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Advancing occupational health in mining: investigating low-cost sensors suitability for improved coal dust exposure monitoring

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Abstract
Exposure to coal dust in underground coal mines poses significant health risks to workers, including the development of diseases such as coal workers' pneumoconiosis and silicosis. Current available methods for monitoring coal dust exposure are expensive and time-consuming, necessitating the exploration of alternative approaches. Low-cost light scattering particulate matter sensors offer a promising solution, and its development in recent years has demonstrated some success in air quality monitoring However, its application in sensing coal particles is limited partially due to that the operating condition in a mine is different than the atmosphere. Thus, the objective of this paper is to evaluate the impact of common factors encountered in a mining environment on these sensors. The findings revealed that the Air trek and Gaslab sensors were unsuitable, showing poor correlation with reference monitors. SPS30 was promising for low concentrations (0–1.0 mg m^{-3}), while PMS5003 effectively monitored up to 3.0 mg m^{-3}. Changing sensor orientation reduced accuracy. Higher wind speeds (3 m s^{-1}) improved results. Low-cost sensors performed well with coal dust but poorly with Arizona road dust. This study underscores the imperative for enhancing these sensors, thereby facilitating their potential application to enhance the occupational health of miners.

Keywords: low-cost sensor, exposure monitoring, particulate matter, coal dust, occupational health

1. Introduction

Coal mining is inherently associated with the production of coal dust, and prolonged exposure to this dust can result in various adverse health conditions (Ishtiaq *et al* 2018). The Mine Safety and Health Administration (MSHA) plays a vital role as the authoritative regulatory agency responsible for establishing regulatory standards and permissible exposure limits (PELs). In the United States, MSHA has set the PEL for coal dust at 1.5 mg m^{-3}, applicable to both underground and surface coal mines. It is important to note that MSHA mandates continuous sampling throughout a miner's shift, even if the shift exceeds 8 h. When the concentration of respirable dust exceeds 1.5 mg m^{-3} over the full shift duration, it is considered an overexposure. Prolonged

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and heightened exposure to respirable coal dust is known to contribute to various lung diseases among mine workers, including coal workers' pneumoconiosis (CWP), silicosis, and increased mortality (Zhang *et al* 2007). Concerningly, reports indicate that the incidence of CWP has steadily risen in underground coal miners since 2000, with recent studies revealing a particularly alarming increase in CWP and other lung diseases, especially among young miners in states such as Ohio, Virginia, West Virginia, and Pennsylvania (Potera 2019, Blackley *et al* 2022). Even with the advancement in underground coal excavation methods, the coal workers in an underground mine are at risk due to longer working hours and inhalation of respirable coal dust (Dos S Antao *et al* 2005). Existing literature has documented that the prevalence of CWP in the overall United States exceeded 10%, reaching as high as 20.6% in central Appalachia by 2017 (Blackley *et al* 2018). Given the significant threat posed by coal dust to the health of miners, it is imperative to maintain constant monitoring of coal dust concentrations.

