularity of data supported a more precise characterization of human exposure (Mead et al., 2013). These networks were also able to identify the pollution hotspots by distinguishing them from the daily averaged values for the city, and generate high-resolution spatiotemporal pollution maps (Gao et al., 2015). It was acknowledged that the calibration and data accuracy of sensors constituting the networks was equally as important as that of sensors operating individually. However, the regular in-situ calibration of such sensor networks might face practical constraints (Rai et al., 2017). Thus the published studies tended to adopt alternative ways, such as advanced statistical techniques that included principal component analyses for fault detection and isolation (Harkat et al., 2006), network data correlations for quality check (Alavi-Shoshtari et al., 2013), and algorithms for mobile quality checks (Hasenfratz et al., 2015).

As a special case it is important to note the expanding networks of stationary sensors for mapping and ultimately managing urban and regional air pollution in China. There is an increasing body of information available on this topic on the Internet (in Chinese), however, these studies were not published in peer-reviewed literature. According to rough estimates (personal communication), there are currently over

30,000 sensors operating to monitor concentration of air pollutants in China. > 10,000 sensors were installed in north China, where the air pollution is the most serious, with > 2000 PM sensors operating in Beijing since 2016, to help evaluate air quality for the city (personal communication).

5.2. Mobile

Measurements are conducted using mobile platforms such as cars, bicycles and unmanned aerial vehicles (UAV), to provide data of high spatial resolution, higher than is possible with stationary platforms. Among the mobile platforms, the UAVs are of interest when extending the scope to include measurements of pollution in the vertical plane.

There have been a number of European-based projects employing portable sensors/monitors for mobile platforms (trams and buses) and citizen participatory initiatives for air quality monitoring; such as the Citi-Sense (http://co.citi-sense.eu) and Opensense (http://www.opensense.ethz.ch) projects (Hasenfratz et al., 2015), as well as the more recent Luftdaten project (http://luftdaten.info). However, while the first two projects above employed portable particle sensors/monitors, which were cheaper than conventional reference instruments, they do not meet the requirements for low-cost sensors, as defined in this paper. The third project does however, and it currently operates an active network of over 2000 PM monitors. Thompson (2016) reviewed applications of air quality sensors/monitors in crowd-sourcing projects and drew attention to the importance of data communication and data quality control analysis prior to drawing any conclusion solely on the data measured by the sensors/monitors.

Although, many studies have used conventional particulate matter instruments on mobile platforms, hardly any have utilized low-cost sensing technologies for this purpose. Devarakonda et al. (2013) installed Sharp dust sensors on public transportation and Suriano et al. (2015) employed a Shinyei sensor in an AirBox monitor in a motor car. A somewhat larger number of studies have been conducted to monitor gaseous pollutants. Low cost gas sensors such as those from Alphasense have been used on bicycles and motor vehicles in several studies (Castell et al., 2013; Devarakonda et al., 2013; Elen et al., 2013; Hasenfratz et al., 2015; Mead et al., 2013; Mueller et al., 2016; Suriano et al., 2015).

A new study conducted in Ji'nan, China, has been utilizing city taxis as mobile platforms for low-cost sensors. One hundred taxis were equipped with PM sensors monitoring $PM_{2.5}$ and PM_{10}. The taxis can collectively drive a distance of 23,000 km, cover 95% of the road in the city and provide 1.2 million PM data points per day. It is hoped that with the help of this system, the city authorities will be able to evaluate the relationship between the air pollution and road emissions (including traffic, dust, near-road emission) to develop a more effective air pollution control strategy (Novafitness, 2017).

Two studies have used low cost sensors mounted on UAVs for outdoor monitoring of dust. Alvarado et al. (2015) developed an unmanned sensing system aiming to characterise the dust levels at mining sites. “Dust” was referred to as particulate matter in this paper, although the particle cut-point as PM_{10} or $PM_{2.5}$ could not be clearly defined. The authors tested the performance of SHARP GP2Y10 and Samyoung DSM501A in measuring $PM_{2.5}$ and PM_{10} concentrations in the smoke from incense sticks against a TSI DustTrak 8520 monitor. As a result, the Samyoung sensor was excluded due to poor correlation with the TSI DustTrak 8520 ($R^2 = 0.5$), while the SHARP GP2Y10 showed better correlation for PM_{10} with a precision of 1 mg/m^3. The SHARP did not respond to particles from an open fire when deployed on the UAV up to altitude of 120 m, but was able to detect talcum powder (classified as PM_{10}) that was dispersed in an open area. Although the method for using UAV for airborne measurement was feasible, the authors emphasised the need for further investigations on assessing the actual particle size cut-point measured by these types of sensors. Koval and Irigoyen (2017) designed and tested a UAV-based air pollution monitoring system using a catalytic sensor (TGS6812-D00) to measure and detect leakage of hydrogen, methane, and liquid petroleum (LP) gas. All the data processing was done at the ground station, which incorporated a robot operation system (ROS Indigo and Ubuntu 14.04) coupled with a drone autonomy package (by Autonomy Lab of Simon Fraser University). The main limitation of the system was identified as the sensor's lag time in measuring concentrations at any point in time. The results of these two studies suggested that further improvement is needed for low cost sensors/monitors to be used effectively on UAV platforms.

