Received: 18 September 2021 | Revised: 30 November 2021 | Accepted: 7 December 2021

DOI: 10.1049/wss2.12034

IET Wireless Sensor Systems

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH

Laboratory and field evaluation of three low-cost particulate matter sensors

Mohammad Ghamari[1] | **Cinna Soltanpur**[2] | **Pablo Rangel**[3] | **William A. Groves**[4] | **Vladislav Kecojevic**[5]

[1]Electrical and Computer Engineering, Kettering University, Flint, Michigan, USA

[2]Department of Electrical and Computer Engineering, University of Oklahoma, Norman, Oklahoma, USA

[3]Department of Engineering, Texas A&M University-Corpus Christi, Corpus Christi, Texas, USA

[4]Department of Energy and Mineral Engineering, Penn State University, State College, Pennsylvania, USA

[5]Department of Mining Engineering, West Virginia University, Morgantown, West Virginia, USA

Correspondence

Mohammad Ghamari, Kettering University, Electrical and Computer Engineering, Flint, MI, USA.

Email: mghamari@kettering.edu

Funding information

Alpha Foundation for the Improvement of Mine Safety and Health, Grant/Award Number: Grant Number AFC417-39

Abstract

Low-cost off-the-shelf particulate matter (PM) sensors have the potentiality to be used for evaluating the air quality in outdoor settings. Monitoring of air quality in surface coal mines is an example of such applications. In coal mines, long-term exposure to inhalation of coal dust is harmful and can lead to coal workers' pneumoconiosis, which is a potentially disabling lung disease. Therefore, continual monitoring of air quality in coal mines is a must and vital and can potentially assist in preventing such diseases. Although, using and deploying of the existing low-cost and lightweight sensors can help to improve monitoring resolution in a much cost-effective manner, there are some concerns regarding the reliability of the collected data from these sensors. Therefore, low-cost PM sensors are required to initially be compared with the standard reference instruments and then be calibrated. In this study, three different types of low-cost, light-scattering-based widely available PM sensors (Shinyei PPD42NS, Sharp GP2Y1010AU0F and Laser SEN0177) are evaluated, compared, and calibrated with the reference instruments in a controlled environment as well as in a field experiment (surface coal mine).

KEYWORDS

calibration, sensors, wireless sensor networks

1 | INTRODUCTION

Particulate matter (PM), also recognised as particle pollution, is a term that is used to describe a combination of liquid and solid droplets suspended in the air [1]. PM, which typically used as a measure of air quality, is one of the common measurement metrics among other environment-related parameters such as volatile organic compound (VOC), carbon dioxide (CO_2), humidity and temperature [2–5]. From the health point of view, increased levels of PM are directly associated with various health-related adverse effects for humans [6]. Black lung, lung cancer, cardiopulmonary and cardiovascular diseases are some examples of the aforementioned adverse effects [7–9]. Coal workers' pneumoconiosis (CWP) is another example of such adverse effects [10]. CWP is a preventable occupational lung disease, which is caused by long-term inhalation of coal mine dust [11] and can lead to premature death among coal miners [12]. Progressive massive fibrosis (PMF) is the advanced version of CWP [13] that can often be fatal [14]. In order to prevent the occurrence of CWP disease in miners, The Federal Coal Mine Health and Safety Act of 1969 established a strict policy for maximum exposure to respirable dust (2.0 mg/m^3) in underground and surface mines [15]. Later, initial surveillance data indicated that the prevalence of CWP among underground coal miners decreased from 11% in the early 1970s to 2% in the mid-to-late 1990s [16]. However, more recent surveillance results have shown that the prevalence of CWP has increased over the past decade, and national institute for occupational safety and health (NIOSH) estimates that the prevalence of the most severe form of CWP (PMF) has reached the highest levels since the early 1970s [16]. In response to an upsurge in the prevalence of CWP, in 2009 mine safety and health administration (MSHA) initiated a campaign, which featured a proposed new rule to lower miners' exposure to respirable coal mine dust [17]. The resulting final rule includes a reduction in the limit for respirable dust concentrations from 2.0 mg of dust per cubic metre of air (mg/m^3) to 1.5 mg/m^3 at underground and surface coal mines [18–20]. To measure various levels of PM concentration, United States Environmental Protection Agency (EPA) has standardised and approved several instruments. Standardized instruments use three different methods to measure various levels of PM concentrations. An instrument may use a filter-based gravimetric method such as personal DataRAM (pDR-1500), a microbalance-based method such as Tapered Element Oscillation Microbalance (TEOM) and Quartz Crystal Microbalance (QCM), or an optical-based method such as DustTraK and SidePak [21]. Although measurements obtained from the filter-based gravimetric instruments are accurate and precise and can assist in collecting data reliably, they are unable to instantaneously present and demonstrate the collected data in real time. Occasionally, it may take days or even weeks from the time that samples are collected until when the presentable data becomes available. This time delay prevents the air quality monitoring agencies from responding promptly to fast-changing parameters of the air quality in an environment [22]. In addition, to perform the accurate analysis of the collected data, filter-based gravimetric instruments are required to sample ambient air for long duration of time in order to be able to collect sufficient amount of particles [23]. Moreover, calculation of PM concentration using the gravimetric instruments is designed based on taking the mean values of low and high levels of PM concentration, which in practice, can lead to a severe disadvantage. For cases in which samples are collected for longer time, it would be very hard to detect short-time duration of signal spikes that are relevant to high PM concentrations [22]. For such cases, missed signal spikes may be responsible for some of the adverse health effects. In order to address the challenges associated with using existing filter-based gravimetric instruments, real-time monitoring systems are used. Real-time monitors such as DustTrak II Aerosol Monitor 8530 have drawn considerable attention in the last decade. These instruments can provide sufficient temporal information and can quickly identify and notify important moments of exposure to high levels of PM concentrations. However, they are relatively expensive (a typical monitor costs more than $6000.00), which leads to obtaining insufficient spatial information from a typical monitored environment [24]. Several real-time air quality monitoring systems operate based on light-scattering principles such as photometers and optical particle counters (OPCs). OPC uses a photodetector to detect the scattered light from an aerosol particle. In this measurement method, pulses of scattered light are counted to provide an approximate estimate for total number concentration and pulse heights and are measured to estimate the size of particles [25]. Photometers use an aerosol sampler to measure the total amount of scattered light. For particles with diameters similar to the wavelength of the light, photometers respond linearly to the mass concentration. In photometers, the scattered light from a particle is highly dependent on particle size and the light wavelength [26]. Although, instruments designed based on OPC and photometer principles are widely being used in industry sectors for real-time monitoring of air quality, they are not able to simultaneously work together within a smart network to be able to exchange data in real-time and cover wider geographical areas. Therefore, a lack of an alternative intelligent and cost-efficient real-time air quality monitoring system is identified. Many original equipment manufacturers nowadays offer low-cost particulate matter sensors such as Shinyei PPD42NS, Sharp GP2Y1010AU0F and Laser SEN0177 to measure PM concentrations. Although, these sensors can be deployed in large numbers because they are cost-efficient, there are still some concerns regarding the quality of data produced by these sensors [27–29]. In addition, the accuracy and precision of these sensors may not be acceptable for the regulatory use [30]. Various models of low-cost PM sensors have been evaluated and tested in the past by many scientists under laboratory conditions as well as in field settings. Authors in Ref. [31] evaluated the performance of three widely used low-cost PM sensors based on light scattering (Shinyei PPD42NS, Samyoung DSM501A, and Sharp GP2Y1010AU0F) and compared the results with commonly used reference air quality instruments [SidePak and Scanning Mobility Particle Sizer (SMPS) spectrometer]. In Ref. [32], authors evaluated the performance of four low-cost optical sensors (Sharp, Shinyei, Samyoung and Oneair) using two reference instruments [TSI DustTrak and Personal Dust Monitor (PDM)] in a controlled environment, in which particles were generated in different size distributions and compositions. Authors in Ref. [33] characterised the field-based performance of different PM sensors in an outdoor urban environment. In this study, authors investigated the long-term (a year-long) evaluation and comparison of several sensors of various models in a field setting, which were arranged to work together as a network of sensors. Authors in Ref. [34] investigated the performance of two different types of low-cost PM sensors in terms of precision, accuracy, noise and limit of detection over 320 days under different ambient conditions including fireworks and wildfires and showed that during these specific environments, the daily level of PM2.5 could increase significantly. The aim of this work is to initially evaluate, compare and calibrate various models of low-cost PM sensors using different sizes and types of particles [three different sizes of Arizona road dust (A1 Ultrafine Test Dust, A2 Fine Test Dust and A3 Medium Test Dust) as well as one type of coal dust] under laboratory conditions. This test specifically focusses on evaluating the low-cost PM sensors for considering the new strict policy that has recently been introduced by MSHA in 2009, which requires that the maximum level of exposure to respirable dust must be limited to 1.5 mg/m^3 at underground and surface coal mines and then to evaluate and validate the performance of the low-cost PM sensors in a real scenario in a surface coal mine.

