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Characteristics and applications of small, portable gaseous air pollution monitors☆

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ABSTRACT

Background: Traditional approaches for measuring air quality based on fixed measurements are inadequate for personal exposure monitoring. To combat this issue, the use of small, portable gas-sensing air pollution monitoring technologies is increasing, with researchers and individuals employing portable and mobile methods to obtain more spatially and temporally representative air pollution data. However, many commercially available options are built for various applications and based on different technologies, assumptions, and limitations. A review of the monitor characteristics of small, gaseous monitors is missing from current scientific literature.
Purpose: A state-of-the-art review of small, portable monitors that measure ambient gaseous outdoor pollutants was developed to address broad trends during the last 5–10 years, and to help future experimenters interested in studying gaseous air pollutants choose monitors appropriate for their application and sampling needs.
Methods: Trends in small, portable gaseous air pollution monitor uses and technologies were first identified and discussed in a review of literature. Next, searches of online databases were performed for articles containing specific information related to performance, characteristics, and use of such monitors that measure one or more of three criteria gaseous air pollutants: ozone, nitrogen dioxide, and carbon monoxide. All data were summarized into reference tables for comparison between applications, physical features, sensing capabilities, and costs of the devices.
Results: Recent portable monitoring trends are strongly related to associated applications and audiences. Fundamental research requires monitors with the best individual performance, and thus the highest cost technology. Monitor networking favors real-time capabilities and moderate cost for greater reproduction. Citizen science and crowdsourcing applications allow for lower-cost components; however important strengths and limitations for each application must be addressed or acknowledged for the given use.

1. Background and objectives

The urban environment cannot be fully characterized using sparse, static networks of air pollution monitors (Mead et al., 2013). While established urban networks of fixed site monitors have spatial densities on the order of 1–10 km^2 (i.e. distance between monitors is generally 1–10 km), concentrations of regulated criteria air pollutants can vary significantly within 10–100 m from roadways (Snyder et al., 2013). To combat this issue, recent advancements in sensor technology have led to the development of small, portable monitors with various and dynamic uses, and in some instances at a very low-cost. Mobile monitors, which can be defined as small devices that are capable of obtaining measurements while in motion, as well as stationary portable monitors, which are designed to be easily moved between various locations for stationary monitoring, are well-suited to address the spatiotemporal variability in air pollution caused by changes in local meteorology, traffic density, street topology, distance from sources, and pollutant chemistry (Bereitschaft, 2015; Snyder et al., 2013; Van den Bossche et al., 2015). The word “monitor” is used synonymously with the

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phrase "instrument-system". In other words, air pollution "monitors" are systems made up of many different parts that perform various functions (e.g. power supply, signal conversion, display screen, etc.), while "sensors" refer to the individual air pollution sensing component.

Improvements in portable air pollution technology are motivated by a widespread desire to create more accurate human air pollution exposure assessments. Quantifying evidence of human exposure is ultimately needed for legislative purposes (Mead et al., 2013) so that urban planning changes can be made. For example, off-road cycling paths can be created and/or maintained for safer and healthier non-motorized travel. In order to advance environmental and human health studies, mobile air pollution monitors are increasingly used to obtain more accurate personal exposure estimates. Studies show that personal sampling of air pollution is preferable when attempting to accurately measure human exposure (Good et al., 2015; Steinle et al., 2013; Weichenthal et al., 2011; Zartarian et al., 2007), and that a high spatiotemporal resolution is required to correct for misinterpretation of actual exposure (Baxter et al., 2013; Kumar et al., 2013). Although there is a lack of concrete information on the effective use of such sensors by individuals and communities, specific vulnerable populations in urban areas could benefit from these sensor systems (e.g. child exposure (Grineski, 2007; McConnell et al., 2010; Vanos, 2015), and environmental justice such as health inequity issues could be addressed (Grineski et al., 2007; Pope, 2014; Wakefield et al., 2001; Wheeler and Ben-Shlomo, 2005; White et al., 2012)). The rapid acceleration of technological innovations in environmental sensing offers vast opportunities to improve individual and collective decision-making, and the ability to pursue improved environmental equality.

However, the measurement accuracy of available monitoring devices vary greatly depending upon their intended applications. With continual and rapid advancements in small sensor technology, it can be difficult for different audiences (i.e. researchers, citizen scientists) to stay informed of the various options, cost, limitations, and benefits specific to their intended use. Furthermore, while numerous research studies and reviews have been published on the use of such mobile and personalized monitors for particulate matter, information on the use of mobile monitors for gaseous pollutants is scarce. Studies have distinguished the technologies of mobile monitors of gaseous pollutants from those of stationary monitors (Kumar et al., 2015; Aleixandre and Gerboles, 2012; Castell et al., 2013; Steinle et al., 2013; Snyder et al., 2013; Van Poppel et al., 2013) and evaluated mobile monitors in comparison to reference analyzers (Gerboles and Buzica, 2009; Lin et al., 2015; Williams et al., 2014b), yet no current study synthesizes these findings or promotes new research directions from the perspectives of specific audiences and intended applications. Therefore, this state-of-the-art review is the first to provide an exclusive assessment of small portable air pollution monitors that measure ambient gaseous outdoor pollutants.