In summary, there are limitations in long-term deployment of sensors/monitors on mobile platforms, especially due to the associated costs in maintaining the data collection and generating outputs (e.g. air pollution maps). However, this area of air pollution monitoring appears to be of high interest within the scientific and public communities and is rapidly progressing with availability of new technologies in modifying monitoring platforms; e.g. both in terms of monitoring sensors/monitors and data processing and communication capabilities.

5.3. Wearable

Sensors/Monitors worn or carried by individuals are used to provide estimates of personal exposure to various types of pollution. Similar to the mobile platforms, the data collected by wearable sensors/monitors together with concurrent GPS data can be used to estimate spatial distributions of the measured air pollutants in different (micro) environments.

This field of research has grown rapidly in recent years; however, there is only a small number of research papers published on the use of low-cost sensors for personal exposure monitoring due to the challenging technological aspects of developing such sensors/monitors. Cao and Thompson (2016) described design, capabilities, and performance of a low-cost ($150 USD), portable ozone sensor for personal exposure monitoring purposes. The testing was conducted by 8 volunteers using the sensor during daytime on the weekdays and weekends over the winter (January to March) in 2015 in Texas, USA. The designed personal ozone monitor used a MiCS-2614 metal oxide semiconductor ozone sensor from SGX Sensortech. The MiCS-2614 performed best for concentrations of 20-100 ppb and had a response time of 1 min. Although the results showed that the volunteers in this study were exposed to concentrations much higher than 20 ppb, the sensor response to low concentrations was one of the limitations of this study. Another limitation was powering the monitor, which requires eight AAA rechargeable batteries lasting for up to 10 h. Jerrett et al. (2017) reported on the performance of personal sensing monitor built at Cambridge University, UK and used for personal exposure monitoring of 56 participants during two epidemiological studies for over one year (September 2013–February 2014) in Barcelona, Spain. The monitor provided the data every 10s and used Alphasense CO, NO and NO_2 sensors as well as sensors for temperature, GPS and General Packet Radio Service (GPRS) transmitter. The results showed that the system was able to detect concentrations of the pollutants in different microenvironments. Comparisons with the reference instruments indicated that the sensors for primary gases (CO and NO) had a better performance than for the secondary gases (NO_2). Another low-cost personal exposure monitoring system (M-Pods) developed by Piedrahita et al. (2014), was capable of collecting, analysing and sharing the data via an Android mobile phone app. The system used sensors for CO, total VOCs, NO_2, and O_3 (metal oxide semiconductor sensors SGX Corporation models MiCS-5525, MiCS-5121WP, MiCS-2710, and MiCS-2611), and CO_2 (NDIR sensor ELT, S100) along with sensors for temperature, relative humidity and light. GPS data were collected using the mobile phone app. Six volunteers used M-Pods over 3 weeks and the M-Pods were tested and calibrated against reference instruments before and after the deployment. Although the actual deployment period was rather short, the comparisons between before and after calibration results showed good agreements and the system was able to perform within the limitation of the sensors' detection limits. With respect to fine particulate matter ($PM_{2.5}$), Steinle et al. (2015) used a Dylos1700 for 17 volunteers who provided 35 personal exposure profiles. Two other studies were carried out using the Sharp GP2Y1010 dust sensor (Wong et al., 2014; Zhuang et al., 2015). Wong et al., developed an Integrated Environmental Monitoring Device (IEMD), which linked the collected $PM_{2.5}$, temperature, humidity, ultraviolet (UV) and sound level data to an Android-based mobile phone app using a web-based database, with the location data obtained from the mobile phone's GPS system. The system provided the measured data in real-time as well as data visualisation through the mobile phone app and was tested for a short period of time by one volunteer in Hong Kong. The results showed that the system was able to respond to changing environments, such as between indoors and outdoors. Zhuang et al. (2015), desgined and tested a similar platform for personal exposure monitoring, called AirSense, which used sensors for GPS, dust, temperature, humidity, and accelerometer in New York, USA. The authors outlined the primilinary tests on the performance of the AirSense, which were performed in stationary locations for each individual sensor. The AirSense reponse to changing microenvironments, such as changes in commuting modes, activity levels (stationary vs moving), during activities at home (e.g. cooking) were tested using data collected over short periods of times (up to 6-h) by one participant. The results supported the suitability of AirSense for personal exposure monitoring as well as for complementing routine ambient monitoring.