2 | MATERIALS AND METHODOLOGY

2.1 | Low-cost particulate matter sensors

In this work, three different types of low-cost PM sensors (Shinyei PPD42NS [31, 35, 36], Sharp GP2Y1010AU0F [31, 37, 38] and Laser SEN0177 [39–41]) are selected for evaluation (herein referred to as PPD4, GP2Y, and SEN0, respectively). Sensors evaluated in this work are designed to operate based on an optical measurement technique of particles by the use of a light scattering principle. A typical PM sensor consists of a light source [laser diode or infrared light-emitting diode (IR LED)], a light-detecting device (phototransistor or photodiode), and an optical lens. Dust particles are passed through a light beam that is generated by the light source, and a photodetector is used to capture the scattered light. The light intensity detected using the photodetector is directly associated with the particle concentrations. Sensors usually contain mini blowers or heated elements to pass the flow of air through the light scattering region. In this work, three different classes of sensors are selected for evaluation. The PPD4 sensor uses a 100-Ω resistor to generate 0.25 W of heat. In this way, a natural convection mechanism is used to make particles flow through a light beam generated by a LED. Unlike the PPD4 sensor that is self-aspirated via the use of an internal resistor for the transfer of particles, and the SEN0 sensor that includes a built-in fan to supply airflow to the sensor, the GP2Y sensor does not contain any internal resistor or built-in fan to provide airflow to the sensor. Although, adding some types of external airflow (e.g. from wind or natural convection) can assist the sensor to react faster to variations in dust concentration, not including an airflow mechanism can also be valuable as it can provide flexibility in terms of sensor positioning and orientation. In addition, a GP2Y sensor including a regulated external convection may react differently to particle concentrations in comparison to a GP2Y sensor that does not include a regulated external convection. The PPD4 sensor outputs modulated pulses where there is a direct relationship between the low pulse occupancy (LPO) (time duration in which the sensors output a low voltage in a total sampling time of 30 s) time and the size of the particles and particle concentrations. The PPD4 sensors can be used to detect particles ranging in size from 0.5 to 2.5 μm [42]. The SEN0 sensor is a digital sensor. It calculates and outputs PM concentrations (the number of suspended particulate matter in a unit volume of air within 0.3 to 10 μm). The SEN0 sensor can detect particles ranging in size from 0.3 to 10 μm [39]. The GP2Y sensor calculates and outputs the voltage. A formula is then used to convert the output voltage into dust density values. The Sharp GP2Y sensor can detect particle sizes of approximately less than 0.8 μm [43]. Dust concentration increases linearly with respect to the output voltage. In order to enable sensors to collect and store data, each sensor was separately connected to a battery-powered acquisition device, which was programmed to log the sensor data.

2.2 | Reference instruments

Three different types of reference instruments were used to evaluate and compare the performance of low-cost PM sensors with the real-time reference instruments: DustTrak DRX Aerosol Monitor, Thermo Scientific Personal DataRAM pDR-1500 Monitor and a PDM3700 Personal Dust Monitor. Similar to the previously mentioned low-cost PM sensors, the DustTrak DRX Aerosol Monitor also measures particle mass concentration through a light scattering method. The DustTrak uses a diaphragm pump to drag aerosol into the sensing chamber continuously. A portion of the stream is detached from the main aerosol stream before entering to the sensing chamber and then passed via a HEPA filter and injected back into the sensing chamber around the inlet nozzle as the sheath stream. The other part of the aerosol stream that is called the sample stream passes through the inlet and enters the chamber. DustTrak DRX uses a laser diode as its light source. The emitted light from the laser enters through a collimating lens and afterwards, a cylindrical lens to generate a beam of light. A gold-coated spherical mirror is incorporated in the optical system of this instrument to capture the light that is scattered in a wide angle and try to focus them onto the photodetector. DustTrak monitors measure particle sizes ranging from 0.1 to 15 μm [44]. The Thermo Scientific Personal DataRAM pDR-1500 instrument is a very sensitive nephelometric monitor that uses a LED source to generate a beam of light with a wavelength of 880 nm in order to measure particle concentrations. PDR-1500's forward-scattering-angle covers a range between 60 and 80°. pDR-1500 is able to cover a broad measurement range for mass concentrations, typically from 0.001 to 400 mg/m^3 and also is capable of measuring a wide range of particle sizes from 0.1 to 10 μm [45]. Unlike previously explained widely used reference instruments that operate based on optical measurement techniques, the PDM3700 Personal Dust Monitor uses a tapered element oscillating microbalance (TEOM) technology to measure particle concentrations [32]. TEOM is a mechanical method that is used for real-time monitoring of particles by measuring particles' mass concentration. A coil driver pulses against two magnets on the tapered element to initiate an oscillating movement. The pausing magnetic field maintains the natural oscillation and air samples start to flow through the system. Particles are collected on the filter set on top of the TEOM. Over time, the particulate mass increases and weighs down against the TEOM reducing oscillation frequency. The change in frequency is measured using a Hall effect sensor. Unlike the light scattering nephelometer, which can be affected by changes in particulate characteristics, the TEOM is unaffected and calibrates the response of the nephelometer by providing a real-time mass reference concentration [32]. The PDM3700 Personal Dust Monitor measures particle sizes of less than 4.5 μm [46].

