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Low-cost $PM_{2.5}$ Sensors: An Assessment of their Suitability for Various Applications

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ABSTRACT

Recently, there has been a substantial increase in the availability and use of low-cost particulate matter sensors in a wide range of air quality applications. They carry the promise of revolutionising air quality monitoring, yet considerable reservations exist regarding their performance and capabilities, thus hindering the broader-scale utilization of these devices. In order to address these concerns and assess their feasibility and accuracy for various applications, we evaluated six low-cost $PM_{2.5}$ sensors (the Sharp GP2Y1010AU0F, Shinyei PPD42NS, Plantower PMS1003, Innociple PSM305, Nova SDS011 and Nova SDL607) in laboratory and field conditions using two combustion aerosols, concrete dust and ambient particles. In assessing the performance of these sensors, we focussed on indicators such as the linearity, accuracy and precision, critically differentiating between these qualities, and employed inter-comparison (the coefficient of determination, R^2). In the laboratory, all sensors responded well, with an $R^2 > 0.91$ when the $PM_{2.5}$ concentration was > 50 μg m^{-3}, as measured by the DustTrak. In particular, the PMS1003 demonstrated good accuracy and precision in both laboratory and ambient conditions. However, some limitations were noted for the tested sensors at lower concentrations. For example, the Sharp and Shinyei sensors showed poor correlations ($R^2 < 0.1$) with the DustTrak when the ambient $PM_{2.5}$ concentration was < 20 μg m^{-3}. These results suggest that the sensors should be calibrated individually for each source in the environment of their intended use. We demonstrate that when tested appropriately and used with a full understanding of their capabilities and limitations, low-cost sensors can serve as an unprecedented aid in a broad spectrum of air quality applications, including the emerging field of citizen science.

Keywords: Low-cost sensors; PM sensors; Atmospheric aerosols; Air pollution.

INTRODUCTION

With the rapid advances in technology, there has been a sharp increase in the availability and use of low-cost particulate matter sensors for many applications (Morawska *et al.*, 2018). Most devices on the market are based on the principle of single- or multiple-particle photometry/nephelometry (Heim *et al.*, 2008). Although these small portable sensors have reduced functionality, they have some advantages over conventional instruments. Firstly, they generally offer low power consumption, permitting long-term battery- and/or solar-powered operation. Additionally, their low cost and compact size facilitates wider deployment and collection of real-time live pollution data and, hence, can be useful in such applications as the large-scale monitoring of personal

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exposure and spatial mapping of pollution (Kumar *et al.*, 2014; Jovašević-Stojanović *et al.*, 2015; Jiao *et al.*, 2016; Castell *et al.*, 2017; Jerrett *et al.*, 2017; Schneider *et al.*, 2017; Zikova *et al.*, 2017). These two applications are of particular importance as adverse health effects of airborne particle pollution have been well documented and are of growing concern in the rapidly expanding urban environments of the world (Kumar *et al.*, 2014). Therefore, it is important to measure pollution levels with high resolution, both spatially and temporally, across the urban landscapes in order to assess the level of exposure to the population, identify its sources, and develop appropriate mitigation measures.

Whilst the concept of optical particle detection has been widely applied to aerosol mass concentration measurement, the principle relies on a number of assumptions resulting in inaccuracy, even in more expensive (reference) instruments (Heal *et al.*, 2000; Heim *et al.*, 2008). Firstly, the initial particle concentration and size detection are influenced by refractive index, coincidence (for single-particle counters) and Mie scattering. Secondly, the conversion from a number/size concentration to mass concentration is then dependent on density and shape factor (aspect ratio) of the particle. Manufacturers of "reference"-type optical particle counters devote considerable time and effort developing mass conversion factors to ensure that their devices are as accurate as possible.

Low-cost sensors have the potential to generate huge amounts of data very quickly. However, as mentioned above, the data thus obtained may be questionable owing to the serious limitations of the accuracy and reliability of these cheap sensors, including the usual lack of calibration. Many of these devices have not been adequately tested and validated in the laboratory and there is very little information in respect to their performance in the literature. Some of them are merely designed to raise awareness of pollution levels and are not meant to report accurate values (Lewis and Edwards, 2016; Sousan *et al.*, 2017). While most low-cost $PM_{2.5}$ sensors have been tested and found to respond reasonably well to larger particles (Austin *et al.*, 2015; Wang *et al.*, 2015; Manikonda *et al.*, 2016; Kuula *et al.*, 2017; Liu *et al.*, 2017; Gupta *et al.*, 2018; Sayahi *et al.*, 2019a), there have been no comprehensive investigations of their performance with smaller particles, especially at low concentrations, such as that found under relatively clean ambient urban conditions. Most testing conducted to date using fine particles has considered only one or two instruments (Sousan *et al.*, 2016).

In this study, we tested six low-cost $PM_{2.5}$ sensors against a number of particle mass and number reference instruments with ambient aerosols, two types of combustion aerosols and concrete dust in an experimental chamber to assess their complete set of performance indicators. The specific aim of the study was to determine the suitability of low-cost $PM_{2.5}$ sensors for a broad range of different applications, such as monitoring at low ambient concentrations and high-pollution events.

METHODS

Sensors

We investigated the performance and reliability of five low-cost $PM_{2.5}$ sensors and a compact monitor with an integrated $PM_{2.5}$ sensor, challenged with a number of aerosols. Figs. S1(a)–S1(f) shows the six sensors while their basic specifications are presented in Table 1 with further details in Table S1.

The Sharp and Shinyei sensors operate with infrared light and have no fans to draw the air into the device, which limits their response time and resolution. While the Sharp sensor monitors the light scattered by particles, in the Shinyei sensor the infrared beam is interrupted by the particles passing through, making the signal go low. The fraction of time during which the signal remains low is proportional to the particle concentration. Thus, the device provides more statistically accurate readings at longer sampling intervals. A more detailed explanation may be found in Canu *et al.* (2018). Also, these two sensors may be affected by stray light, causing false readings. Care was taken to prevent this from happening by using proper shielding during the experiments. The Shinyei sensor contains a small heating resistor to provide thermal convection to drive the air through it and, therefore, it can only be placed with the cross-section of the aperture horizontal. The thermal currents may have affected the air flow rate through the sensing device, resulting in some fluctuation of the readings (Canu *et al.*, 2018).

The Plantower, the Innociple and the Nova SDS011 sensors are improvements over the above sensors as they include a fan and use a fine laser beam instead of the broader infrared beam for scattering (Cavaliere *et al.*, 2018; Zheng *et al.*, 2018; Hapidin *et al.*, 2019; Levy Zamora *et al.*, 2019). The scattered light is transformed into electrical signals and the number and diameter of the particles is related to the signal waveform. The particle monitor, the Nova SDL607, uses a Nova SDL307 sensor housed in a compact box with additional electronics and display panel. The device can also display a real-time graph and evaluate 24-h average values.