The United States Environmental Protection Agency (EPA) *Air Sensor Guidebook* (Williams et al., 2014a) includes a table comparing the performance characteristics (e.g. accuracy and precision) of several mobile monitors, which is useful for researchers undertaking mobile studies, yet some of the monitors are outdated or discontinued. The format and utility of this EPA resource was a primary influence for the current paper.

This review aims to help future experimenters interested in studying gaseous air pollutants choose monitors appropriate for their application and sampling needs. Moreover, we highlight particular aspects of currently available sensor technologies used within the small monitors that may influence and motivate future portable/mobile monitor development, which will remain useful long after the current monitors are replaced. Further, a detailed examination of the components and characteristics of several handheld mobile devices is provided to address the relations between cost and data quality. Finally, the current review distinguishes the current technologies based upon different research areas (e.g. epidemiology/public health, atmospheric chemistry, urban planning) and different applications (e.g. government, citizen scientists, researchers) so that there is less confusion amongst groups. While there are many small monitors that measure particulate matter (PM) that have been widely used in mobile monitoring studies, these are not the focus of this review. For detailed reviews and further information on research and applications regarding PM spatial assessments and monitoring, the reader is referred to Jovašević-Stojanović et al. (2015) and Gozzi et al. (2015).

2. Methods

A "state-of-the-art review" addresses more current matters instead of focusing on the combined retrospective of an entire body of scientific literature (Grant and Booth, 2009). Therefore, this review first addresses the broad trends in portable monitor use during the last 5–10 years, further narrows its focus to gaseous monitor technologies, and finally highlights specific aspects of a select list of recently available small, portable gaseous monitors.

In order to select specific monitors for the review, online searches were performed on general and scientific databases (e.g. Google Scholar and Science Direct) using keywords: "portable/mobile air pollution monitor" and "handheld air quality monitoring". These searches included articles from both commercial websites and peer-reviewed journals and were performed in 2015. Only monitors that measure one or more of three specific gaseous air pollutants (O_3, NO_2, and CO) were selected. These three gases are common criteria urban air pollutants that have been widely analyzed in the recent scientific literature and can be harmful to human health (e.g. Castell et al., 2013; Deville Cavellin et al., 2015; Good et al., 2015; Lin et al., 2015). The air pollution monitors were chosen based upon the availability and accessibility of the comparable information. For example, if a monitor was found on the online search that measured one of the selected gases, but specifics such as test results and the distinct components could not be found, then the monitor was excluded from this review. Only resources that provided specific information that was useful to the comparisons presented in Tables 1 and 2 (e.g. intended application, tested precision, sensing range, battery life) were included. The available information also helped establish the variables to be compared. For instance, many resources did not list monitor "accuracy", but many sources listed the "precision", therefore, the precisions were compared in this review and accuracies were not.

The search revealed seven small, portable air pollution monitors: the Personal Ozone Monitor (2B Technologies Inc.), the SENS-IT (Unitec), the CairClip (Cairpol), the Series 500 Portable Monitor (Aeroqual Inc.), the AGT Environmental Sensor (AGT International), The Smart Citizen Kit (Acrobotic Industries), and the AirCasting Air monitor (HabitatMap).

3. Review of literature

3.1. Applications of mobile air pollution monitors

Three of the most prevalent uses for mobile air pollution monitors include (1) personal exposure monitoring, (2) the supplementation of existing air pollution monitor networks, and (3) citizen science or education (Williams et al., 2014a). Mobile air pollution monitors can also be used for measurements of near point sources for safety reasons; however, this paper seeks to specifically address applications intended for monitoring general human

Table 1
A comparison between various applications and physical features of seven portable gaseous air pollution monitoring devices.

Device Name	Developer	Applications	Non-Pollutant Measurements	Components	Battery Life and Storage	Data Acquisition	NotableReferences
PersonalOzone Monitor	2B Technologies	personal exposure, industrial safety, vertical profiles, urban networks, long-term monitoring	internal temp/pres GPS location	air pump lamp O_3 scrubbers GPS LCD screen zeroing cartridge	5–8 h 8192 lines	Internal logger serial port USB	2B Technologies (2012) 2B Technologies (2016)
SENS-IT	Unitec	outdoor monitoring, industrial/urban, fence-line monitoring, smart city networks	internal temp	aluminum case internal fan	no battery-needs 12 V power	external logger digital RS485 LEMO	Unitec (2016a) Unitec (2016b) Williams et al. (2015)
CairClip	Cairpol	real-time, personal exposure	N/A	aluminum case and clip micro fan replaceable filter LCD screen	24–36 h 28,000 + points	internal logger USB	CairPol (2016) Williams et al. (2014b)
Series 500 Portable Monitor	Aeroqual	personal exposure, seasonal variations, rural monitoring, urban monitoring, traffic emissions, network monitoring	optional: temp/humidity	internal fan LCD screen	± 8 h 8188 points	internal logger analog via RJ12 digital via-RS232 to USB	Aeroqual (2016a) Aeroqual (2016b) Cattaneo et al. (2010) Elampari et al. (2010) MacDonald et al. (2014) Jallad and Espada-Jallad (2012)
Environmental Monitor	AGT	personal exposure, traffic emissions, industrial emissions	internal temp/humidity noise pressure UV radiation ambient light	internal fans solar panels	4–8 h without solar	Bluetooth uses smartphone GPS	Williams et al. (2014b)
Smart Citizen Kit	Acrobotic Industries	Crowdsourcing, citizen monitoring, real-time	temp/humidity noise ambient light	two circuit boards	several hours solar panel input	Wi-Fi microSD card	Smart Citizen (2016)
AirCasting Air Monitor	HabitatMap	Crowdsourcing, real-time, do it yourself	internal temp/humidity	open source	N/A	Bluetooth	HabitatMap (2016)