FIGURE 1 Aerosol test chamber

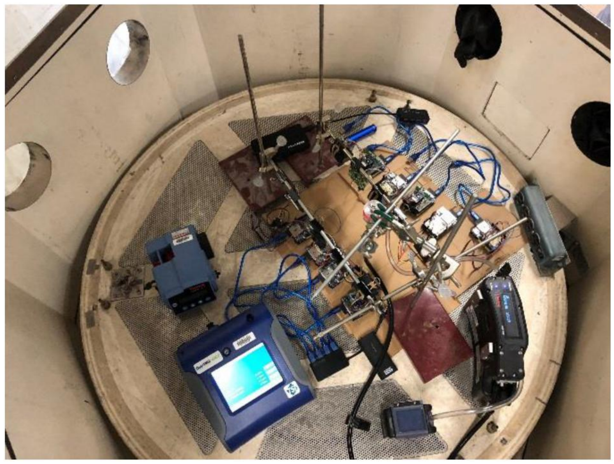

FIGURE 2 Experimental set up inside the test chamber

2.3 | Dust chamber for PM measurements

The aerosol test chamber used in this work is shown in Figure 1. The test chamber is designed and manufactured such that it has a hexagonal geometric shape. The chamber has an approximate height of 2.4 m along with an actual inner diameter of 1.2 m [47]. The aerosol test chamber uses an appropriate aerosol generator such as a vibrating orifice aerosol generator [48] or a fluidised bed dust generator [49] along with dilution air at the top of the chamber to provide aerosol to the chamber. From this section of chamber, the aerosol is then conducted downward through a 10 cm honeycomb structure in which turbulence in the air is decreased, thus, producing a low velocity downward conducted aerosol stream through the test part of the aerosol chamber. A table with an approximate diameter of 1.16 m that contains a perforated plate to let the air stream flow through the table forms the floor of the test section of this chamber. Underneath the table, the aerosol that is not sampled goes through the HEPA filter and lower distribution plate, in which the particles are detached from air flow. A blower is used to exhaust the air from the test chamber. Three sides of the hexagonal chamber are designed such that they can be used as workstations. Each of these three sides is equipped with a 50 × 75 cm lightweight and shatter-resistant window in addition to a pair of glove ports. These windows enable up to three persons (one person at each window) to work simultaneously on instrumentation placed within the chamber during a test. Windows are held in place by quick-acting toggle clamps. Thus, windows can quickly be removed in order to ease placement of instruments into and out of the chamber.

3 | IN-LAB EXPERIMENTAL SET UP

Nine low-cost PM sensors, three for each type, are interfaced with Arduino boards (Arduino Uno REV3) in order to enable sensors to collect the data. Experiments generally consist of placing these nine low-cost PM sensors along with reference instruments including the PDM 3700, DustTrak DRX, PDR 1500, and personal sampling pump/cyclone, to yield estimates of respirable dust concentration into the dust chamber as shown in Figure 2. The primary reference measures of respirable dust are the PDM 3700 and personal sampling pump with cyclone, both of which yield gravimetric estimates of the respirable dust concentration. The PDM 3700 also logs a 15 min time-weighted average (TWA) measure of respirable dust concentration to which the dust sensor output can be compared. The performance of the reference direct reading instruments is compared in Figure 3, which shows the 15 min TWA respirable dust concentration for the reference PDM 3700 along with the respirable corrected dust concentrations logged by the DustTrak DRX and PDR 1500 instruments. The DustTrak and PDR 1500 instruments are calibrated by the manufacturer using ISO Ultrafine (A1) Arizona road dust and can be adjusted using a correction factor for different dusts. The test dust used in this experiment was ISO Fine (A2) test dust, and therefore a correction factor was used to adjust the DustTrak and PDR 1500 results. The correction factor is simply the ratio of the respirable dust concentration measured using a reference instrument (PDM 3700, or a sampling pump gravimetric/cyclone result) and the DustTrak or PDM 1500 result, and then the instrument results are multiplied by the resulting correction factor. An example of readouts from the reference instrument and corrected results is shown in Figure 3 for a range of PM concentration. Note that instrument inlets locations, which could affect dynamic response and/or spatial and temporal variability of the concentrations within the chamber, are chosen within approximately 6–12 inches of each other in order to minimise spatial effects. The target concentration range for experimental runs was approximately 0.15–3.0 mg/m^3 respirable dust, which represents a range of approximately 0.1–2× the exposure limit of 1.5 mg/m^3. The chamber concentrations were controlled by varying the air flow rate and dust feed rates into the fluidised bed dust generator that supplies the chamber. Although it is difficult to precisely control the dust concentration, the intent is to vary concentrations several times over the course of an experimental run over the range of interest.

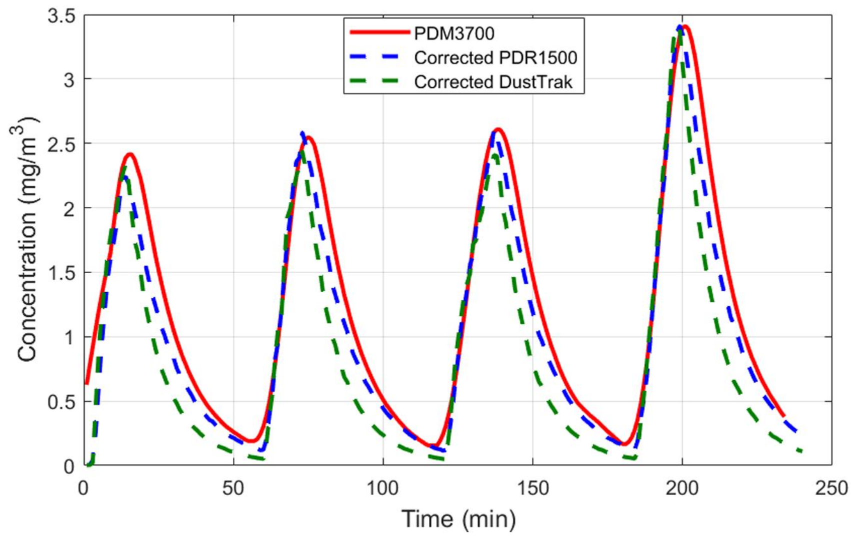

FIGURE 3 Comparison of direct reading instruments for measurement of respirable dust concentrations—15 min time-weighted average for PDM 3700, corrected PDR 1500, and corrected DustTrak DRX

For experiments, PM sensors along with the reference instruments placed in the chamber, were exposed to different levels of dust concentrations. We then compared the response of low-cost PM sensors with reference instruments.

4 | RESULTS AND DISCUSSIONS

4.1 | Data collection

Data was collected in a controlled environment. The experimental set up that was previously described in Section 3 was used to collect dust data for our analysis. Data was collected from the three different types of PM sensors along with the reference instruments over a course of four days, and the same experimental set up was used in all the experiments. However, for each experiment, we either used different sizes of particles or different types of particles. Thus, the type or the size of particles was different for each experiment. The particle size and composition can effectively affect the measuring performance of low-cost sensors. Authors in Ref. [50] investigated how low-cost sensors react to particles with different size and composition. Their analysis showed that the performance of sensors was driven by the particle size more than composition. In this work, for the first three experiments, we used Arizona road dust, but each time with different sizes of particles. For day one, we used A1 Ultrafine Test Dust, which has an average size between 0 and 10 μm [51]. For day two, we used A2 Fine Test Dust, which has an average size between 0 and 80 μm [51] and for day three, we used A3 Medium Test Dust, which has an average size between 0 and 80 μm with a lower 0 to 5 μm content than A2 Fine Arizona Test Dust [51]. In the last day of the experiment, we used coal dust that has particles of 74 μm or less in diameter [52]. Please note that the readout from the sensors not only depends on the concentration of dust particles but also other factors, such as humidity, temperature etc., affect the calibration. In the controlled environment where we calibrated the sensors, the temperature and humidity were kept fixed.

