Environment International 116 (2018) 286–299

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Review article

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

Lidia Morawska[a,b,*], Phong K. Thai[a,b], Xiaoting Liu[a,b], Akwasi Asumadu-Sakyi[a,b], Godwin Ayoko[a,b], Alena Bartonova[c], Andrea Bedini[d], Fahe Chai[e], Bryce Christensen[a,b], Matthew Dunbabin[f], Jian Gao[e], Gayle S.W. Hagler[g], Rohan Jayaratne[a,b], Prashant Kumar[h], Alexis K.H. Lau[i], Peter K.K. Louie[j], Mandana Mazaheri[a,b,k], Zhi Ning[l], Nunzio Motta[b], Ben Mullins[m], Md Mahmudur Rahman[a,b], Zoran Ristovski[a,b], Mahnaz Shafiei[b,f,n], Dian Tjondronegoro[o], Dane Westerdahl[l], Ron Williams[g]

[a] Queensland University of Technology, International Laboratory for Air Quality & Health, Brisbane, QLD, Australia
[b] Queensland University of Technology, Science and Engineering Faculty, Brisbane, QLD, Australia
[c] Norwegian Institute for Air Research, POB 100, N-2027 Kjeller, Norway
[d] KZN Group, 12 St Georges Terrace, Perth, WA 6000
[e] Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[f] Queensland University of Technology, Institute for Future Environments, Brisbane, QLD, Australia
[g] U.S. Environmental Protection Agency, Office of Research and Development, Research Triangle Park, NC, USA
[h] Global Centre for Clean Air Research (GCARE), Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, GU2 7XH, Surrey, United Kingdom
[i] Hong Kong University of Science and Technology, Hong Kong, China
[j] Environmental Protection Department, Government of the Hong Kong Special Administration Region, China
[k] Climate and Atmospheric Science Branch, NSW Office of Environment and Heritage, Sydney, NSW, Australia
[l] School of Energy and Environment, City University of Hong Kong, Hong Kong, China
[m] Curtin Institute for Computation, Occupation and Environment, School of Public Health, Curtin University, Perth, WA, Australia
[n] Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia
[o] School of Business and Tourism, Southern Cross University, QLD, Australia

ARTICLE INFO

Handling editor: Robert Letcher

Keywords:
Low cost sensor/monitor
Air pollution sensing
Sensor data utilisation
Air sensor/monitor performance
Personal exposure monitoring

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

* Corresponding author at: Queensland University of Technology, Australia.
E-mail address: l.morawska@qut.edu.au (L. Morawska).

https://doi.org/10.1016/j.envint.2018.04.018
Received 8 February 2018; Received in revised form 11 April 2018; Accepted 11 April 2018

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

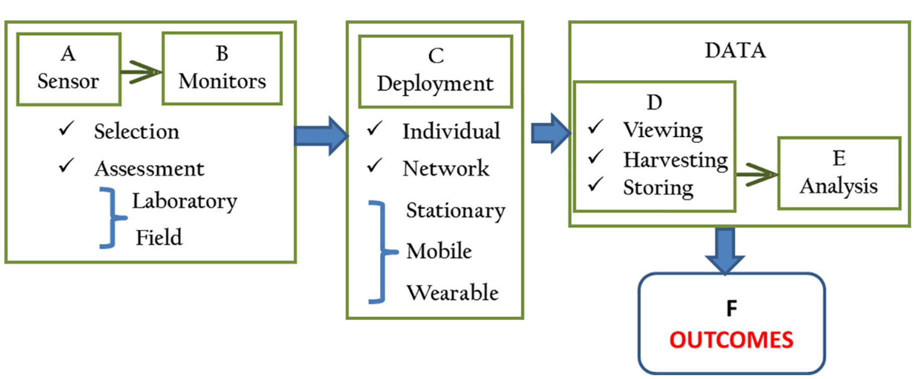

Fig. 1. Conceptual framework for the utilisation of low-cost sensing technologies.