exposures.

Personal monitoring helps researchers better understand the relationship between specific gaseous air pollutants and human health based on activity pattern and personal exposure (e.g. Bales et al., 2014; Beckx et al., 2009; Kaur et al., 2005; Wu et al., 2010). By equipping subjects with mobile air pollution monitors that can be worn near their face or on their body, researchers can accurately assess pollution exposure relative to typical ambient measurements (Cattaneo et al., 2010; Stevens et al., 2014; Zartarian et al., 2007).

Supplementary monitoring improves the density of air pollution observations, which can help engineers quickly identify hazardous areas and help scientists improve fine-scale air quality models (Kumar et al., 2015). By filling the spatial gaps between established fixed-site monitors, supplementary monitors improve the spatial and temporal resolution of air quality data (Williams et al., 2014a). One method for supplementary monitoring involves the use of low-cost, portable *stationary* monitors in dense networks consisting of many devices that wirelessly transmit data to a central server (e.g. AirSensa, 2016); however, *mobile* monitors (which may be worn by individuals, attached to bicycles, or transported alongside commuter vehicles) have the capability to collect supplementary data with higher spatial and temporal resolution because data may be crowdsourced by the use of smartphones or Bluetooth (e.g. Antonic et al., 2014). Such data can cover large areas and may be filtered into real-time computer navigation systems. For example, an air quality analysis project in Copenhagen, Denmark (Common Scents) used mobile monitors to collect real-time data across the entire city, which showed that the use of crowdsourcing for environmental monitoring and public health decision-making is feasible (Boulos et al., 2011). In addition, the CITI-SENSE project in Oslo, Norway was designed to provide real-time resources for citizens from the use of portable sensors and mobile applications (Castell et al., 2015).

Citizen science connects everyday citizens to information for educational and awareness purposes (Williams et al., 2014a). The small size and low cost of many mobile air pollution monitors allow more schools, teachers, and health programs to receive hands-on experience and gain improved understanding of how air pollution data is collected and analyzed. For individuals with health ailments, these tools may become essential to enhance their awareness and thus allow them to consciously avoid harmful exposure. Community-based monitoring allows access to location-based and/or personal, real-time air pollution data (White et al., 2012; Wheeler and Ben-Shlomo, 2005; Wakefield et al., 2001), thus helping average, healthy citizens improve their individual understanding of community/neighborhood air pollution and empowers people to change their behavior (Bales et al., 2014).

Each of these three applications require measurements with varying degrees of accuracy and temporal resolution, yet many current monitors are not characterized by use or efficacy, thus it is a challenge for different audiences to find monitors that fit their application appropriately. Personal monitoring — because it directly links air pollution and human health — requires monitors with the greatest accuracy, particularly if medical diagnoses or health risk assessments are the goal. Health studies require mobile monitors with customizable sampling rates for various movement speeds and exposure times. For example, a study of a subject's

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Table 2
A comparison of the sensing capabilities, associated characteristics, and costs for each separate portable gaseous air pollution monitoring device. The list is sorted from high to low cost.

Device Name	Developer	SensorType[a]	Pollutant(s)	Precision (ppb)	SampleTime	Range (ppb)	Approx. Cost USD	Notable References
Personal Ozone Monitor	2B Technologies	UV	O_3	2.0	10s	2–10000	$4900	2B Technologies (2012)
SENS-IT (O_3 or NO_2)	Unitec	MOS	O_3 or NO_2	10	data logger	10–250	$2250	Unitec (2016a) Unitec (2016b) Williams et al. (2015)
SENS-IT (CO)	Unitec	MOS	CO	200	datalogger	100–8000	$2250	Unitec (2016a) Unitec (2016b) Williams et al. (2015)
CairClip	Cairpol	EC	O_3/NO_2 ratio	9.3	1 min	0–250	$1076	CairPol (2016) Williams et al. (2014b) Duvall (2014)
Series 500Portable Monitor (O_3)	Aeroqual	MOS	O_3	± 5.0[b1] 6.0[b2]	1 min	0–500 0–150	$460	Aeroqual (2016b)[1] MacDonald et al. (2014)[2] Lin et al. (2015)
Series 500 Portable Monitor (NO_2)	Aeroqual	EC	NO_2	± 20	1 min	0–1000	$460	Aeroqual (2016b)
Series 500 Portable Monitor (CO)	Aeroqual	EC	CO	± 50[c]	1 min	0–250000 −100000	$460	Aeroqual (2016b)
Environmental Monitor	AGT	MOS	$O_3/NO_2/COCO_2/PM_{10}$	10.3 (O_3) 1.2 (NO_2)	N/A	10–1000	N/A[d]	Williams et al. (2014b)
Smart Citizen Kit	AcroboticIndustries	MOS	NO_2/CO	N/A	any	1000–1000000 (CO) 50–5000 (NO_2)	$230	Smart Citizen (2016)(e2v Technologies, 2008)
AirCasting Air Monitor	HabitatMap	MOS	NO_2/CO	3.0 (NO_2)	N/A	50–5000 (NO_2)	$180[e]	HabitatMap (2016) Williams et al. (2014b) Component Distributors, Inc. (2016)