Test Instruments

The following test instruments were used to assess the performance of the sensors:

$PM_{2.5}$ Mass Concentration

The TSI DustTrak DRX Model 8530 aerosol monitor with a $PM_{2.5}$ impactor was selected because the sample flow rate of the TEOM was too large in relation to the size of the measurement chamber. Although the DustTrak has been used in several previous studies to assess the performance of other PM sensors (Jamriska *et al.*, 2004; Gao *et al.*, 2015; Liu *et al.*, 2017; Cavaliere *et al.*, 2018; Curto *et al.*, 2018; Sayahi *et al.*, 2019b), and its performance characteristics are understood very well, it has some limitations (Rivas *et al.*, 2017). Jamriska *et al.* (2004) calibrated a TSI DustTrak Model 8520 against a TEOM in ambient air and showed that, although there was a linear relationship, the DustTrak over-estimated the $PM_{2.5}$ concentration by a factor of between 2.0 and 2.5. As the aim of the present study was to assess the performance of the low-cost sensors and compare them, and not to perform an absolute calibration of the sensors, it was deemed suitable for the purpose. Absolute calibration has to be carried out where they are used, and using a calibration

Table 1. Specifications of the sensors tested in this study.

	Sharp GP2Y1010AU0F	Shinyei PPD42NS	Plantower PMS1003	Innociple PSM305	Nova SDS011	Nova SDL607
Operating principle	Infrared	Infrared	Laser	Laser	Laser	Laser
Lowest particle detection size		~1 µm	0.3 µm	0.5 µm	0.3 µm	0.3 µm
PM ranges (µm)	< 2.5	< 2.5	< 1, 2.5, 10	< 1, 2.5, 10	< 2.5, 10	< 2.5, 10
Particle number concentration size bins (µm)	N	N	> 0.3, 0.5, 1, 2.5, 5, 10	> 0.5, 1, 2.5	N	N
Detection concentration range PM (µg m^{-3}), PN (particles L^{-1})	PM: 500	PN: 0–28,000	PM: 0–500	PM: 10–1000, PN: > 10^5	PM: 0.0–999.9	PM: 0.0–999.9
Built-in fan (Y/N)	N	N	Y	Y	Y	Y
Resolution	(0.35–0.65 V)/(100 µg m^{-3})		1 µg m^{-3}	0.1 µg m^{-3}	1 µg m^{-3}	0.1 µg m^{-3}
Response time	< 1 s	60 s	≤ 10 s		1 s	
Number of sensors tested	4	4	3	3	1	4

factor from another study/location is always only an approximation (Johnson *et al.*, 2016; Morawska *et al.*, 2018). Therefore, prior to the present measurements, the performance of the DustTrak was evaluated against a standard TEOM at an outdoor air quality monitoring station using ambient aerosols. Its mean reading was found to be 3% higher than the TEOM over a continuous measurement period of 8 h. As such, no corrections were applied to the readings.

Particle Number Size Distribution

The TSI Aerosol Particle Sizer (APS) Model 3312 was chosen to determine the size distribution of particles from 0.5 to 20 µm with a scan time of 5 s, and the TSI Scanning Mobility Particle Sizer (SMPS) Model 3938 was used for particles in the range 9 to 429 nm.

Sensor Interfacing, Sampling and Data Communication

To suit the individual communication and measurement modalities of the sensors (i.e., pulse counting for Shinyei; analogue voltage for Sharp; serial/UART for the Nova, Plantower and Innociple) custom interface boards and software were developed to simultaneously sample the sensors and transfer the data to a computer for logging and analysis. The interface board included a low-power microcontroller with multiple serial interfaces, high-resolution analogue-to-digital converters (16 bit), I2C, and a real-time clock that provided accurate time stamping of the measurements to allow direct comparison with the off-board reference sensors. The sensors were mounted to a frame along with the interface board, allowing unobstructed air flow into and out of each. The software developed was fully customisable and allowed the sample rate to be varied, typically between 2–30 s, as well as perform any necessary sample integration/averaging and power management (e.g., fan switching). The time-stamped data were transferred in real time via USB serial communications to a computer outside the chamber and logged into a text file for post-analysis.

Experimental Chamber

The measurements were conducted in a chamber of volume 1 m^3 for up to 3 h, with the sensor boards placed on a raised platform above its floor (Fig. S1(g)). The reference instruments, located outside the chamber, sampled the air through short lengths of conductive rubber tubing. The chamber was flushed with filtered air before each experiment and the aerosols were introduced through a small window. A small fan on the floor of the chamber was used to ensure that the air was well mixed to give uniform concentrations throughout its volume.

Test Laboratory Aerosols

We selected two types of combustion aerosols with different mean particle sizes—cigarette smoke (100 nm) and emissions from lighting a match (25 nm) which we shall refer to as "match emissions". Match emissions were used because the particles were similar in size to petrol-fuelled vehicle emissions (Ristovski *et al.*, 2005) and were easier to produce in the laboratory. We also used concrete dust, with most of the particles in the µm size range. Particle size

distributions for the various aerosols used are shown in Fig. 1. The cigarette smoke and match emissions were introduced by inserting the source into the chamber for about 1 s to provide a $PM_{2.5}$ concentration of 10^2–10^3 μg m^{-3}. Concrete dust, collected at a construction site, and finely ground, was manually blown into the chamber through the window. As it was found that the Sharp and Shinyei sensors were not very responsive to changes in $PM_{2.5}$ concentration below 100 μg m^{-3}, in the experiments using these two sensors, we set the initial $PM_{2.5}$ concentration to near 1×10^3 μg m^{-3}, while for the other aerosols, it was set to near 1×10^2 μg m^{-3}.

Ambient Field Measurements

The same sets of sensors and DustTrak were placed on an open balcony of a residence situated about 20 m away from a busy intersection with typical $PM_{2.5}$ concentrations in the range 5–20 μg m^{-3} and left to sample over several hours, both during the day and overnight (Fig. S1(h)). This provided several unbroken periods of 2–4 h when the $PM_{2.5}$ concentration, as reported by the DustTrak, did not vary by more than about ± 1 μg m^{-3}. The readings of the sensors during such periods were used to assess their precision and accuracy.