4.2 | Results for the linear regression model

A simple linear regression statistical method was used to indicate the relationships of low-cost sensors and one of the reference instruments (DustTrak). Based on these relationships, several equations were obtained, which were later used for the calibration processes. PM sensors were used as independent variables while the reference instrument (DustTrak) was used as a dependent variable. The result of this calibration process is illustrated as fitted curves. These fitted curves are expressed in terms of polynomial functions given in Tables 1 and 2. In Tables 1 and 2, the order of the polynomial functions that can present the best performance among others are also highlighted. Higher adjusted R^2 [53] represents more accurate models for each type of sensor. Laser sensors exhibit more non-linearity in their response. As can be seen, the best calibration polynomial models for Sharp, Shinyei, and Laser sensors are all third-degree. To select the best regression model for the calibration procedure, we employ statistical tools such as the F test [54]. A statistic made of the variance ratio, designated as the F test, is to test how well the fitted data match the chosen model. The probability value (p value) also shows the possibility of acquiring test results at least as extreme as the results that were observed during an experiment.

The best calibration model for each type of sensor is selected from Table 2 and illustrated in more detail in Figures 4–6. The calibration equations obtained from Tables 1 and 2 are then applied into the uncalibrated sensors' output signals and shown in Figures 7 and 8. In Figures 7 and 8, the DustTrak monitor was used as a reference instrument. DustTrak uses a mass measurement technique, which is superior to either an OPC or a simple photometer [44]. Although photometers are used for measuring the high mass concentrations, they are not usually able to provide any information related to size (unless used with size-selective inlets). Alternatively, OPCs offer size-related information but cannot be used at high mass concentration. The DustTrak monitor however

TABLE 1 Calibration equations and the best calibration models for different types of particulate matter sensors when Arizona Road Dust was used as the main source of producing dust particles

Equation	R^2 (adj) (%)	*F* test	*p* value
DustTrak = 0.1114 + 0.7226 Shinyei − 0.0814 Shinyei^2 + 0.0109 Shinyei^3	84.53	1954.11	0.0001
Dust Trak = −0.02383 + 3.379 Laser + 5.247 Laser**2 − 6.780 Laser**3	79.30	1375.20	0.0001
DustTrak = −0.2489 + 0.5731 Sharp − 0.0250 $Sharp^2$ + 0.0174 Sharp^3	86.15	2224.21	0.0001

TABLE 2 Calibration equations and the best models for different types of particulate matter sensors when Coal Dust was used as the main source of producing dust particles

Equation	R^2 (adj) (%)	*F* test	*p* value
Dust Trak = 0.1679 + 1.965 Shinyei − 0.2962 Shinyei^2 − 0.2532 Shinyei^3	83.9	627.21	0.0001
Dust Trak = 0.07471 − 0.1288 Laser + 9.269 Laser**2 − 8.047 Laser**3	95.3	2454.22	0.0001
Dust Trak = 0.03483 − 0.1043 Sharp + 0.3206 Sharp^2 − 0.04581 Sharp^3	94.1	1906.31	0.0001

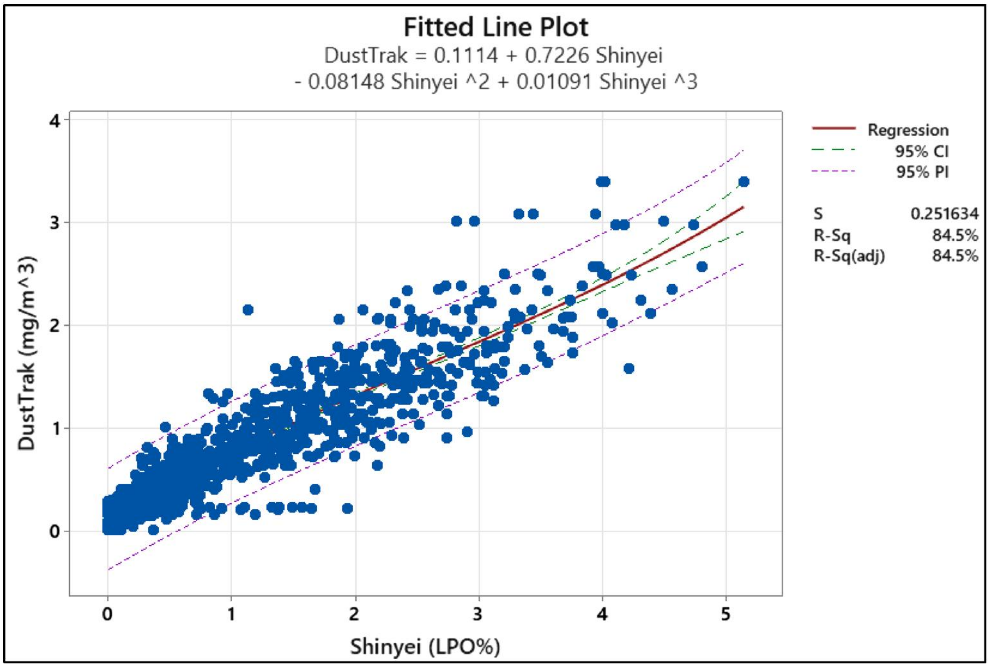

FIGURE 4 In this figure, regression is shown with a solid red line, confidence intervals = 95% and is shown with dashed green lines, and prediction intervals = 95% and is shown with dashed pink lines

can do both measurement techniques [44]. Light-absorbing particles composed of coal dust from coal mining [55] may provide slightly different response to OPC style devices such as DustTrak. As an example, authors in Ref. [56] used an OPC device to measure the size distribution of the coal dust particles and showed that the height of the output signal of the OPC was considerably lower for the coal particles compared to the spherical oil drops of the same size. In Figure 8 also can be seen that the output response of the low-cost sensors along with DustTrak is slightly lower for the coal dust particles compared to the different sizes of Arizona Road Dust. Different environmental conditions and in particular relative humidity (RH) can affect the performance of the low-cost sensors as shown in Refs. [57, 58]. The hygroscopic properties of coal dust have been investigated in the past. As an example, authors in Ref. [59] investigated the wetting performance of coal dust by evaluating the contact angle and the reverse osmosis hygroscopic capacity. The hygroscopic properties of coal dust can possibly affect the performance of the low-cost sensors. However, to the best of our knowledge, not much work has been done in this domain in the past to evaluate the effect of hygroscopicity on the performance of the low-cost sensors.

5 | FIELD EXPERIMENT

A substantial number of coal deposits in the United States are located near the surface of the Earth [60, 61]. Surface mining is usually used when coal beads are located less than approximately 60 m underground [62]. Surface mining is carried out by