[a] Sensor type abbreviations are: UV - Ultraviolet absorption, MOS - Metal Oxide Semiconductor, EC - Electrochemical.
[b] There are two O_3 sensor heads available for outdoor use: (0–0.5 ppm and 0–0.15 ppm). This precision is for the 0–0.15 ppm sensor head.
[c] There are two CO sensor heads available for outdoor use: (0–25 ppm and 0–100 ppm). This precision is for the 0–25 ppm sensor head.
[d] This monitor is not available for direct purchase online.
[e] Instructions on how to build this monitor and which materials to use are online (HabitatMap, 2016).

average daily exposure while walking may only require 1-min samples, while a study of personal exposure during a short time period at higher speeds, such as during a 20-min commute via bicycle, may need data on the order of seconds or less.

Supplementary monitoring also requires accurate air quality measurements, however, since this application requires monitors in proximity to a reference monitoring network, the supplementary mobile monitors may be frequently calibrated (e.g. Deville Cavellin et al., 2015), thus the monitors themselves may not need to have high independent performance. The temporal resolution of supplementary monitors must be high enough to capture the changing environment and averaged to the resolution the regulatory network.

Mobile monitors used in citizen science require less accuracy than the previous applications because data is less likely to be used for policy or direct health outcomes. The sampling rate of citizen science monitors must take into account how it is used, but also battery power. If a mobile monitor is used passively or frequently sends and receives data to a mapping application, a lower sampling rate may be crucial to allow the monitor to run for longer time periods without charging.

3.2. Trends in research

The current section provides information on the state of the science for small, mobile air pollution monitors in research, including the viability of applications and future research needs. This information highlights that research must address the inconsistencies that occur when using the monitors in the real world, as each application comes with unique challenges. For example, monitoring applications across widespread urban areas may require different experimental methods compared to applications at smaller spatial scales (e.g. neighborhood, community-level).

Many mobile air pollution monitoring studies from the early-to-mid 2000s focused on fine particulates collected in the commuter microenvironment (e.g. Kaur et al., 2007; Westerdahl et al., 2005; Zhu et al., 2002). More recently, technological advancements have resulted in the ability to study gaseous pollutants in a mobile fashion. Gas-sensing monitors have been employed by hand (Cao and Thompson, 2016; Chaudhry, 2013) and with different platforms (e.g. rolling cases (Cattaneo et al., 2010), bicycles (Elen et al., 2012; MacNaughton et al., 2014; Weichenthal et al., 2011)), and for various applications (e.g. health (Cattaneo et al., 2010; Delgado-Saborit, 2012; Wu et al., 2010), environment (MacNaughton et al., 2014), air pollution mitigation (White et al., 2012)). More advanced studies have described the technologically innovative development of sensor systems that may be directly connected to smartphones (Hasenfratz et al., 2012; Honicky et al., 2008), wirelessly connected to smartphones (Bales et al., 2014), and paired with smartphone apps (Antonic et al., 2014; Dutta et al., 2009).

Mobile monitoring with wireless connections to cell phones has become increasingly popular because it allows for crowdsourcing of information using GPS coordinates (Al-Ali et al., 2010; Antonic et al., 2014; Castell et al., 2013; Dutta et al., 2009; Hasenfratz et al., 2012). The increase of cellular bandwidth in conjunction with the emergence of portable air pollution sensors have resulted in such capabilities (Devarakonda et al., 2013), generating large amounts of data; however, in order to apply the information to

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policy and/or decision making, the limitations, misuse of the sensor systems, and individual sensor issues (e.g. environmental sensitivity to temperature and humidity) must be accounted for. Honicky et al. (2008) highlighted various challenges with the quality of air pollution sensor data from networked mobile monitors, challenges that include privacy, interference of user behavior, location coverage, calibration accuracy, and social aspects of mobile sensing.