Overall, personal exposure monitoring platforms using low-cost wearable sensors/monitors is of high interest in relation to fine-scale exposure and ambient data required for health impact assessments and epidemiological studies, as well as citizen science applications. Similar to the mobile platforms, the current limitations in their implementation are power restriction; reliability and accuracy of miniaturized sensors under dynamic conditions of use; and robustness to withstand use by individuals.

6. Data: communication, storage, cloud services, processing, and dissemination

Behind every sensor/monitor network there is an underlying data architecture which supports the collection, processing and dissemination of the data (Castell et al., 2015). The complexity and capacity of the sensor/monitor network architectures is proportional to the number of sensors/monitors deployed, the predicted future capacity of the network, the amount of data gathered per sensor, the required level of availability/reliability the backend services require, the post-processing requirements and the data dissemination methods desired (Guo et al., 2012).

The solution each project implements is tailored to these various factors, subsequently there is no one best practice for the development of supporting data services for sensor/monitor data. Any architecture designed for a sensor/monitor network system is about a balance of trade-offs between cost, reliability, scalability and longevity.

6.1. Data communication

The data sent from sensors/monitors, in terms of traditional internet capacities, would be considered very small in size, and low in frequency. The main limitation found in low-cost sensors/monitors is not in the storage of the data once it is received by the centralized network, but more in the capacity of the device to send data due to power limitations, network availability and security protocol support on low-computing hardware (Lin et al., 2012). Another consideration is data security (Breitegger and Bergmann, 2016). Many sensors/monitors require data transmission back to centralized servers for processing or data hosting, or transmit to a cloud-based system. Few if any of the current sensor/monitor manufacturers have achieved compliance with official cloud-based data security standards (e.g., FedRAMP for the United States federal government).

As with any solution design, there are trade-offs to be considered when designing hardware. In the case of low-cost sensors/monitors, the main driving factor is power consumption and data storage. The methods of data communication once the device has captured environmental information can range from mobile networks, Wi-Fi, Bluetooth and direct physical serial connections (Breitegger and Bergmann, 2016). Generally, a sensor/monitor will use more power when it uses the always available communication protocols like WiFi and Bluetooth. Lower power usage can be achieved through the implementation of on-demand protocols like mobile networks which only connect and transmit data at pre-defined intervals. This demand for low-power usage is only a need for sensors/monitors in remote locations without access to hardwired power. The nature of air quality sensing often drives a need for sensing in remote and diverse locations, hence power consumption is often a consideration, although the improvement in solar and battery efficiency is reducing the impact of this design consideration (Kadri et al., 2013).

With the emergence of more efficient circuit boards and components which provide greater computing power for the power usage, implementation of stronger security protocols is allowed, leading to a more robust and secure network. This security factor becomes more important as the scale of networks increases, and the potential for breaching or manipulation of sensor/monitor devices and their associated data. The nature of changes in security best practices and increases in breaching of devices in more recent times means that this is becoming a more important design consideration.

It must also be stated that in many situations, data transmission cannot occur due to a lack of Wi-Fi or cellular service. It is imperative that sensors/monitors have sufficient internal storage to ensure that data are not lost if/when data transmission cannot be secured or maintained.

6.2. Databases and storage

A common aspect of all sensor/monitor data services is the need to store spatial data, which provides context and meaning to environmental conditions at a given location. While the concept of storage of location information is not a new field, over time there has been a filtering and trend to towards the use of certain databases which have been proven to be the most scalable, fast and reliable for this need.

The most common database used for the storage of sensor/monitor data is PostgreSQL with PostGIS providers attached (Ježek, 2011). This allows the querying of large quantities of geo-spatial data in a flexible manner, while maintaining performance as the capacity grows. PostgreSQL has a theoretically unlimited row-storage capacity which is only limited by physical storage size on the database cluster. It is not uncommon to be storing 1 million rows per day into one of these databases with no impact on performance and reliability, while still slowing complex geo-spatial queries to be performed.