Environmental Parameters

The influence of temperature and relative humidity (RH) on the response of the sensors was examined and recorded with a TSI Q-Trak which was calibrated against a Monitor weather station. The sensors were placed in the chamber and exposed to ambient air at a temperature of 23°C, RH of 45% and a steady $PM_{2.5}$ concentration of 5 ± 1 μg m^{-3}. A low air flow from outside was used to ensure that the aerosol concentration within the chamber remained steady in time at this ambient value. A small fan heater was used to increase the air temperature in the chamber from 23°C up to about 60°C. In a series of preliminary experiments, it was established that the fan heater did not introduce any particles into the chamber and the RH inside the chamber did not show any sharp changes during this process. The RH in the chamber was increased to about 60% by placing moist tissue on its floor. In order to obtain higher values of humidity, controlled amounts of steam were introduced into the chamber from a small boiler, taking care to prevent a significant increase in air temperature and the introduction of water droplets. In this manner, the air temperature in the chamber did not increase by more than 2°C, no water droplets were produced, and it was possible to raise the RH from 45% to over 90%.

Data Analysis

All data from the sensors and reference instruments were processed and averaged over the same intervals of time so that the sensor readings could be compared against the reference instruments. Linearity of response was tested using a basic linear regression method at a confidence level of 95% (R^2 determined at $p < 0.05$), while significant differences in means were tested using a Student's *t*-test also at a confidence level of 95%. The coefficient of variance (CV) was used to assess the precision of the readings in time and the inter-comparison of readings between pairs of the same type of sensors. In each of these two tests, the analysis was based on all sensor output data points over several periods of time during which the required actual $PM_{2.5}$ level remained within ±1.0 μg m^{-3}.

RESULTS AND DISCUSSION

Characteristics of the Sensors

The Sharp and Shinyei Sensors

The time series readings obtained from the Sharp and Shinyei sensors, together with the $PM_{2.5}$ readings of the DustTrak, at a sampling interval of 1 min, with all three types of aerosols, are shown in Fig. S2. Note that the readings on

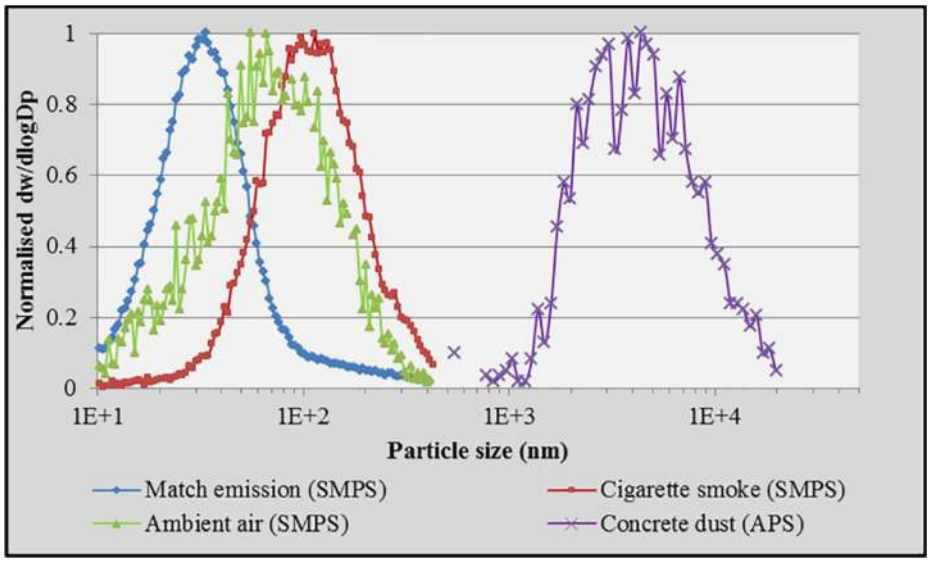

Fig. 1. The initial particle size distributions obtained with each of the four types of aerosols with the modal particle sizes given within parentheses: match emissions (25 nm), cigarette smoke (100 nm), ambient aerosols (80 nm) and concrete dust (4 μm).

the Shinyei sensor show greater fluctuation than the Sharp sensor. We attribute this to unstable air flow driven by the heating element within the aperture in the Shinyei, as described earlier. Figs. 2(a)–2(c) shows the linear correlations of the sensors against the DustTrak readings. It can be observed that both sensors responded well at high PM concentrations of all aerosols with the coefficients of determination, R^2, in the entire $PM_{2.5}$ concentration range up to 1×10^3 μg m^{-3} being between 0.85–0.99 ($p < 0.05$). However, as reflected by more scattered data points and a decreasing R^2, the response became increasingly poor as the $PM_{2.5}$ concentration decreased below 100 μg m^{-3} (Figs. 2(d)–2(f)) and, with the two combustion aerosols used, there was no relationship below 20 μg m^{-3}. Our results show that, although these sensors provide a linear response ($R^2 > 0.90$, $p < 0.05$) at relatively high $PM_{2.5}$ concentrations (> 100 μg m^{-3}), they are not suited for measurements in relatively clean ambient conditions. Another point to note was that, with concrete dust, we noticed some saturation of the output signals at $PM_{2.5}$ concentrations above about 600 μg m^{-3} (Fig. 2(c)).

Previous studies reported good performance of the Shinyei PPD42NS under high $PM_{2.5}$ concentrations in determining on-road emission factors of motor vehicles (Johnson *et al.*, 2016) and in the highly polluted urban environments of Xian, China (Gao *et al.*, 2015), and Hyderabad, India (Johnson *et al.*, 2018). Wang *et al.* (2015) evaluated the performance of the Shinyei PPD42NS and the Sharp GP2Y1010AU0F against a TSI SidePak PM sensor using particles generated by burning incense. All three sensors demonstrated a high linearity with concentrations up to 1000 μg m^{-3}. At a given concentration, the outputs of the sensors depended highly on the size and composition of particles and differed by up to an order of magnitude. The output generally increased with particle size. Manikonda *et al.* (2016) tested four low-cost PM monitors in the laboratory, two of which incorporated the Sharp GP2Y1010AU0F sensor. The tests were conducted in a room-sized chamber under controlled temperature and RH using cigarette smoke and Arizona test dust. Although