An active area of research involves examining the fundamental science behind collection methods, variability of common air pollutants in urban areas, and testing and validation of methods not using crowdsourcing (Cao and Thompson, 2016; Good et al., 2015; Mead et al., 2013; Van den Bossche et al., 2015). Here, researchers routinely cite the need for post-processing methods, such as background normalization, event detection, and corrections for sensor drift over long time scales to be applied for accurate assessment of measurements. Such post-processing methods are limited in crowdsourcing studies, and hence validating crowdsourced data is a challenge (Honicky et al., 2008).

Many of these fundamental research studies utilize mobile platforms to assess on-road or near-road air quality and spatio-temporal gradients in pollution (Devarakonda et al., 2013; Weichenthal et al., 2011). For example, Good et al. (2015) studied the impact of route choice on air pollution exposure utilizing many separate instruments including small particle monitors, a CO sensor, and heart rate monitor, yet the techniques used were more advanced than those affordable or feasible for average citizens. However, the researchers provided notable findings, wherein a commute by car resulted in 15–20% higher exposures to CO than a commute by bicycle, consistent with related studies (De Nazelle et al., 2012; Kaur et al., 2005). Such a significant finding is an example of valuable and quantifiable evidence directly related to human health (in one city: Ft. Collins, Colorado), showing the benefit of increased data collection in further cities (Good et al., 2015).

3.3. Sensor technologies

The growing interest in mobile air pollution monitoring has led to the research and development of many innovative low-cost air pollution technologies. The methods of integration and operation are quite variable; therefore it is necessary to focus on the main differences between the technologies and their limitations in order to make direct comparisons. The most common techniques used in commercially available gas sensors are: metal oxide semi-conduction (MOS), electrochemical (EC), non-dispersive infrared radiation absorption (NDIR), and photo ionization detection (Castell et al., 2013). The first two techniques (MOS and EC) involve interactions between a sensing material and a specific gas (such as O_3, NO_2, or CO), while NDIR involves the absorption of light at specific wavelengths (Snyder et al., 2013).

MOS sensors [$\sim 12 \times 12$ mm] (also known as resistive sensors) are chemically reactive and output a change in resistance or conductivity proportional to exposure to various ambient gases (Castell et al., 2013). These sensors have the most ideal properties for designing gas sensors that may detect a large number of gases (Korotcenkov, 2013), but they have been found to require frequent calibration due to poor stability, sensor drift, and high cross sensitivity (Castell et al., 2013). MOS sensor responses are sensitive to temperature and often include a heater for more favorable internal reactions (Castell et al., 2013). Resistive sensors also have a one or two year lifetime are inexpensive and stable (Deville Cavellin et al., 2015); however, they can have interfering responses from changes in humidity, pressure, as well as other pollutant gases and they are typically less sensitive than EC sensors (Snyder et al., 2013).

EC sensors [$\sim 20 \times 20$ mm] are similar to the MOS sensors in that the air pollutant measurements are based on chemical reactions; however, EC sensors are based on amperometric methods involving an electrolyte and multiple electrodes (Mead et al., 2013). EC sensors are designed to output current that is directly proportional to a specific target gas. Similar to the MOS sensors, EC sensor performance can also be influenced by humidity, pressure, and temperature (Williams et al., 2014a), but the influence from temperature and other reactants (e.g. O_3) can be modeled (Castell et al., 2013). Gerboles and Buzica (2009) found that EC sensors experienced interference from varying wind velocities. EC sensors are low-cost, low-power, and more sensitive than MOS sensors; however, they have short lifetimes (1-year), need frequent calibration, experience drift, and have interferences from CO, $VOCs$, and NO_2 (Snyder et al., 2013).

NDIR sensors [$\sim 5 \times 5$ mm] include an infrared light and measure the intensity of the radiation through narrow absorption bands matching the absorption of the gas of interest. The intensity of the infrared radiation passing through the absorption band is related to the concentration of the gas. Sensors that use this technique for measuring hydrocarbons can experience cross-sensitivity, yet this technique works well for sensing CO_2 (Castell et al., 2013). NDIR sensors are compact and stable to changing temperature and humidity, but calibrations may be misinterpreted or inaccurate (Snyder et al., 2013).

Photo ionization detector sensors [$\sim 20 \times 16$ mm] (also known as ultraviolet (UV) sensors) use UV light absorbed by gas molecules to generate electrically charged ions and electrons that produce a current proportional to a concentration of a target gas (Castell et al., 2013). These sensors are relatively stable, but they can require frequent calibration, especially if the UV lamp is replaced (Castell et al., 2013). UV sensors have high accuracy and are stable to changes in pressure; however, they are sensitive to changes in humidity and anything that ionizes (Snyder et al., 2013).

The four air pollution sensing techniques described, although unique in their individual characteristics, share in common that they can be employed in small, low-cost air pollution monitors. The small differences in the technology are important when various monitors measuring similar chemicals are compared.

4. Comparison of commercially available monitors

4.1. Device descriptions and comparisons

Each air pollution monitor reviewed in this study has unique physical characteristics and individual sensing capabilities. Table 1 displays the differences between the intended applications and physical components of these monitors, while Table 2 compares each device's sensor aspects and associated costs. In order to compare differences between these portable monitors, a short background of each device is provided before the monitors are compared and discussed. Further information on each individual monitor, including specifics on how they are used, specifications (e.g. dimensions and accessories), test results, and photos, may be found in the supplementary material accompanying this review article.