An additional storage need for these sensor/monitor systems is the storage of metadata associated with the sensors/monitors sending data into the network. There is more flexibility in which type of database is used in this area as many database providers can handle the capacity required for metadata. Traditionally this will be done using Relational Database Management System (RDBMS) which provides more complex query capacities and the ability to create “relationships” between different components of the data itself. Some common RDBMS employed by sensor/monitor networks include Oracle, Microsoft SQL Server and MySQL.

This metadata storage service can contain information relating to the sensor/monitor owner, service types, hardware settings, sensing capabilities, maintenance schedule and more. This area is flexible, and can be tailored to suit the needs of the particular sensing network while being decoupled from the raw geo-spatial sensor/monitor data stored in the main PostgreSQL database.

6.3. Cloud service providers

There is a clear tendency for the more recently developed sensing network data services to be hosted in cloud computing environments (Mehta et al., 2016). Although mainly driven by cost savings, the benefits of high availability computing that scales as needed is perfectly tailored to the requirements of large scale sensing data.

There are 3 main commercial cloud computing providers which offer tailored, scalable and pay-as-you-go computing services. The main providers in this now mature computing space are Amazon Web Services (AWS), Microsoft Azure and Google Cloud Computing (Fioccola et al., 2016).

Low-cost sensors/monitors are sometimes referred to under the moniker of “Internet of Things” (IoT), where the sensors/monitors referred to as “things” and data feed into a cloud-hosted database. Currently, the majority of cloud-hosted sensor/monitor networks have been built on the AWS system, supports IoT data inputs, scalable infrastructure and low-cost long-term storage. AWS is the most mature of the cloud providers in this field and has been shown to iterate faster with new services and economy of scale cost reductions.

6.4. Data processing

There are needs for processing of sensor data once it reaches the internal storage architecture, although this can vary depending on the sensor types and the data dissemination requirements.

In some cases, the sensor/monitor only sends raw voltage readings, without calibration and conversion occurring at the hardware level. In this case the network needs the ability to support the calibration, and in some cases iterative re-calibration, of the data before it is outputted for consumption.

In more complex sensors/monitors hardware, calibration is often done during build and deployment, so the data received by the network have already undergone its conversion (Schneider et al., 2017). This has benefits of consistency when the sensor/monitor is deployed, but also can lead to data slowly “sliding” out of its initial calibration over time as the sensor/monitor hardware ages, unless drift-over-time is incorporated into the calibration. On-board data conversion also reduces data post-processing needs as well as supports offline use of sensors/monitors. Keeping the sensors/monitors well calibrated during deployment is a challenge and various approaches for calibration/data adjustment have been proposed including the following:

1. Sensor/Monitor is collocated with a reference monitor as a “training period”, where a machine learning algorithm is developed. The specific parameters and adjustments that are appropriate for inclusion are of debate. These algorithms are often kept proprietary by the manufacturer as their intellectual property.
2. Sensor/Monitor calibration algorithms are developed by the manufacturer and are applied either on-board or in the cloud. These also are often kept proprietary.
3. Sensors/Monitors in a network have their data adjusted based upon expected agreement with a reference monitor located some distance away – for example, isolating middle of the night time periods and using the sensor/monitor vs. reference comparison to make adjustments to the data baseline.

An emerging issue for data integrity is the use of proprietary algorithms, which may include algorithms changing through time, applied on servers or in data post-processing. A number of commercial entities are utilizing proprietary data adjustment algorithms, generally conducted on a server or cloud, which is their key intellectual property given the commonality of the OEM sensor/monitor components. This creates questions of data integrity and reproducibility. A general comment on cloud-based, machine learning that is proprietary and opaque to the user is that if the algorithms are changing over time and the details of the adjustments are not known to the user, this can cause a data integrity issue.

6.5. Data dissemination and communication

After the point of measurement, how the data are communicated and shared varies based upon the objective of the organization implementing the monitoring. Public-facing data streams are challenged to provide meaningful interpretation of the data at the timebase it is reported. Until recently, many organizations implementing sensors/monitors would utilize the U.S. EPA Air Quality Index (AQI), or similar indices from other countries, as their means to provide messaging of their sensor/monitor data. However, this approach was in conflict with the AQI system, which was designed for generally long-averaging periods and applied for regional-scale air monitoring sites based on a body of health research. Newer approaches, such as the U.S. EPA Sensor Scale, have been introduced to provide an alternative guide on communicating high time-resolution sensor data (EPA, U.S., 2017).

With every sensor/monitor network developed, there is an obvious need to communicate the data back once it has been collected. There are many ways in which this has been implemented, but given that the data storage networks are all internet hosted, the obvious and most efficient method for data publishing is through internet services which are supported by the sensing networks data store. This can be tightly coupled to the data store, for instance directly querying the spatial database, or more loosely associated through the publication of services which provide access to raw, collated or aggregated data (Park et al., 2011).