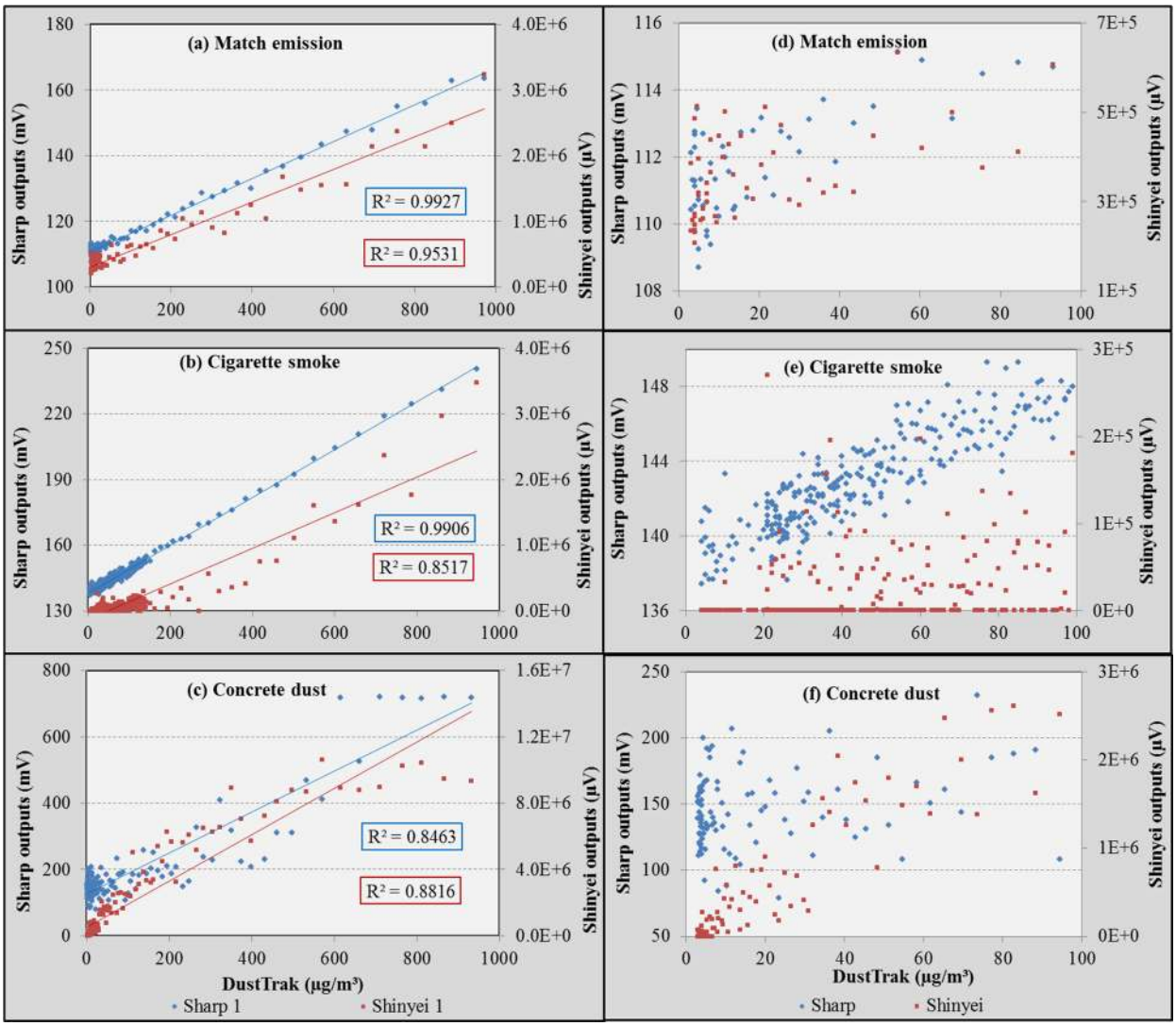

Fig. 2. Scatter plots of Shinyei (red) and Sharp (blue) sensor readings against the corresponding DustTrak readings using match emissions, cigarette smoke and concrete dust (a, b, c) in the $PM_{2.5}$ concentration range up to 1×10^3 μg m^{-3} and (d, e, f) in the $PM_{2.5}$ concentration range below 1×10^2 μg m^{-3}.

the sensors responded well in indoor environments, they raised concerns regarding their use in outdoor environments where conditions are more variable. In terms of response to different levels of concentration, Austin *et al.* (2015) demonstrated good performance of a Shinyei PPD42NS sensor for larger particles, > 0.5 µm polystyrene spheres. For 1 µm spheres a good relationship of $R^2 = 0.99$ was found for $PM_{2.5}$ concentrations in the range 0–50 µg m^{-3}. The authors concluded that Shinyei sensors were not suited for assessing exposures to ultrafine particles (UFP) such as combustion aerosols that dominate urban environments. In summary, all these previous observations are in agreement with our results at $PM_{2.5}$ concentrations greater than about 100 µg m^{-3}. However, in the absence of any previous results, no comparison is possible at lower concentrations with small particles.

As explained in the "Methods" section, the output signal of the Shinyei sensor was critically dependent on the sampling interval. In order to quantify this, we tested the four sensors at eight different sampling times ranging from 5 s to 10 min. Fig. 3 shows the voltage outputs when the sensors were exposed to concrete dust at a $PM_{2.5}$ concentration of 50 µg m^{-3} measured by DustTrak. The output signal voltage increased by almost two orders of magnitude within this time range. It is useful to make the sampling time as short as possible in order to have a suitable time resolution of the data. However, as apparent from Fig. 3, the accuracy of the reading decreased significantly as the sampling time was decreased. It was necessary to strike a balance between these two. In consideration of these two opposing factors, although the sampling interval could be set to any value down to 1 s, we selected a sampling time of 1 min for the measurements using the Shinyei sensors. Hence, the sensor is not recommended for applications that require a higher time resolution. The output signals of the Sharp sensors were not affected by the sampling interval.

The Plantower Sensor

With all three types of aerosols used, the Plantower responded very well to $PM_{2.5}$ concentration range up to 100 µg m^{-3} ($R^2 > 0.9$, $p < 0.01$) and extremely well to concentrations greater than 100 µg m^{-3} ($R^2 = 1.0$, $p < 0.01$). For higher concentrations this may be compared with the results of Kelly *et al.* (2017) who tested a Plantower PMS1003 in a controlled wind tunnel environment and found a linear response in the range 200–850 µg m^{-3}. Here, we focus on the concentration range below 100 µg m^{-3} as it is more relevant to most ambient concentrations. The three Plantower sensors showed linear correlation with the readings on the DustTrak for the three different aerosols (Fig. 4). The relationship of the sensor readings to the $PM_{2.5}$ concentration was near perfect ($R^2 = 0.99$, $p < 0.01$). At low concentrations ($PM_{2.5}$ concentration reported by DustTrak below 20 µg m^{-3}) the relationship was still very good with $R^2 = 0.95$ and $p < 0.01$.