The 2B Technologies Personal Ozone Monitor (POM) is a mobile ozone monitor built for robust applications such as vertical profiling with balloons and long-term monitoring. This device is essentially a miniaturized version of the developer's larger, regulatory-grade ozone-sensing instruments and contains many components that are associated with its advanced UV sensing technique (i.e. lamp, scrubbers) as well as an internal GPS (2B Technologies, 2012). This device's UV sensor observes with high precision and accuracy (2 ppb for both) within a wide range of O_3

concentrations (2–10000 ppb) (2B Technologies, 2016).

The SENS-IT monitors by Unitec were built strictly for outdoor applications and have physical characteristics designed for easy integration into sensor networks (Unitec, 2016a). These devices are not individually battery powered, thus they require a 12 V power source to run. Individual SENS-IT monitors may be integrated into groups (Williams et al., 2015). SENSE-IT monitors are available for several ambient pollutants besides the three discussed in this section including: sulfur dioxide, hydrogen sulfide, ammonia, VOCs, carbon dioxide, benzene, and methane (Unitec, 2016a).

The CairClip by Cairpol was originally developed for real-time measurement of air pollutants for a survey on industrial exposure and the associated respiratory effects on workers (CairPol, 2016). For industrial applications, this monitor has great portability, monitors continuously, and may be attached to personal items such as a belt. In a study of the CairClip's performance, it was found that the O_3/NO_2 sensor was more sensitive to O_3 than NO_2 (Williams et al., 2014b).

The Series 500 Portable Monitor by Aeroqual has been the most widely used in scientific research for diverse applications (compared to the other monitors in this review). Many of the applications shown in Table 1 demonstrate that this monitor has been used both individually and in networks, in several different environments, and in many countries around the world. The monitor's base allows for the user to employ one of many sensor heads, each designed to measure an individual gas. It has been shown that the ozone sensor head is the most effective when compared to a reference analyzer (Lin et al., 2015; MacDonald et al., 2014) and that other sensor heads need corrections in order to have similar accuracy (Lin et al., 2015). A recent research study employed both NO_2 and O_3 monitors to develop a land-use regression model and exposure surfaces in a large city (Deville Cavellin et al., 2015), demonstrating the ability of this monitor to obtain useful spatial and temporal information about urban air pollution.

The AGT Environmental Monitor was designed as a tool for bicyclists and pedestrians to measure air quality from traffic and industrial sources. Many of its features make it ideal for promoting citizen involvement in air quality monitoring. The device measures many different environmental variables (PM_{10}, temperature, humidity, noise, pressure, and UV radiation) and contains built-in solar panels to help charge the battery (Williams et al., 2014b). In an evaluation, the O_3 and NO_2 sensors showed high precision, similar to that of the SENS-IT monitor (Williams et al., 2014b).

The Smart Citizen Kit (SCK) by HabitatMap is a crowdsourcing tool that collects environmental data and has the capability of pushing data to the internet. The device measures CO, NO_2, temperature, light intensity, sound levels, and humidity and may send data over Wi-Fi, where it can be viewed in real-time on an online platform. Data can also be stored onto a microSD memory card (Smart Citizen, 2016). The SCK connects to a small battery, which has an input for solar panel charging. Unlike the previously mentioned monitors, this device does not come with a protective case; however, designs are available online so that individuals can separately buy or 3D print their own enclosures.

Similar to the SCK, the AirCasting Air Monitor (ACAM) is designed for crowdsourcing. The ACAM monitor may connect with a smartphone via Bluetooth using a custom application (HabitatMap, 2016). This device is unique in this review because its design is completely open source (i.e. step by step instructions on how to build it are available online) and thus it is purposed mostly for “do-it-yourself” projects and initiatives. The ACAM's MOS NO_2 sensor (MiCS-2710) has been tested by the EPA, revealing that the sensor has high precision (3 ppb), matching well with a reference monitor up to 100 ppb (Williams et al., 2014b). However, the NO_2 sensor was found to have a high out-of-the-box variability from the manufacturer (Williams et al., 2014b) and in February, 2014 a newer version of the MOS NO_2 sensor (MiCS-2714) became available (Component Distributors, Inc., 2016).

4.2. Sensor characteristics versus cost

Upon comparing the various monitor precisions in the small sample (Table 2), it is apparent that in general, more precise ozone instruments have higher costs. For instance, the most expensive O_3 monitor on the list, the POM, has a relatively high precision of 2 ppb, compared to 10.3 ppb by the AGT Environmental Monitor. The AGT monitor is believed to cost significantly less because it contains lower-cost MOS air pollution sensors and is intended for fewer, more personal applications. However, ozone data measured by the Aeroqual Series 500 Portable Monitor, which is for sale at one tenth of the cost of the POM, has a been found to have sufficient precision for spatial monitoring using a network of stationary monitors (6 ppb) (MacDonald et al., 2014). However, given the sample times and applications of the POM and Aeroqual S500, the POM would be recommended for sensing ozone while at higher speeds. The POM is listed as useful for vertical profiling of ozone using weather balloons, which is one such mobile application that makes the monitor unique and likely more costly.