Some common raw data formats employed by the reviewed sensor/monitor networks include XML, JSON, KML, RDF, GeoRSS and CSV. Typically, these are delivered through web based HTTP REST services, often unauthenticated for public consumption. This gives users and researchers access to the data itself, in both raw and calibrated formats. Other networks hide these services from public consumption and provide web and mobile app interfaces to view and consume the data in a decoupled manner.

The security models implemented around the data dissemination vary depending on the public nature of the data and the projects desired publication outcomes. Some providers are catering to the public consumption and interpretation of their collated data, and hence require no authentication or registration to consume the data. Other providers are locked down and only allow data to be accessed to registered users, applications or websites for publication.

Some further decoupled data services can include the production of visualizations through interactive and static mapping, heat maps, graphing and the creation of service orientated alert systems over SMS, email and social media notifications (Castell et al., 2015; Schneider et al., 2017).

7. Applied outcomes of low-cost sensors/monitors projects

This review identified references to over 17 projects which reached the *Deployment* stage (C – see Fig. 1), followed by utilisation of the *Data* (viewing, harvesting, storing - D and analysis - E) and *Outcomes* (F). It should be stressed that in addition to the identified large projects, which reached the outcome stage (F), with the outcomes documented in peer-reviewed literature and/or on the project websites, our literature search found also many other, smaller projects, often based at a university, or run by small commercial companies (usually related to technology development). The large projects were always consortia, not single universities, organizations or companies (with the exception of the U.S. EPA). Supplementary Information Section 3 lists all the projects found, many of them through search of grey literature. In most cases the information available was insufficient to conclude on the outcomes of the project.

Table 1 provides a list of the selected projects, together with the periods of their duration, funding source (government or commercial/crowd), summary of applied outcomes (as listed on projects' websites), and specifically whether there is an operating network of sensors/monitors (left by projects which ended or operating in case of ongoing projects). More detailed information about these projects is provided in Supplementary Information Section 3.

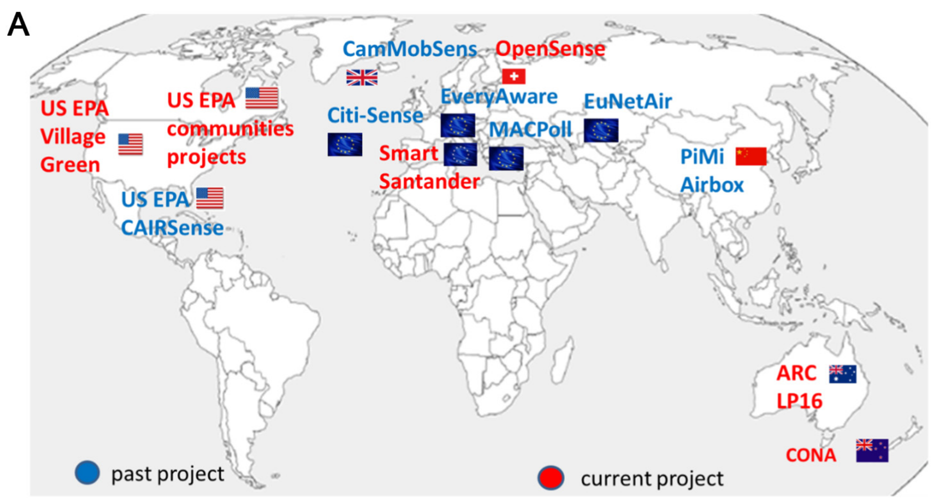
It can be seen from Table 1 that out of the 17 projects, 11 are/were government funded and 6, commercial/crowd funded. There are two avenues of government funding of such research: either via competitive national/multinational grants – which is/was the case for majority of projects, or directly, which is the case for the two U.S. EPA funded projects (CAIRSENSE and Village Green). The fact that such a sizable fraction of the large projects is commercial/crowd funded (about 30%) is by itself very significant and may signal the paradigm change in air quality monitoring: a shift from it being controlled by government agencies and conducted for regulatory purposes, to being conducted with the contribution from many stakeholders, and potentially providing information beyond regulatory compliance.

From a global perspective, of interest is the geographical spread of the application of low-cost sensors/monitors, and to obtain a better understanding of this, the projects were placed on the map of the world, separately for government (Fig. 2a), and commercial/crowd funded projects (Fig. 2b).