The majority of the particles in match emissions (Fig. 1) are smaller than the minimum size of particle that the Plantower sensor is specified to detect (300 nm; Table S1). Therefore, it was not surprising to find that the $PM_{2.5}$ concentration values reported by the sensors grossly underestimated the actual values. With match emissions at $PM_{2.5}$ concentrations greater than about 20 µg m^{-3}, the mean correction factor of the three Plantower sensors was close to 1.3 (Fig. S3(a)). At lower concentrations, although the

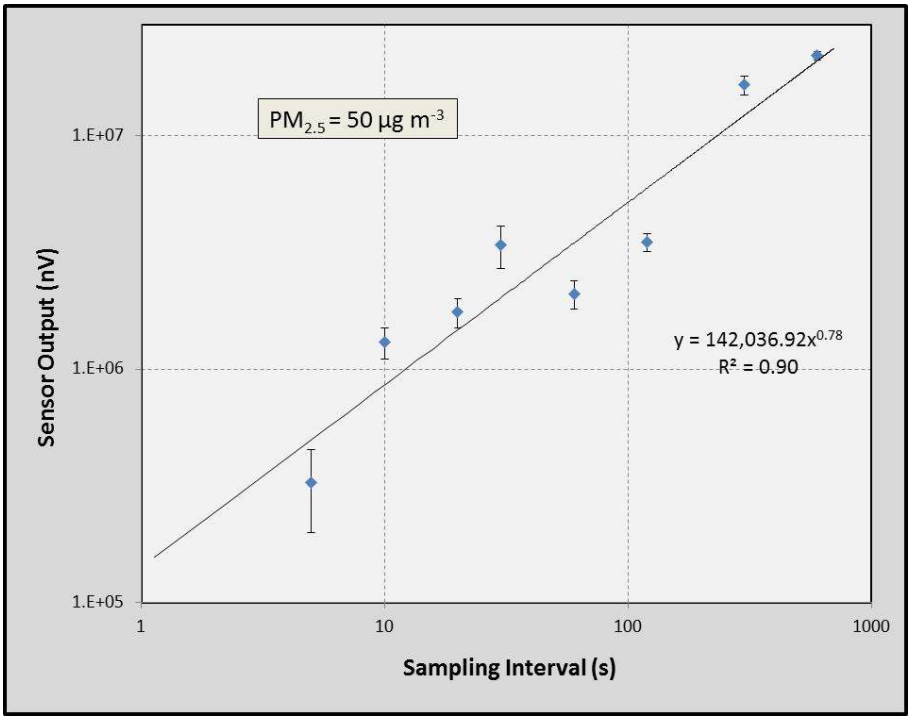

Fig. 3. Variation of the Shinyei sensor readings with sampling interval at a fixed concrete dust concentration ($PM_{2.5}$ = 50 µg m^{-3}). The error bars represent the standard deviation of multiple measurements at each time interval.

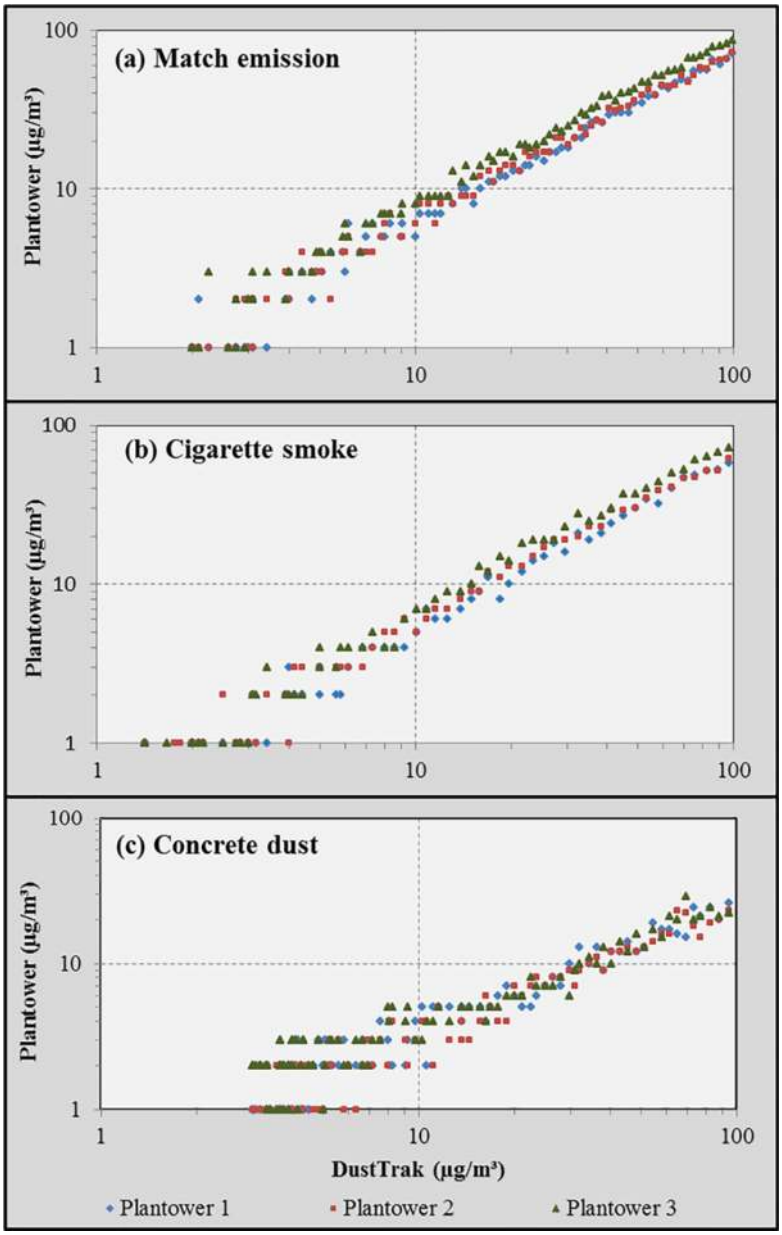

Fig. 4. Scatter plots of Plantower sensor readings and actual $PM_{2.5}$ concentration using (a) match emission, (b) cigarette smoke, (c) concrete dust.

uncertainty of the sensor reading remains the same, the percentage uncertainty becomes very large, thus accounting for a large scatter in correction factor values. The correction factors may be compared to other studies, for example 1.6 (Levy Zamora *et al.*, 2019) and 1.3 (Kelly *et al.*, 2017), both for ambient particles.

The mean size of the cigarette smoke particles was about 100 nm and, therefore, the Plantower sensors responded much better to these particles than to match emission particles (Fig. S3). Note that the sensor readings agree well with the actual readings at all $PM_{2.5}$ concentrations. At concentrations greater than about 20 µg m^{-3}, the mean correction factor of the three Plantower sensors was close to 0.75 (Fig. S3(b)). As with match emissions, at lower concentrations, the percentage uncertainty becomes very large, giving a large scatter in correction factor values.