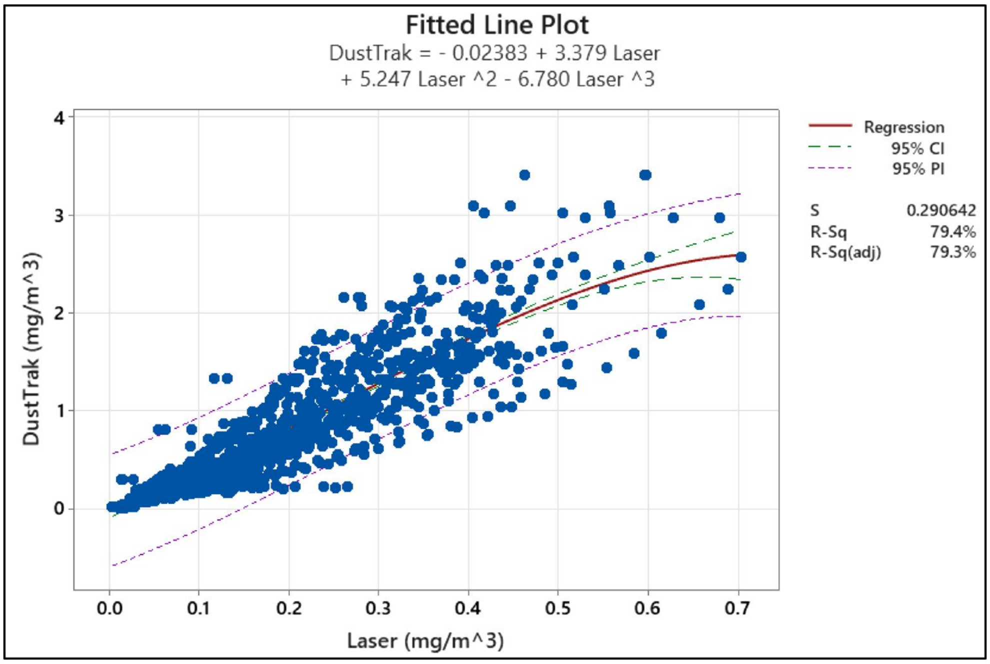

FIGURE 5 In this figure, regression is shown with a solid red line, confidence intervals = 95% and is shown with dashed green lines, and prediction intervals = 95% and is shown with dashed pink lines

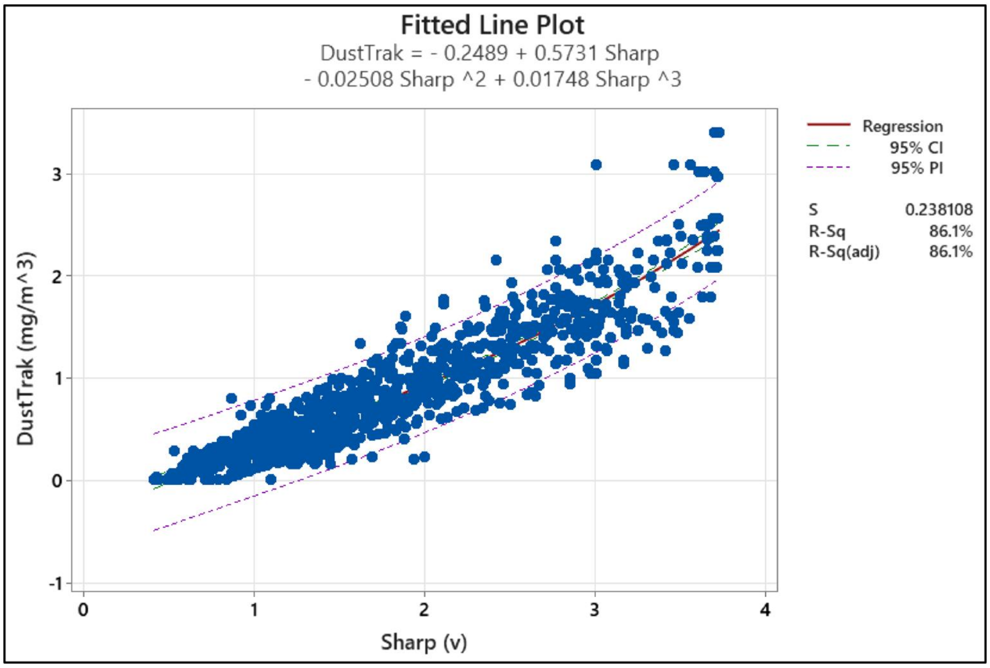

FIGURE 6 In this figure, regression is shown with a solid red line, confidence intervals = 95% and is shown with dashed green lines, and prediction intervals = 95% and is shown with dashed pink lines

removing the topsoil and rock layers to uncover the coal beads. Different mining techniques can be used for surface mining. However, operations such as drilling, blasting, loading and hauling is included in most of the surface mining techniques [62]. Surface mining is less expensive in comparison to underground mining, and it produces most of the coal in the United States. Unfortunately, coal workers who are overexposed to coal dust are at great risk of developing lung diseases. In order to gain insights into the possibility of inhalation of coal dust over the allowable limit in miners, a field study was conducted in a surface coal mine site located in West Virginia in the United States. For the initial test, a load-out platform was selected. Therefore, an area sample was collected on the load-out platform during rail car loading. Coal

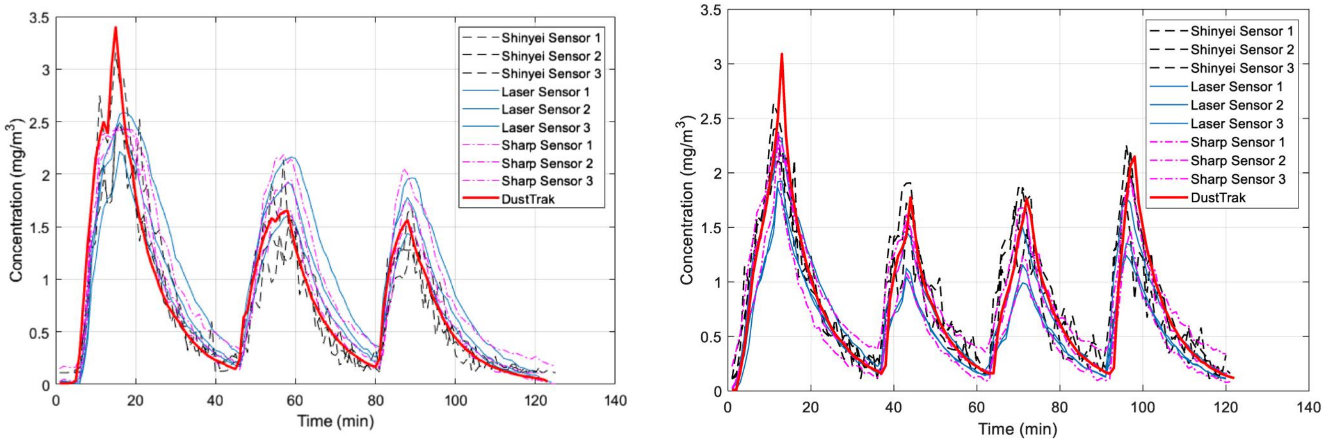

FIGURE 7 Calibrated data—on the left, with Arizona Test Dust-ISO 12103-1-A1 Ultrafine and on the right, with Arizona Test Dust- ISO 12103-1- A2 Fine

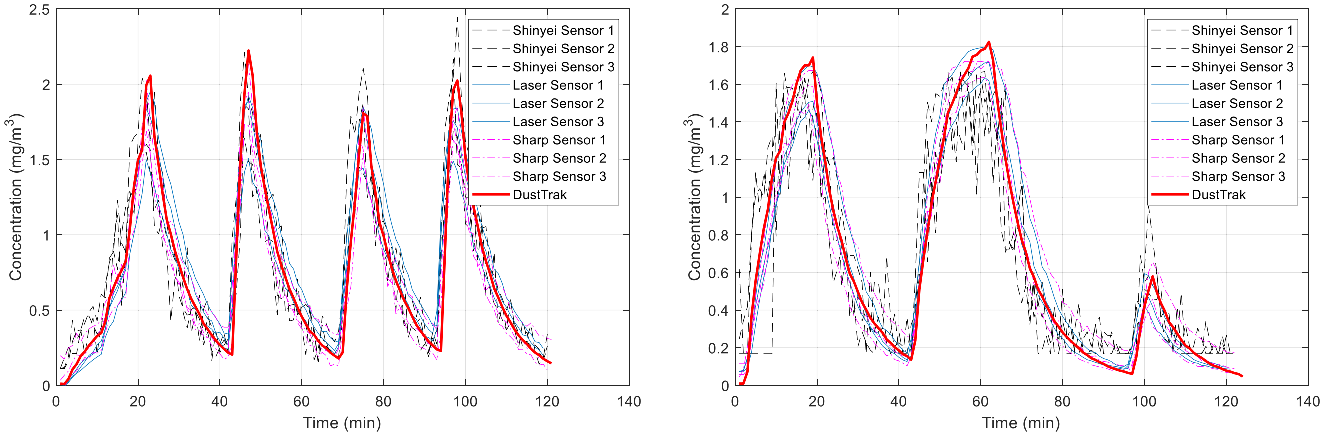

FIGURE 8 Calibrated data—on the left, with Arizona Test Dust-ISO 12103-1-A3 Medium and on the right, with Coal Dust