It can be seen that the majority of the government funded projects were/are conducted in the US and Europe, with one project conducted in China, one in Australia and one in New Zealand. As for the commercial/crowd funded projects, the U.S. has four current projects while Europe has one project in latent mode. There are currently some limited sensor/monitor activities in low and middle income countries (LMICs) and their consideration for use in this context has motivated several recent workshops and a white paper in development by World Bank, U.S. EPA, LMICs representatives, and others.

An overarching issue in the use of sensor/monitor technology is the level of expertise required for successful use and interpretation of the data. Sensors/Monitors are often marketed as easy to use and interpret; however, air monitoring experts have demonstrated the current technology can have significant complexity in both implementation and data analysis. Not only does one have to have an understanding of what sensors/monitors might serve the best purpose, but one must also have the skills to often deal with highly complex, high frequency, and sometimes erroneous data. These issues often confound many new entrants to air monitoring, who are attracted by the low price point of sensor/monitor technology, including community groups, researchers from other fields, and private sector use.

Secondly, we may ask what the life span of individual projects is. To answer this question Fig. 3 compiles the projects together with their duration (as stated on the relevant websites). Here we focused on projects which started more than three years ago, to consider only those



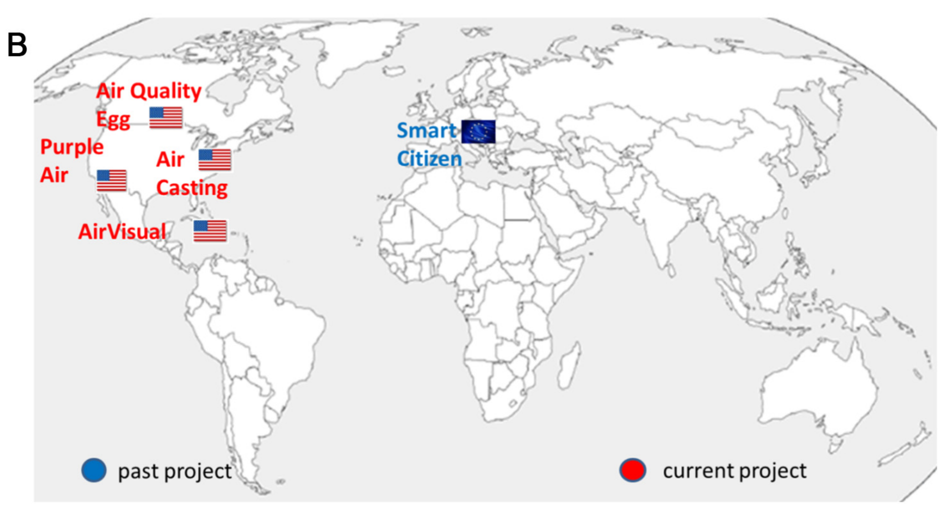


Fig. 2. Geographical locations of low-cost sensor/monitor network hubs (while the networks themselves range from covering a single country to being global): a) government funded projects, and b) commercial/crowd funded projects.

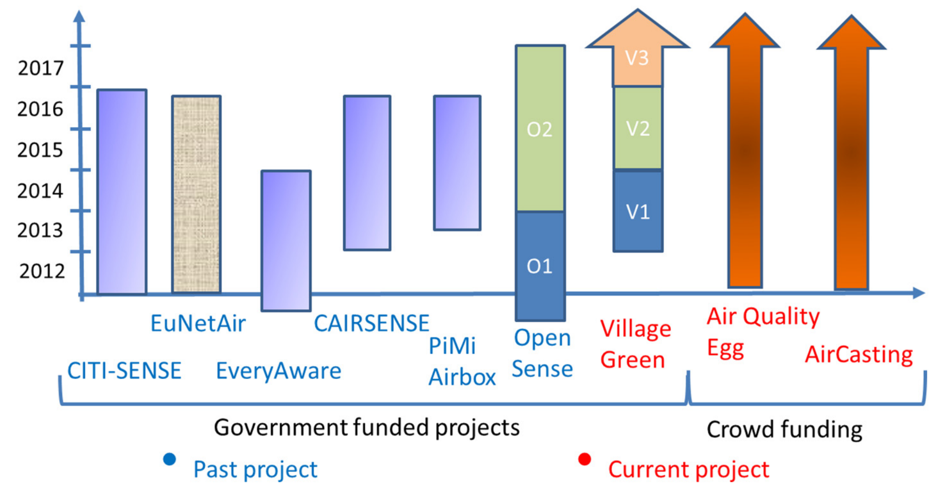


Fig. 3. Life span of the selected low-cost sensor/monitor projects (O1, O2, V1, V2, and V3 are different phases of the project).

which passed the typical duration of government funding, of three to four years. An interesting observation can be made from inspecting Fig. 3 that two of the commercial/crowd funded projects which started the earliest (Air Quality Egg and Air Casting) still continue, while most of all the government funded projects appear to have finite life.