The Innociple Sensor

With match emissions, as with the Plantower sensors, the Innociple sensors grossly under-estimated the $PM_{2.5}$ concentration, with a correspondingly larger correction factor of 5–10, which can be explained by the significantly higher detection size of the Innociple sensor (Table 1). At concentrations less than about 20 µg m^{-3} the readings on the Innociple sensors showed a wider scatter than the Plantower sensors. However, at higher concentrations, they responded well to changes in concentration (R^2 = 0.99, $p < 0.01$; Fig. S4(a)). The response to cigarette smoke (Fig. S4(b)) and concrete dust (Fig. S4(c)) were also good, with R^2 in the range 0.97–0.99, $p < 0.01$.

The Nova SDS011 Sensor and SDL607 Monitor

In the $PM_{2.5}$ concentration range greater than about 10 μg m^{-3}, both these devices responded very well to changes in concentration with an $R^2 = 0.99$, $p < 0.01$, for each of the three aerosols (Figs. S5 and S6). However, the values reported by the SDS011 were 2–3 times as high as the actual readings for all three aerosols, while that reported by the SDL607 were significantly lower. Results from other studies using the SDS011 have also shown that the readings are higher than actual, for example the correction factors reported by Cavaliere *et al.* (2018) and Liu *et al.* (2019) were 0.52 and 0.7–0.9, respectively. With match emissions and concrete dust, the values reported by the SDL607 were about one-sixth the actual values. The difference in readings between monitors was also considerably larger than with the Plantower and the Innociple. This means that the devices can still be used effectively but need to be individually calibrated against a standard instrument.

Possible Effects of Size and Composition of Aerosols

For each type of sensor and aerosol, we extracted the mean output voltage signal or reported $PM_{2.5}$ concentration value at a fixed DustTrak reading of 50 μg m^{-3}. The results are shown for the three aerosol types in Table S2. Considering the scatter of the data and the R^2 values in the linear correlation graphs for the two combustion aerosols, all sensors were more sensitive (showed a higher reading) with cigarette smoke than with match emissions. This is in agreement with their specifications which stipulate that the minimum detectable particle size is of the order of 0.3 μm. With combustion aerosols, a significant fraction of the particles are smaller than this value. However, the cigarette smoke particles have a longer tail extending to larger sizes. At higher concentrations, increased coagulation leads to larger particles that are detected by the sensors.

The response of the sensors to concrete dust was mixed. While the Sharp, Shinyei, Innociple and Nova SDS011 were observed to be more sensitive to the larger concrete dust particles, the Plantower and Nova SDL607 were significantly less sensitive. Since the sensors operate on the scattering of infrared or laser light off the surface of particles, it would be expected that, in addition to the surface area, the readings are affected by other factors, perhaps particle shape, colour and composition. The results also show that the various types of sensors need to be calibrated for each type of aerosol separately.

Response to Ambient Particles

The Sharp and Shinyei sensors responded very poorly to $PM_{2.5}$ concentrations below 15 μg m^{-3} ($R^2 < 0.1$, $p > 0.05$), and are not shown here. Fig. 5 shows the response of the other four sensors to ambient aerosols in the concentration range 5–15 μg m^{-3}.

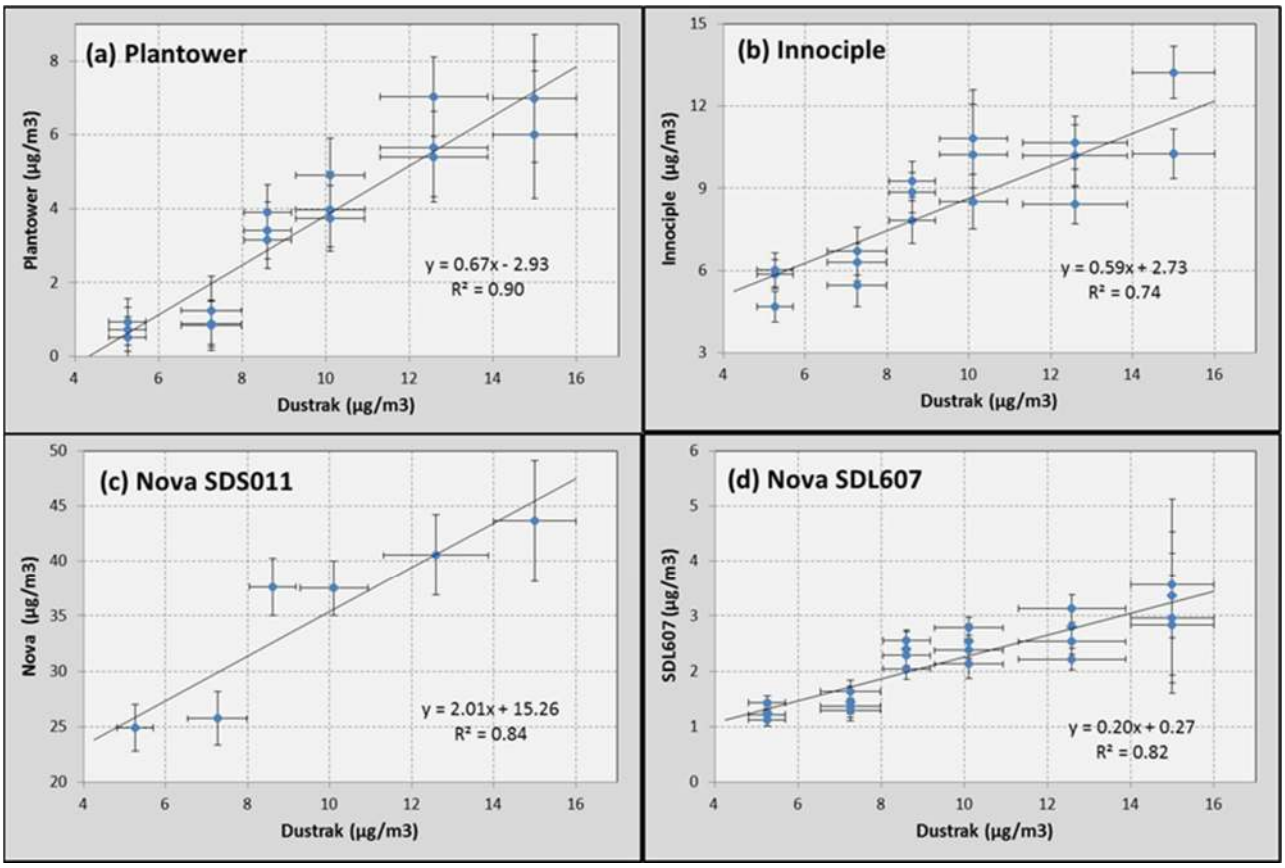

Fig. 5. Scatter plots of (a) Plantower, (b) Innociple, (c) Nova SDS011 and (d) Nova SDL607 readings with DustTrak readings at ambient conditions in the $PM_{2.5}$ concentration range 5–15 μg m^{-3}. The error bars on both axes represent the associated standard deviations.