FIGURE 9 On the left, load-out platform. On the right, respirable dust monitoring during rail car loading operation

loading operation was an example of a scenario where coal workers may be at the risk of excessive inhalation of coal dust. A train loading system works by passing a train through the load-out at a pre-determined speed without stopping while train cars are being loaded. Each batch is calculated based on the maximum gross weight and the empty tare weight. Individual car data is obtained either from a master database or via a radio frequency badge installed on each car. In Figure 9, the reference dust sensing node consists of the TSI DustTrak DRX with its environmental enclosure being placed along with all three different types of inexpensive PM sensors (Sharp, Shinyei, Laser) nearly 3 m away from the coal loader. During this experiment, 54 cars were filled with coal, each car took around 1 min and 22 s to be filled out and each car had a length of 53 feet and a height of 12 feet and 10 inches. Figure 10 shows the calibrated results of the above experiment. As can be seen, all PM sensors and the reference instrument have shown that particle concentration in this specific location

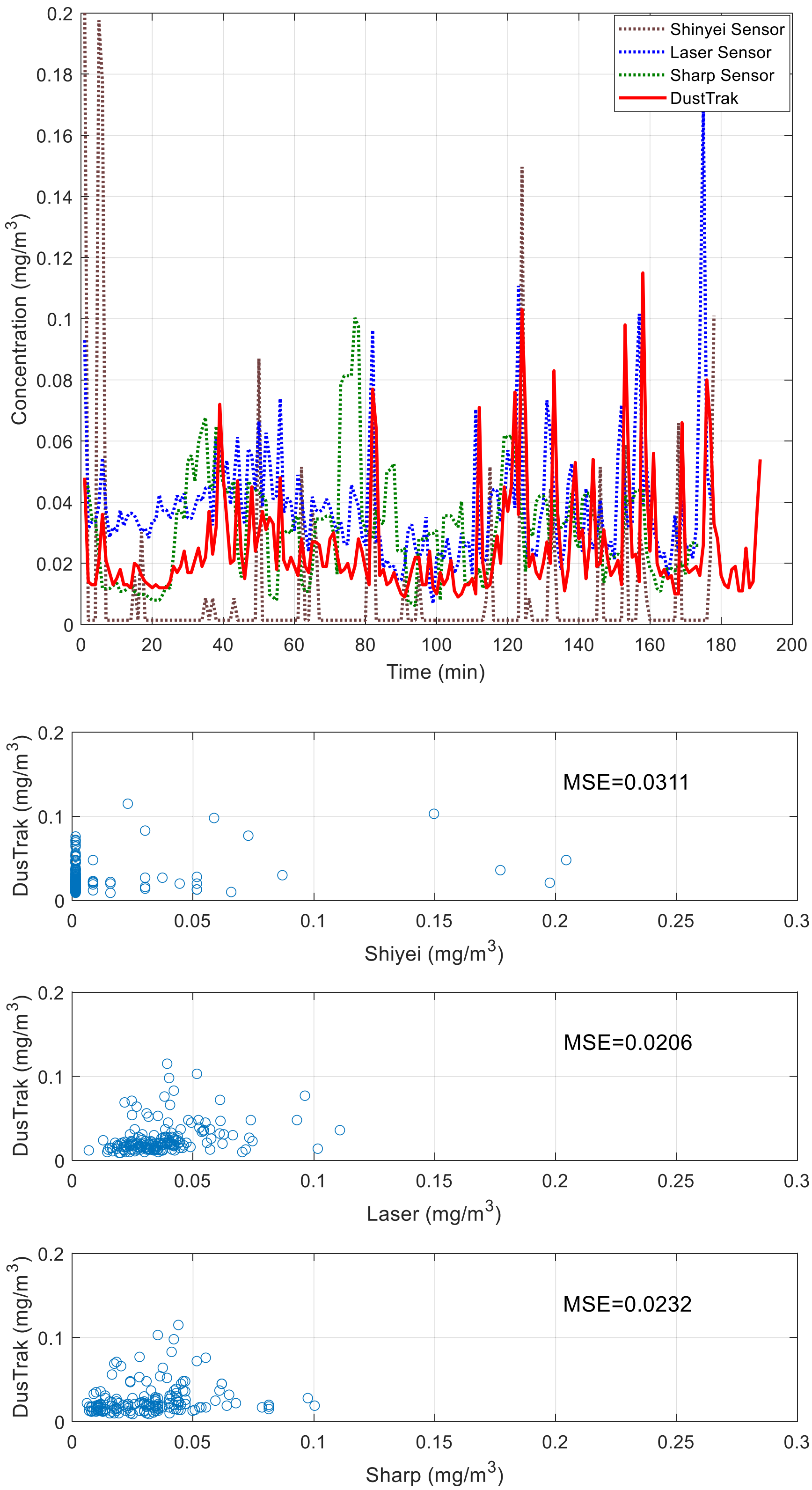

FIGURE 10 Calibrated result for respirable dust monitoring during rail car loading operation

is below the limit of 1.5 mg/m^3. However, as can be seen in Figure 10, these sensors follow the reference but with different degrees of accuracy. The scatter plots of the low-cost sensors versus the DustTrack shown in Figure 10 illustrate the measurements of these three sensors against the reference device. As indicated in the scatter plot, the measurements show the difference between the readouts from the three sensors. The Shinyei sensor shows less sensitivity in the lower end of concentration. Sensors had small offsets, which could be due to the change of the environment and measurement circumstances. We also used a moving average filter to smooth out the response of the Sharp sensor. It can also be seen from this figure that the Laser response closely matches the DustTrak, which is also indicated in the lower root mean square error for the Laser sensor. The mean square error for Shinyei, Laser and Sharp sensors with respect to the reference sensor are 0.0311, 0.0206, and 0.0232, respectively. However, it should be noted that this is only true for the low concentration regime. The full picture becomes clearer when we consider the statistical analysis done in Section 5.