There are many different types of potential applied outcomes of the projects, and they include:

Peer reviewed journal publications. Each of the large government funded projects generated peer reviewed publications, and thus contributed to scientific body of information. Many of the publications focused on the technology itself, or demonstration of the proof of concept (that sensors, monitors or their networks can be deployed and utilized), however, fewer publications provided new information, not available from the existing monitoring networks, on some aspects of pollution, source emissions or exposures. For example, within Citi-Sense project, Moltchanov et al. (2015) demonstrated the feasibility of wireless sensing network in urban area while Castell et al. (2017) evaluated the performance of a commercial low-cost air quality sensor platform (AQMesh); Jiao et al. (2016) described the outcome of the U.S. EPA funded project CAIRSENSE in evaluating the performance of different sensors/monitors.

Website information. All the projects except PiMiAirBox, have their website providing updates on the progress of the projects, as well as information on air pollution, source emissions or exposures, and rising awareness. AirVisual is a good example of website that contains up-to-date information about air pollution.

Information sessions open to the public. Many projects organized workshops, or seminars to engage with citizens. Some project also developed social media platforms including building apps to facilitate communication between the project partners, and to facilitate citizens' engagement, participation and network building e.g. Citi-Sense project or U.S. EPA Air pollution monitoring for communities grant.

School children education. Recognising that education of children have lasting, lifelong effect on the children, projects like Citi-Sense have developed a program that enables schools to take part in air quality monitoring.

Operating networks of sensors/monitors with data being utilized. Utilisation includes making data available on the website, providing visual maps on air pollution on the websites or through mobile phone applications, information about personal exposure, and warnings of high pollution/exposure. While most government-funded projects did not result in an operating network many crowd-funded projects currently maintain maps of sensor/monitor networks (e.g. AirCasting, Air Quality Egg, AirVisual and PurpleAir). It is most likely a result of the low maintenance cost and the interest of participants in the networks.

In the context of the conceptual framework outlined in Fig. 1, two large projects listed in Table 1 are discussed below to highlight their applied outcomes.

Citi-Sense (http://co.citi-sense.eu) operated between 2012 and 2016 in nine European cities, covering a variety of climatic and cultural conditions, from Oslo (Norway) to Haifa (Israel) and Edinburg (United Kingdom) to Beograd (Serbia). Sensor/Monitor networks were deployed to investigate three use cases: ambient air quality, indoor environment at schools, and the quality of urban spaces. The project broadly followed the steps outlined in Fig. 1, first in a pilot and then in a field study.

For the ambient air quality and indoor environment, the project's technical starting point were eight existing operational sensor platforms for monitoring air pollution, assuming that they were ready for deployment in sufficient numbers across the participating cities. All sensors/monitors in the devices came from the same manufacturer, but the devices' designs varied in most aspects. The project also assumed that it would be possible within a realistic time to build a common communication platform. This communication platform was designed to facilitate access to data and information to citizens, supporting the ultimate aim of the project to empower them on air quality. A number of tools and products were suggested for end users, and stakeholders in each use case were asked to participate on their final development.

In each of the steps of Fig. 1, a number of practical issues had to be solved. Prior to delivery of sensor platforms, it was necessary to solve platform malfunctions, to develop a testing protocol to ensure data comparability across the locations, and thus ultimately, to support further development of the platforms. In the field study, four platforms were used across the two air related use cases, each for a different purpose (stationary and wearable platforms for outdoor use, a stationary platform for indoors, and a stationary radon unit for indoors). The pollutants measured were NO_2, oxides of nitrogen (NO_x), O_3, PM and carbon dioxide (CO_2), but not all platforms were configured for all the pollutants. The deployment of the units in the field by the city teams required agreements on a number of levels and which was technically challenging. For the communication platform, data ingestion and data provision were based on common standardized protocols, and a common data model for the whole project. Efficient retrieval of the collected data was dependent on the internal architecture of the data repository. The functioning steps A-D of the Fig. 1 were required for development of the products that were to be the basis of the citizen empowerment. Web portal for simultaneous visualisation of all project measurements and a derived map for air quality was the main project product, complemented by a number of assessment questionnaires and questionnaires on air quality perception and knowledge, and a kit for assessment of outdoor spaces.

In the final 12 months of the project, CITI-SENSE was able to deploy the full chain A-F of Fig. 1, and demonstrate a full technical implementation. At one time for over one month, the project operated a network of > 330 sensor platforms for air quality providing data for hourly updates of air quality information in eight cities. The project outcomes, including computer codes, project deliverables describing all steps summarized above as well as publications, are publicly available.