The Plantower sensor responded relatively well (R^2 = 0.90, $p < 0.01$) at these low $PM_{2.5}$ concentrations (Fig. 5(a)). At a fixed concentration of 20 μg m^{-3}, the readings on each of the three Plantower sensors showed good stability with CV = 0.19. At the same concentration, the comparison between sensors was good with CV = 0.05. The Innociple did not respond as well ($R^2 = 0.74$, $p < 0.01$) as the Plantower at these low $PM_{2.5}$ concentrations (Fig. 5(b)). However, the precision of the readings was better than with the Plantower and showed good stability with CV = 0.16. At the same concentration, the inter-comparison between sensors was worse than the Plantower with CV = 0.12. For Nova SDS011 and SDL607, the R^2 values in this size range were good at 0.84 ($p < 0.01$) and 0.82 ($p < 0.01$), respectively (Fig. 5(c) and 5(d)). However, as seen in the graphs, both these sensors showed a very poor response at concentrations below 10 μg m^{-3}.

Performance at Varying Air Temperature

The readings of most of the sensors were generally steady up to a certain temperature, beyond which they tended to increase and sometimes fluctuate (Fig. S7, left panels). The Sharp sensors were the most sensitive to temperature, showing a linear increase of about 50% in the range from room temperature, 23°C, up to about 50°C, while the corresponding variation for the Shinyei sensors was about 5% (Fig. S7(a)). The Plantower readings remained steady with temperature up to about 45°C, and then showed a small linear increase of about 20% between 45°C and 65°C (Fig. S7(b)). The Innociple and the Nova readings remained relatively steady with temperature up to about 45°C, and then increased at higher temperatures (Figs. S7(c) and S7(d)). We conclude that, in conditions where the air temperature varies in time, the Sharp sensor is not suitable for use as its output is too sensitive to changes in temperature but the performance of all the other sensors is not affected.

Performance at Varying Humidity

The output signals of the Sharp and Shinyei sensors did not show a systematic variation until the RH reached about 75% (Fig. S7(e)) beyond which they fluctuated. The output of the Sharp sensors increased significantly and appeared to reach saturation as the RH exceeded 90%. The other three sensors (Plantower, Innociple and Nova) did not show any significant effect with RH up to about 90% (Figs. S7(f)–S7(h)). However, previous studies using a Plantower PMS1003 sensor at an outdoor location showed that the readings began to increase when the RH exceeded about 75% (Jayaratne *et al.*, 2018). In that study, this increase was attributed to the hygroscopic growth of particles in the atmosphere when the RH exceeded about 75%. The absence of such an increase in readings up to a RH of 90% or more in the present laboratory experiments with all three sensors mentioned is surprising. We suggest that the hygroscopic particles that are abundant in the outside atmosphere are largely absent within the chamber in the air-conditioned laboratory, an aspect that requires further investigation. These results show that, at least in outdoor air, the use of low-cost particle sensors needs to be limited to conditions where the RH is below 75%. It should be noted that the ambient RH in many cities, especially in the coastal tropics, often exceed 90%, so this is a factor that needs to be considered when choosing a sensor for use at such locations.

General Performance

The performance characteristics of the sensors are listed in Table 2. The types of aerosols and sizes correspond to match emissions (25 nm), cigarette smoke (100 nm) and ambient (80 nm). Ambient $PM_{2.5}$ concentrations were < 20 μg m^{-3}. The averaging times used in the analysis were 1.0 min for the Plantower, Innociple and Nova SDS011 and 5.0 min for the Nova SDL607.

Accuracy

Table 2(a) shows the correction factors for the three sensors—the Plantower, Innociple and Nova SDS011—and the monitor Nova SDL607. The accuracy is not relevant to the other two sensors—the Sharp and Shinyei—as they do not report $PM_{2.5}$ concentrations directly. The readings of the four sensors show a large variation in absolute terms. At the higher concentrations, the values reported by the Plantower and Nova SDS011 are within a factor of 2 (Figs. 4 and S5), whereas the Innociple grossly under-estimated the $PM_{2.5}$ concentration by an order of magnitude (Fig. S4). This is not surprising as the specified lower detectable particle size of the Innociple is 0.5 μm, which is higher than the other two sensors, 0.3 μm (Table S1). While the modal sizes of the match emission particles and cigarette smoke are in the UFP size range (≤ 0.1 μm), due to coagulation they both have a long detectable tail that extends over 0.3 μm in size (Fig. 1). The Nova SDL607 monitor under-estimates the $PM_{2.5}$ concentration by about 80% with match emissions and by about 60% with cigarette smoke. It is worth noting that the best-performing devices in this study all had a 90° scattering angle, which has been shown to minimise error-inducing effects such as Mie scattering (Heal *et al.*, 2000).

Linearity

Even if the sensor readings are not accurate in absolute terms, if the values reported show a good relationship to the actual concentration, they can be calibrated against a standard instrument for use in many applications. Table 2(b) presents the respective coefficients of determination, R^2, derived from the calibration graphs of the sensor outputs against the actual $PM_{2.5}$ concentration. The results show that all six sensors responded linearly to $PM_{2.5}$ concentration > 50 μg m^{-3} and the sensor outputs demonstrated a strong relationship to the actual concentrations ($R^2 > 0.9$, $p < 0.05$). The Shinyei has some limitations but this can be mitigated by using longer sampling time intervals as observed in Fig. 3. At lower concentrations, the Sharp and Shinyei sensor readings show a wide scatter and the R^2 value becomes very low (< 0.3) with $p > 0.05$ below 20 μg m^{-3} so that they are not suited for measurement of ambient particles. The other four sensors perform reasonably well ($R^2 > 0.7$, $p < 0.05$), with the Plantower sensor showing the highest R^2 value of 0.90 with $p < 0.01$ (Fig. 4).

Table 2. The performance characteristics of the sensors.