6 | CONCLUSION

Three different types of low-cost PM sensors (Shinyei PPD42NS, Sharp GP2Y1010AU0F and Laser SEN0177) were evaluated, calibrated and compared with the reference instruments. PM sensors were compared with the DustTrak DRX Aerosol Monitor and Thermo Scientific Personal DataRAM pDR-1500 Monitor. The results showed that although these sensors can be used as an alternative to the more expensive instruments, they exhibit different levels of accuracy. The statistical analyses done in Section 4 help to better understand the characteristics of each sensors' response. The methodology given here can be used to assess whether the sensor is compliant with the required accuracy of the proposed application. The use of such accessible sensors will enable a wide network to be installed in the field at different locations. The sensors can be congregated in one location or spread out over a spatial spectrum. The optimum configurations for placement of sensors are the subject of future research. Once the data are collected wirelessly and accumulated over the cloud for a fixed interval of time, a more accurate picture of the environment is attainable. Tens or hundreds of these low-cost off-the-shelf PM sensors can potentially simultaneously work together in mines and form an intelligent wireless network [63]. This smart wireless network consists of three main units of monitoring, communication and control system and is able to intelligently address the problems associated with safety monitoring of coal miners.

ACKNOWLEDGEMENT

This study was funded by the Alpha Foundation for the Improvement of Mine Safety and Health (Grant Number AFC417-39).

CONFLICT OF INTEREST

The author confirms that none of the authors have a conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

Data that support the findings of this study are available on request from the corresponding author. Data are not publicly available due to privacy or ethical restrictions.

ORCID

Mohammad Ghamari https://orcid.org/0000-0002-7752-4270

REFERENCES

1. Lee, S., Shin, J.: Hybrid model of convolutional LSTM and CNN to predict particulate matter. Int. J. Inf. Electron. Eng. 9(1), 34–38 (2019). https://doi.org/10.18178/ijiee.2019.9.1.701
2. Fuzzi, S., et al.: Particulate matter, air quality and climate: lessons learned and future needs. Atmos. Chem. Phys. 15(14), 8217–8299 (2015). https://doi.org/10.5194/acp-15-8217-2015
3. Brown, S.K., et al.: Concentrations of volatile organic compounds in indoor air—a review. Indoor Air 4(2), 123–134 (1994). https://doi.org/10.1111/j.1600-0668.1994.t01-2-00007.x
4. Jokl, M.V.: Evaluation of indoor air quality using the decibel concept based on carbon dioxide and TVOC. Build. Environ. 35(8), 677–697 (2000). https://doi.org/10.1016/S0360-1323(99)00042-6
5. Fang, L., Clausen, G., Fanger, P.O.: Impact of temperature and humidity on the perception of indoor air quality. Indoor Air 8(2), 80–90 (1998). https://doi.org/10.1111/j.1600-0668.1998.t01-2-00003.x
6. Shaughnessy, W.J., Venigalla, M.M., Trump, D.: Health effects of ambient levels of respirable particulate matter (PM) on healthy, young-adult population. Atmos. Environ. 123, 102–111 (2015). https://doi.org/10.1016/j.atmosenv.2015.10.039
7. Patra, A.K., Gautam, S., Kumar, P.: Emissions and human health impact of particulate matter from surface mining operation—a review. Environ. Technol. Innov. 5, 233–249 (2016). https://doi.org/10.1016/j.eti.2016.04.002
8. Pope, C.A., et al.: Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287(9), 1132–1141 (2002)
9. Riediker, M., et al.: Particulate matter exposure in cars is associated with cardiovascular effects in healthy young men. Am. J. Respir. Crit. Care Med. 169(8), 934–940 (2004). https://doi.org/10.1164/rccm.200310-1463OC
10. Dos, V.C., et al.: Rapidly progressive coal workers pneumoconiosis in the United States: geographic clustering and other factors. Occup. Environ. Med. 62, 670–674 (2005). https://doi.org/10.1136/oem.2004.019679
11. Hall, N.B., et al.: Current review of pneumoconiosis among US coal miners. Curr. Environ. Health Rep. 6(3), 137–147 (2019). https://doi.org/10.1007/S40572-019-00237-5
12. Mazurek, J.M., et al.: Coal workers pneumoconiosis–attributable years of potential life lost to life expectancy and potential life lost before age 65 years—United States, 1999–2016. Morb. Mortal. Wkly. Rep. 67(30), 819–824 (2018). https://doi.org/10.15585/MMWR.MM6730A3
13. Laney, A.S., Attfield, M.D.: Coal workers pneumoconiosis and progressive massive fibrosis are increasingly more prevalent among workers in small underground coal mines in the United States. https://doi.org/10.1136/oem.2009.050757
14. Research, O., et al.: Severe occupational pneumoconiosis among West Virginian coal miners. Chest 139, 1458–1462 (2011). https://doi.org/10.1378/chest.10-1326
15. Neumann, G.R., Nelson, J.P.: Safety regulation and firm size: effects of the Coal Mine Health and Safety Act of 1969. J. Law Econ. 25(2), 183–199 (1982). https://doi.org/10.1086/467012