In contrast, the monitors that measure NO_2 show less of a connection to cost. The NO_2-sensing device with the highest cost in this review is the SENS-IT, measuring with 10 ppb precision, while some inexpensive monitors (the AGT Environmental Monitor and the AirCasting Air Monitor) have been tested to record with precisions of 1.2 ppb and 3 ppb respectively.

Based on precision and cost, the CO monitors show a similar relationship compared to the NO_2 monitors. The lower-cost Aeroqual CO monitor has a precision on the order of 50 ppb, while the SENS-IT CO monitor has a precision of 200 ppb even though it is sold at nearly five times the cost. In general, the more precise O_3 monitors tend to be more costly, while the CO and NO_2 monitors are available with comparable precision, even at low costs.

One characteristic of these monitors that may better explain the discrepancy in cost is sensor range. It appears that the higher-cost monitors have generally smaller or narrow ranges. For example, the more costly SENS-IT CO monitor has a set range of 100–8000 ppb, while the less costly Aeroqual CO monitor and The Smart Citizen Kit have ranges of 0–25000 ppb and 1000–1000000 ppb respectively. This is also generally true for both O_3 and NO_2 monitors reviewed in this section. Narrower sensor ranges may imply that a sensor is appropriately manufactured and pre-calibrated for better accuracy, although it is not known if sensor range is a true indication of sensor superiority.

5. Discussion

Each mobile gaseous air pollution monitor compared in this study has capabilities that fit well within at least one of the three prevalent applications discussed in the *Applications of Mobile Air Pollution Monitors* section: personal exposure monitoring, supplementation of existing networks, and citizen science. Despite being designed and used for personal monitoring applications, the Cairclip and Aeroqual S500 only sample once every minute, which may be too slow for quickly moving mobile applications (i.e. from an individual on public transit or on a bicycle). In comparison, the SENS-IT and SCK are capable of recording data at much faster rates (i.e. every 1 or 5 s), which provides higher temporal resolution. The sample rate and sensor performance are both factors important for personal monitoring applications, as observations for medical and health audiences need to be highly accurate and sample more quickly depending on the movement speed of the subject (Baxter

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et al., 2013; Weichenthal et al., 2011; Williams et al., 2014a).

The Unitec SENS-IT devices are small and portable, but power needs and the lack of an internal data logger separate their primary use as a stationary portable monitor compared to the other monitors in this comparison. The SENS-IT monitor is most practical when used in fixed locations, rather than in a mobile fashion, therefore it is a prime example of a small, stationary monitor that may be integrated into supplementary networks. As previously mentioned, although the Aeroqual S500 can gather mobile data, it has also been used in temporary supplementary monitoring networks to improve the spatial density of measurements (Deville Cavellin et al., 2015; MacDonald et al., 2014). These supplemental monitors require good-to-moderate individual performance because their audience is typically researchers in academia or the government desiring data with high spatial resolution. Generally speaking, sample rates can be lower (e.g. 1 min) and mobile battery power is not a concern for this application.

Monitors purposed for citizen science or crowdsourcing tend to utilize lower-cost components in order to efficiently mass-produce, which is why monitors such as the SCK and ACAM are available at costs an order of magnitude less than the POM and SENS-IT monitors. This may be the reason that these low-cost monitors have greater sensor ranges and may have trouble producing responses that can be used to obtain accurate measurements of air pollution concentrations. The performance of individual SCK or ACAM sensors are not sufficient for mobile citizen science applications because without proper and very frequent calibrations, the measurements from these individual monitors are misleading and possibly quite inaccurate (McKercher, 2016; Williams et al., 2014a). Citizen science applications require monitors with longer independent lifetimes (e.g. calibrations are not needed on a frequent basis) because the resources to combat these issues are not available to the public. Monitors such as the SCK and ACAM may exclusively serve beginners in educational settings when used individually because each low-cost monitor only gives general responses to certain gases. Despite this, a great number of these monitors (if crowdsourced effectively) may provide useful results. In fact, the idea of crowdsourcing indicates that a greater *quantity* of data (to some degree) might be able to replace the need for individual monitor data *quality*. This idea is based on the statistical assumption that with enough data points, any single error is not significant.

Overall, the differences between these commercial mobile air pollution monitors (e.g. cost, precision, techniques and materials used) are quite large. For example, the POM, which requires additional components to sense using the photo ionization (UV) technique is much more costly than the other monitors. It is noticeable that within this sample of commercial instruments, there are two or three emerging categories of monitors. In order for users to select devices that fit within their intended application, this review suggests that specific categories be created to distinguish between the various mobile monitoring types in the future. The low sample size within this review — due to the low number of currently available mobile monitors that fit the review criteria — and a lack of thorough evaluation data, have been major challenges for creating a comprehensive analysis of the current technology; however, it was possible to notice an important discrepancy in monitor use based on cost. Therefore, it is recommended at minimum that high-cost mobile air pollution monitors be categorized separately from the lower-cost monitors. A secondary option is to categorize mobile air pollution monitors by the three main applications: personal exposure monitoring, supplementary networks, and citizen science or crowdsourcing.