Village Green – The Village Green was first deployed in 2014 with a single pilot station in Durham, NC. The station was designed to be a test platform involving compact, solar-powered monitoring system informing local communities about continuous near real-time environmental data. The station was evaluated for measurement performance against a nearby reference monitoring station (Jiao et al., 2016), whereby it was determined to have reasonable performance despite its solar-powered operation that subjected monitoring equipment to ambient environmental conditions and power interruptions. The pilot station success prompted the deployment of seven additional stations throughout the US, that were competitively selected from state and local air quality agency proposals based upon their intended location and application purpose. Public parks, libraries, museums and other locations of high public access linked the stations to local partners devoted to sustainable energy practices, environmental awareness, and educational opportunities. The Village Green has provided a wealth of community-based knowledge and data from these sites are being used to assist the U.S. EPA in establishing short-term data messaging (Jiao et al., 2015).

Two commercial/crowd funded projects, AirVisual and Purple Air, which are listed in Table 1 but not included in Fig. 3 because both started only two years ago, should be highlighted separately due their consistent and global progress.

AirVisual is a global project, monitoring $PM_{2.5}$ and CO_2 using the AirVisual Node as a monitor and providing air pollution app. The app offers free access to a large air quality database of 9000+ cities globally with > 8000 AirVisual nodes distributed in 44 countries around the world. The app and AirVisual website provide a 3-day pollution forecast, using machine learning and artificial intelligence, together with a 3-D air pollution map. AirVisual map utilize the data from the AirVisual nodes as well as from the regulatory monitoring stations.

Purple Air has grown rapidly over the past year or two, and has about 900 Purple Air nodes that measure PM_1, $PM_{2.5}$ and PM_{10} across 5 continents although the majority of them operate in the US and Europe, with the number of nodes growing currently by about 30 a day. Purple Air provides information on air pollution as color-coded AQI, together with the actual concentration of PM at the monitoring point, and the data can also be accessed by researchers upon request for academic purposes.

8. Concluding remarks

As for the first question set by this review, we have concluded that *the sensors/monitors were fit for many specific purposes* for which they were applied. Regarding the second question (*How far these technologies and their applications have progressed to provide answers and solutions, beyond just demonstrations that they can be utilized?),* it is clear that while different projects had/have different objectives and focused on different set of outcomes. Overall, application of low cost sensors/monitors have already changed the paradigm of air pollution monitoring, and application of these technologies is set to grow. In particular, the current low-cost sensing technologies are able to fulfil two of the four tasks recommended by Snyder et al. (2013), including: (1) *supplementing routine ambient air monitoring networks*, and (2) *expanding the conversations with communities*. With some of the commercial/crowd funded projects of global reach and fast expanding, both these tasks are fulfilled beyond single authority responsible for air quality management, and beyond single community. There is still more work to do on point (3), *enhancing source compliance monitoring*, which is of particular necessity and urgency in developing countries. Also, there has been somewhat less progress in wide scale *monitoring of personal exposures* (4) because the personal exposure monitoring is more demanding, for example, than stationary deployment as it requires engagement and commitment from the study volunteers. Furthermore, the bulkiness and power requirement of the sensors/monitors is another restraint. Improvement in downscaling the sensor and its power consumption will further this field of research. It can be argued that with a significant expansion of monitoring networks, and with not only the data on concentrations available to the individuals, but also practical information (on, for example, whether the air quality is good or bad), individuals will not have to carry sensors/monitors to be able to assess their exposure to outdoor air pollution. Personal exposure monitoring would, however, still be important to provide information on the fraction of exposure at home resulting from operation of indoor sources, as well as on exposure to combustion products such as ultrafine particles (< 0.1 μm). Concentrations and exposures to ultrafine particles (measured in terms of number, rather than mass concentrations) are not correlated with those of $PM_{2.5}$, as they have different sources (although at very high concentration of ultrafine particles, when they rapidly grow by coagulation, there could be a measurable contribution to mass concentration). At this stage, however, no low-cost technologies are available to monitor ultrafine particles.

Disclaimer

The opinions expressed in this paper are those of the author and do not necessarily reflect the views or policies of the Government of the Hong Kong Special Administrative Region, nor does mention of trade names or commercial products constitute an endorsement or recommendation of their use. The U.S. Environmental Protection Agency through its Office of Research and Development participated in the development of this article. It has been reviewed by the U.S. EPA and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. The authors have no conflicts of interest or financial ties to disclose.

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Appendix A. Supplementary information

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