16. Laney, A.S., Weissman, D.N.: Respiratory diseases caused by coal mine dust. J. Occup. Environ. Med. 56(Suppl 10), S18–S22 (2014). https://doi.org/10.1097/JOM.0000000000000260
17. Halldin, C.N., et al.: Debilitating lung disease among surface coal miners with no underground mining tenure. J. Occup. Environ. Med. 57(1), 62–67 (2015). https://doi.org/10.1097/JOM.0000000000000302
18. DEPARTMENT OF LABOR.: Lowering miners exposure to respirable coal mine dust, including continuous personal dust monitors; final rule. Fed. Regist. 79(84), 24814–24994 (2014)
19. Shekarian, Y., et al.: Respirable coal mine dust: a review of respiratory deposition, regulations, and characterization. Minerals 1111(7), 696 (2021). https://doi.org/10.3390/MIN11070696
20. Doney, B.C., et al.: Respirable coal mine dust at surface mines, United States, 1982–2017. Am. J. Ind. Med. 63(3), 232–239 (2020). https://doi.org/10.1002/AJIM.23074
21. Amaral, S.S., et al.: An overview of particulate matter measurement instruments. Atmosphere. 6(9), 1327–1345 (2015). https://doi.org/10.3390/atmos6091327
22. Chung, A., et al.: Comparison of real-time instruments used to monitor airborne particulate matter. J. Air Waste Manag. Assoc. 51(1), 109–120 (2001). https://doi.org/10.1080/10473289.2001.10464254
23. Wang, Z., et al.: Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building. J. Air Waste Manag. Assoc. 66(11), 1109–1120 (2016). https://doi.org/10.1080/10962247.2016.1201022
24. White, W.H.: Considerations in the use of ozone and PM2.5 data for exposure assessment. Air Qual. Atmos. Health 2(4), 223–230 (2009). https://doi.org/10.1007/s11869-009-0056-9
25. Burkart, J., et al.: Characterizing the performance of two optical particle counters (Grimm OPC1.108 and OPC1.109) under urban aerosol conditions. J. Aerosol Sci. 41(10), 953–962 (2010). https://doi.org/10.1016/J.JAEROSCI.2010.07.007
26. Santi, E., et al.: Real-time aerosol photometer and optical particle counter comparison. Nuovo Cim. Soc. Ital. Fis. B. 125 (2010). https://doi.org/10.1393/ncb/i2010-10904-5
27. Morawska, L., et al.: Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? Environ. Int. 116, 286–299 (2018). https://doi.org/10.1016/J.ENVINT.2018.04.018
28. Lewis, A., Edwards, P.: Validate personal air-pollution sensors. Nature. 535(7610), 29–31 (2016). https://doi.org/10.1038/535029A
29. Kumar, P., et al.: The rise of low-cost sensing for managing air pollution in cities. Environ. Int. 75, 199–205 (2015). https://doi.org/10.1016/J.ENVINT.2014.11.019
30. Castell, N., et al.: Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? Environ. Int. 99, 293–302 (2017). https://doi.org/10.1016/J.ENVINT.2016.12.007
31. Wang, Y., et al.: Laboratory evaluation and calibration of three low-cost particle sensors for particulate matter measurement. Aerosol Sci. Technol. 49(11), 1063–1077 (2015). https://doi.org/10.1080/02786826.2015.1100710
32. Liu, D., et al.: Performance calibration of low-cost and portable particular matter (PM) sensors. J. Aerosol Sci. 112(May), 1–10 (2017). https://doi.org/10.1016/j.jaerosci.2017.05.011
33. Bulot, F.M.J., et al.: Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment. Sci. Rep. 9(1), 1–13 (2019). https://doi.org/10.1038/s41598-019-43716-3
34. Sayahi, T., Butterfield, A., Kelly, K.E.: Long-term field evaluation of the Plantower PMS low-cost particulate matter sensors. Environ. Pollut. 245, 932–940 (2019). https://doi.org/10.1016/J.ENVPOL.2018.11.065
35. Canu, M., et al.: What does the Shinyei PPD42NS low-cost dust sensor really measure? Int. J. Environ. Sustain. Dev. 12(1), 1–9 (2021). https://doi.org/10.18178/IJESD.2021.12.1.1310
36. Kuula, J., et al.: Response characterization of an inexpensive aerosol sensor. Sensors 17(12), 2915 (2017). https://doi.org/10.3390/S17122915
37. Jovanovic, U.Z., et al.: Low-cost wireless dust monitoring system. In: 2013 11th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services, vol. 2, pp. 635–638 (2013). https://doi.org/10.1109/TELSKS.2013.6704458
38. Kodali, R.K., Sarjerao, B.S.: MQTT based air quality monitoring. In: 5th IEEE Region 10 Humanitarian Technology Conference 2017, R10-HTC 2017, vol. 2018-January, pp. 742–745 (2017). https://doi.org/10.1109/R10-HTC.2017.8289064
39. Markowicz, K.M., Chiliński, M.T.: Evaluation of two low-cost optical particle counters for the measurement of ambient aerosol scattering coefficient and Ångström exponent. Sensors. 20(9), 2617 (2020). https://doi.org/10.3390/S20092617
40. Migos, T., et al.: On the evaluation of low-cost PM sensors for air quality estimation. In: 2019 8th International Conference on Modern Circuits and Systems Technologies (MOCAST) 2019, May 2019. https://doi.org/10.1109/MOCAST.2019.8742041
41. Chiang, Y.L., et al.: Urban area PM 2.5 prediction with machine methods: an on-board monitoring system. In: 2018 12th International Conference on Sensing Technology (ICST), pp. 25–30 (2019). https://doi.org/10.1109/ICSENST.2018.8603564
42. Austin, E., et al.: Laboratory evaluation of the Shinyei PPD42NS low-cost particulate matter sensor. PLoS One. 10(9), e0137789 (2015). https://doi.org/10.1371/JOURNAL.PONE.0137789
43. Kuula, J., et al.: Laboratory evaluation of particle-size selectivity of optical low-cost particulate matter sensors. Atmos. Meas. Tech. 13(5), 2413–2423 (2020). https://doi.org/10.5194/AMT-13-2413-2020
44. TSI. DustTrak DRX Aerosol Monitors Models 8533, 8533EP And 8534 (2014)
45. Zhang, J., Marto, J.P., Schwab, J.J.: Exploring the applicability and limitations of selected optical scattering instruments for PM mass measurement. Atmos. Meas. Tech. 11(5), 2995–3005 (2018). https://doi.org/10.5194/amt-11-2995-2018
46. Scientific, T.: PDM3700 Personal Dust Monitor. https://www.thermofisher.com/order/catalog/product/PDM3700. Accessed 20 Nov 2021
47. Marple, V.A., Rubow, K.L.: An aerosol chamber for instrument evaluation and calibration. Am. Ind. Hyg. Assoc. J. 44(5), 361–367 (1983). https://doi.org/10.1080/15298668391404978
48. Berglund, R.N., Liu, B.Y.H.: Generation of monodisperse aerosol standards. Environ. Sci. Technol. 7(2), 147–153 (1973). https://doi.org/10.1021/es60074a001
49. Sansone, E.B., Christensen, W.D.: A dust generator for laboratory use. Am. Ind. Hyg. Assoc. J. 39(1), 12–16 (1978). https://doi.org/10.1080/0002889778507707
50. Zou, Y., Clark, J.D., May, A.A.: Laboratory evaluation of the effects of particle size and composition on the performance of integrated devices containing Plantower particle sensors. Aerosol Sci. Technol. 55(7), 848–14 (2021). https://doi.org/10.1080/02786826.2021.1905148
51. Teipel, U., et al.: Characterization of test dust for product qualification. Bulk Solids Powder Sci. Technol. 3(4), 155–161 (2008)
52. Shahan, M.R., et al.: Characterization of airborne float coal dust emitted during continuous mining, longwall mining and belt transport. Min. Eng. 69(9), 61–66 (2017). https://doi.org/10.19150/ME.7746
53. Wooldridge, J.M.: A note on computing r-squared and adjusted r-squared for trending and seasonal data. Econ. Lett. 36(1), 49–54 (1991). https://doi.org/10.1016/0165-1765(91)90054-O
54. Cornell, J.A.: Classical and modern regression with applications. Technometrics. 29(3), 377–378 (1987). https://doi.org/10.1080/00401706.1987.10488247
55. Khan, A.L., et al.: Impacts of coal dust from an active mine on the spectral reflectance of Arctic surface snow in Svalbard, Norway. J. Geophys. Res. Atmos. 122(3), 1767–1778 (2017). https://doi.org/10.1002/2016JD025757
56. Liu, B.Y.H., et al.: Size distribution measurement of airborne coal dust by optical particle counters. Am. Ind. Hyg. Assoc. J. 35(8), 443–451 (2010). https://doi.org/10.1080/0002889748507058
57. Crilley, L.R., et al.: Evaluation of a low-cost optical particle counter (Alphasense OPC-N2) for ambient air monitoring. Atmos. Meas. Tech. 11(2), 709–720 (2018). https://doi.org/10.5194/AMT-11-709-2018

58. Crilley, L.R., et al.: Effect of aerosol composition on the performance of low-cost optical particle counter correction factors. Atmos. Meas. Tech. 13(3), 1181–1193 (2020). https://doi.org/10.5194/AMT-13-1181-2020
59. Wang, P., et al.: Effects of metamorphic degree of coal on coal dust wettability and dust-suppression efficiency via spraying. Adv. Mater. Sci. Eng. 2020, 2020. https://doi.org/10.1155/2020/4854391
60. Jordan, B., et al.: Coal demand, market forces, and US coal mine closures (2018)
61. Energy Information Administration.: Annual Coal Report 2018 (2019)
62. Ramani, R.V.: Surface mining technology: progress and prospects. Procedia Eng. 46, 9–21 (2012). https://doi.org/10.1016/j.proeng.2012.09.440
63. Zhang, Y.B.: Wireless sensor network's application in coal mine safety monitoring. In: Lecture Notes Electrical Engineering, vol. 144 LNEE, vol. 2, pp. 241–248 (2012). https://doi.org/10.1007/978-3-642-27326-1_31

How to cite this article: Ghamari, M., et al.: Laboratory and field evaluation of three low-cost particulate matter sensors. IET Wirel. Sens. Syst. 12(1), 21–32 (2022). https://doi.org/10.1049/wss2.12034