Although this state-of-the-art review aimed for a comprehensive search of current literature and offered important future contributions, such a review does not provide a formal quality assessment. Further, a breadth of sources based on current availability were used to complete this review, sourced from reports, websites, as well as published research articles. While we addressed the most up-to-date matters, the rapid development of low-cost sensors and updates to reports and websites may outpace such a review; thus, we feel it is important for the research community to focus on making updated information available in one place, such as a comprehensive online resource table, and in peer reviewed literature as much as possible.

6. Addressing future research

In order for fundamental research, citizen science, and commercial development of small air pollution monitors to advance, progress must be made along four potential avenues. First, technological advances in the monitor hardware (i.e. sensor components, data acquisition) and monitor software (i.e. internet applications) must continue with the goal of providing reliable, accurate, and useful data that can be readily interpreted for individual purposes. The use of low-cost mobile air pollution monitors is still a developing area of interest (Kumar et al., 2015) and thus improving the technology can lead to more accurate air pollution research assessments. Small-scale air pollution monitoring studies for all applications (including personal, supplementary, and citizen science) can benefit from sensor technologies that have greater comparability to reference monitors and less error related to environmental variables such as temperature, humidity, and other gases.

A second area of improvement, as identified by this review, is remedying the mismatch of application and audience between categories of low-cost monitors and higher-cost commercially available monitors. The mismatch can be exemplified in fundamental research, wherein many groups have developed their own prototype monitors because the needed tools are not available (i.e. Hasenfratz et al., 2012). One suggestion for a research and development solution is to create a greater number of “one-size-fit-all” approaches similar to that of the Aeroqual S500 portable monitors (which have average cost and decent comparability to reference sensors) to appeal to greater and broader audiences. For example, a handheld mobile monitor that accurately measures several environmental variables (i.e. GPS location, temperature, humidity, and several air pollutants), stores its own data, and comes with useful accessories (i.e. attachments, cases, custom features) may appeal to both scientific and citizen audiences. Another suggestion is to carefully implement improved quality control procedures into existing monitors with software updates rather than depending on newer “off-the-shelf” instruments to make improvements. Improved quality control may help reduce issues with low-cost monitors (e.g. short monitor lifetimes). Despite these improvements, however, there is need for a differentiation between instruments that are sufficient for accurate measurements on their own and monitors that require frequent calibrations or collocation with reference analyzers. For example, colors can differentiate between each mobile monitor's intended application (green for crowdsourcing, yellow for network monitoring, and red for exposure analyses).

The existence of many different portable air pollution monitors is in part a result of evolving technology, but it may also be from an overarching concern to whether these portable sensors are valid for fundamental research. Although groups such as Gerboles and Buzica (2009) and Williams et al. (2014b) have paved the way for small air pollution sensor testing — allowing for this review and comparison — it seems that greater efforts are needed to understand the limitations of each monitor. A third potential step forward

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may be to standardize the necessary performance testing and calibration procedures required of monitors for specific applications. For instance, citizen science monitors may be held to much lower precision standards than stand-alone research monitors, however, the citizen science monitors may need a general, frequent calibration procedure in order to express that the results are valid.

Lastly, in order to achieve advances in citizen-use and crowdsourcing of air pollution data, education and outreach programs require continued and enhanced support. Many low-cost air pollution monitors have originated from non-profit environmental health justice programs (i.e. Smart Citizen, 2016) and open-source, "do-it-yourself" groups (i.e. HabitatMap, 2016). If the ideas and development of the open-source community can transfer to the greater public and governmental level, the portable techniques may receive greater attention such that the low-cost monitors become refined and more accurate. Methods that use wireless communication with smartphones and real-time feedback are crucial for each monitor in this discipline, so it would also be beneficial to consider efforts to consolidate data into a nationwide community-driven database.

Similar reviews about developing air pollution technology will continue to be necessary as the technology adapts and changes. As this paper lacks a full literature review that includes the whole body of literature on all air pollutants, a similar comprehensive review on both gaseous and particulate mobile/portable monitors may be impactful for researchers and citizen scientists in the future. More specifically, it would be beneficial to review the lifetimes of particular monitors. Finally, the components and technologies of each monitor result in variable degrees of sensor drift and calibration errors depending on how long each monitor is used (Williams et al., 2014a), thus a review of test results from extensive use of each type of monitor would be helpful. For example, it has been recommended that SENS-IT monitors be calibrated or regenerated every six months (Unitec, 2016b), while the low-cost ACAM air pollution sensor components must be individually calibrated more frequently due to drift and high out-of-the-box variability from the manufacturer (Williams et al., 2014b). A comprehensive comparison between monitor lifetimes will prevent users from making mistaken inferences by highlighting each monitor's need for calibration attention, which is often ignored or overlooked, yet critical for accuracy and application type of select gaseous air pollution monitors.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2016.12.045.

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