$PM_{2.5}$ Concentration	< 20 μg m^{-3}		> 20 μg m^{-3}		< 20 μg m^{-3}
Particle Type and Size	Match emission (25 nm)	Cigarette smoke (100 nm)	Match emission (25 nm)	Cigarette smoke (100 nm)	Ambient (80 m)
(a) Correction Factor (CF)					
Plantower	1.4	0.70	1.5	0.75	1.3
Innociple	5.0	2.2	9.0	2.4	1.7
Nova SDS011	0.5	0.3	0.5	0.4	0.5
Nova SDL607	5.0	2.6	5.3	3.0	5.0
(b) Coefficient of Determination (R^2)					
Sharp	0.01	0.13	0.98	0.99	0.08
Shinyei	0.08	0.35	0.91	0.86	0.06
Plantower	0.98	1.00	1.00	1.00	0.90
Innociple	0.96	0.96	0.98	0.97	0.74
Nova SDS011	0.97	0.95	1.00	0.99	0.84
Nova SDL607	0.99	0.99	0.99	1.00	0.82
$PM_{2.5}$ Concentration	20 μg m^{-3}		10 μg m^{-3}		20 μg m^{-3}
Particle Type and Size	Match emission (25 nm)	Cigarette smoke (100 nm)	Ambient (80 nm)	Cigarette smoke (100 nm)	Ambient (80 m)
(c) Precision Coefficient of Variation (CV)					
Plantower	0.14	0.08	0.22	0.10	0.19
Innociple	0.05	0.06	0.10	0.08	0.16
Nova SDS011	0.02	0.02	0.05	0.03	0.07
Nova SDL607					0.11
(d) Inter-comparison Coefficient of Variation (CV)					
Plantower	0.07	0.05	0.04	0.09	0.05
Innociple	0.20	0.20	0.21	0.21	0.12
Nova SDL607	0.27	0.14	0.22	0.14	0.14

Precision of a Given Sensor

The coefficient of variation was used to evaluate the precision of the values reported by individual sensors. The smaller the value of CV, the more stable the output of the sensor (CV = 0 indicates a perfectly stable sensor output). The Sharp and Shinyei showed very low precision at these low concentrations with extremely high CV values. Table 2(c) shows the CV values of the Plantower, Innociple and Nova SDS011 sensors. The precision of the Nova SDL607 for match emissions and cigarette smoke could not be assessed as its sampling time of 5 min was too long to obtain a sufficiently large number of readings at a fixed $PM_{2.5}$ concentration. Therefore, we have provided the CV value for the SDL607 under ambient conditions only.

As expected, the precision was generally better at 20 μg m^{-3} than at 10 μg m^{-3}. The best precision was demonstrated by the Nova SDS011 under all conditions. The Innociple demonstrated a better precision than the Plantower under all conditions. However, this is partially due to the fact that the Plantower reports concentrations at a resolution of 1.0 μg m^{-3} whereas the resolution of the Nova and Innociple (0.2 μg m^{-3} and 0.1 μg m^{-3} respectively) are much better. This, however, does not mean that the readings on the Plantower are less stable than the other two sensors.

Inter-comparison between Sensors of the Same Type

This comparison was done for the Plantower, Innociple and Nova SDL607 sensors as there was more than one sensor of each type. It could not be evaluated for the Nova SDS011 sensor as we had only one device. Table 2(d) shows the result. The CV was again used to compare the values reported by pairs of sensors. The smaller the value of CV, the better the inter-comparison between sensors (CV = 0 indicates identical sensor outputs). Despite its lower resolution, the Plantower clearly showed a better inter-comparison between sensors (CV < 0.1) than the Innociple and Nova under all conditions, including at concentrations below 20 μg m^{-3}.

Suitability of Sensors for Ambient Monitoring and Other Applications

The results of this study provide information on the suitability of the sensors tested in various applications. Clearly, the Sharp and Shinyei sensors are not suited for ambient monitoring when the $PM_{2.5}$ concentration is below 20 μg m^{-3}. The other four sensors can be used down to about 5 μg m^{-3} at a linear response given by $R^2 > 0.7$, $p < 0.05$. The Plantower proved to be the best for this purpose with an R^2 of 0.90 and $p < 0.01$. All six sensors may be used confidently ($R^2 > 0.90$, $p < 0.01$) in environments with relatively high $PM_{2.5}$ concentrations, above 50 μg m^{-3}. This may include polluted mega-cities, industrial areas and near major traffic routes. However, to add a word of caution, it has been shown that laboratory results do not always agree with field results (Johnson *et al.*, 2016; Morawska *et al.*, 2018). There are many reasons for this such as the varying composition of

particles (Johnson *et al.*, 2016; Liu *et al.*, 2017; Sayahi *et al.*, 2019b). All the sensors performed better with large combustion aerosols than small. However, the Plantower did not perform well with concrete dust and it will probably have some limitations in monitoring $PM_{2.5}$ concentrations in, for example, dust storms. The performance of the sensors is not significantly affected by changes in air temperatures up to a temperature of about 45°C, except the Sharp sensor which showed a linear increase starting at ambient temperatures. If using a Sharp sensor, we recommend that individual sensors be calibrated against temperature. The readings on all sensors, except the Plantower, were affected at high RH. The Sharp and Shinyei began to show departures at a RH as low as 75%. These two sensors are thus not recommended to be used in environments where the RH exceeds this value. The other sensors performed well up to 90%.

One of the applications of sensors commonly discussed is citizen science (Jerrett *et al.*, 2017). Not clearly specified, however, is whether the use of the sensors by the citizens is for the purpose of raising awareness of air pollution and potential risks in specific locations or to specific individuals, or whether the citizens desire to have reliable air quality data to gain quantitative understanding of their exposures compared to the health guidelines and, therefore, whether or not there is need to take actions. In principle all the sensors are suitable for raising awareness: in general, they respond to the changes to particulate matter concentration, and all of them do this when the concentrations are high. However, if they are to be used for quantisation of the citizens' exposure, clearly the sensors which respond only to high concentrations, which are well above the World Health Organization 24-h $PM_{2.5}$ guideline of 20 μg m^{-3}, are not suitable for this purpose.

CONCLUSIONS

In summary, we demonstrate that whereas each type of sensor is suitable for some applications, no sensor is ideal for all applications. There are many characteristics of sensor performance, and the choice of sensor for a specific application should be based on the most critical characteristics for that application. Unfortunately, such information is generally missing, and prospective users, when searching for a sensor, are often assured by manufacturers' promotional claims that every product is perfect for every application. This misleading advertising potentially creates misinformation and results in the loss of time and resources while undermining the enormous potential of this technology. The issue is further aggravated when the manufacturer does not specify the sensor that is being used in a monitor or package. In many cases, the sensor output is electronically processed and conditioned in order to stabilize and amplify the signals. Smoothing circuits frequently mask much of the information that is available from the raw sensor. Therefore, it is extremely important that standard protocols for sensor testing be developed by the appropriate professional bodies and that manufacturers subject their sensors to the required tests and provide a complete set of information about the capabilities and limitations, thereby enabling users to make informed decisions on sensor selection.

These sensors can be applied in a multitude of applications. Given that the field of research for airborne particulate matter is very broad and complex, it is not surprising that "one size does not fit all". Thus, every type of sensor may be able to find a niche, but the choice of sensor must suit the purpose of the application.

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DISCLAIMER

The authors declare that there are no conflicts of interest.

SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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