Current methods of monitoring coal dust concentration are filter-based methods or the MSHA-certified personal dust monitor model 3700 (PDM3700) monitor. The filter-based sampling method takes samples for the entire working shift and thus can only get one data point at the end of the shift, which is too late to take action if the worker is overexposed to high dust levels (Chung *et al* 2001, Wang *et al* 2016). Additionally, it takes several days of analyzing and data processing, making it inconvenient to use because it cannot provide real-time response. The PDM3700 uses a tapered element oscillation microbalance (TEOM) to measure real-time dust exposure information and track the shift-average respirable coal dust exposure as it approaches regulatory thresholds. It measures primary current mass concentration, primary cumulative mass concentration, and per cent of limit (Thermo Scientific 2014). However, the cost of PDM3700 and its heavy weight are two significant disadvantages. In 2023, the cost of a single PDM3700 unit is approximately $19 000, which presents a prohibitive expense for all the miners to utilize on a per-shift basis. It is also characterized by its considerable physical dimensions, measuring 6.75 inches in height, 9.57 inches in width, and 3.25 inches in depth. Furthermore, the weight of the device is 4.4 lbs., which may cause discomfort to mine workers and add to their physical burden. Consequently, the high cost and heavy weight may limit their implementation and accessibility in mining operations, despite their potential benefits for monitoring and controlling occupational dust exposure. Low-cost light scattering particulate matter (PM) sensors have shown promise in addressing the aforementioned challenges. These sensors are characterized by their affordability, lightweight design, low power consumption, and capacity for real-time monitoring. Low-cost PM sensor works on light scattering principle. A light source is a major part of these sensor, which can be a laser, white light, or infrared LED. The other components include a microprocessor, an air flow controller, lenses, and photodetector. The dust particles entre through the inlet. An inlet may utilize a DC fan or a thermal resister. The thermal resister creates natural convection as it is electrically heated which result in particle flow from the inlet to the sensing area. The particles are exposed to the light beam in the sensing area, and the intensity of the light scattered by particles is detected by a photodetector. The photo-diode detector captures scattered light and subsequently converts it into electrical pulses that are transmitted to the microprocessor. The microprocessor then processes the signal, utilizing the MIE theory to convert the intensity and quantity of electrical pulses into corresponding values of particle count and mass (van den Bossche *et al* 2017, Yong and Haoxin 2023). In one study, three different low-cost PM sensors (Shinyei PPD42 NS, Sharp GP2Y1010AU0F and Lase SEN0177) were tested for coal dust, and their response was compared with Tsi DustTrak DRX Aerosol Monitor Model 8533 and Thermo Scientific Personal Data RAM pDR-1500 Monitor as the reference monitor. Shinyei PPD42 NS is generally air quality monitoring. Air purification, air conditioner and ventilator (Shniyei 2023). The sharp GP2Y1010AU0F dust sensor is a specialized device designed for the detection of household dust, cigarette smoke, and similar particles. It serves as a sensor for the automated operation of applications such as air purifiers and air conditioners equipped with air purifying functionality (Sharp 2013). Lase SEN0177 is digital sensor which has application in air quality monitoring. This sensor is capable of quantifying the quantity of suspended PM in a given volume of air, specifically particles ranging in size from 0.3 to 10 µm (DFRobot 2013). The experimental runs were conducted within a target concentration range of approximately 0.15–3.0 mg m^{-3} of respirable dust. This range corresponds to approximately 0.1–2 times the established exposure limit of 1.5 mg m^{-3}. The result indicated that these sensors could measure coal dust concentrations as they gave a fair response when compared to reference monitor. The mean square error (MSE) was used as the evaluation metric, with lower values indicating superior performance. The MSE was found to be 0.0206 for the laser sensor, while the MSE for the Shinyei and Sharp sensors were 0.0232 and 0.0311, respectively. These findings suggest that the laser sensor demonstrated the most favorable response among the tested sensors (Ghamari *et al* 2022). In another study, a newly developed optical sensor was used for coal dust concentration measurement. It was found to exhibit a relative error of less than 5% when measuring dust concentrations ranging from 200 mg m^{-3} to 800 mg m^{-3}, indicating its reliable performance. Notably, when the dust concentration was kept constant at 200 mg m^{-3}, the relative error across the five data sets increased with the data acquisition interval yet remained below 5% without significant data fluctuations. These findings emphasize the potential of the optical sensor to provide a highly accurate and dependable solution for monitoring coal mine dust concentration. mg m^{-3} (Zhang *et al* 2021a). In a recent investigation involving low-cost PM sensors, the PMS 5003 sensor was identified as capable of accurately measuring coal dust concentration up to a threshold of 3.0 mg m^{-3}. The sensor demonstrated strong linearity concerning the reference monitors PDM 3700 and APS, as reflected in R^2 values ranging from 0.70 to 0.90 for concentration levels below 3.0 mg m^{-3}. The intra-model linearity of the PMS 5003 sensor was also found to be excellent, with R^2 values of 0.97. These results suggest that the PMS 5003 sensor holds significant potential for use in accurately and reliably monitoring coal dust concentration (Amoah *et al* 2023).

The response of low-cost PM sensors varies with the nature of the measured particles. A study tested an optical PM sensor with Arizona road dust (ARD) and coal dust in the concentration range of 0.15 mg m^{-3} to 3.0 mg m^{-3} and reported that the response of sensors was lower for coal dust particles than Arizona dust (Ghamari *et al* 2022). A study reported that a low-cost sensor (Dylos-1700 sensor) was challenged with different particle sources, including wood smoke, polystyrene latex spheres and ammonium sulfate. Dylos-1700 is generally used in air quality monitoring and it can report particle readings as either particle concentration (>0.5 µm, >2.5 µm) or as mass concentration in PM2.5/PM10 (µg m^{-3}) (Dylos corporation 2017). The experimental setup utilized a chamber with a volume of 1 m^3, with the flow rate maintained at either 1.5 or 3.5 LPM. The mass concentration levels of wood smoke, polystyrene latex spheres, and ammonium sulfate within the chamber were controlled at ranges of 0–1.2 mg m^{-3}, 0.–0.19 mg m^{-3}, and 0–0.12 mg m^{-3}, respectively. The outcome revealed that the sensor response differed for all sources compared to the reference instrument (Northcross *et al* 2013). As such, to enhance the accuracy and reliability of these sensors, it is essential to undertake more comprehensive studies aimed at comprehending the factors that influence their performance when measuring diverse types of particles.

The few available studies that have evaluated low-cost PM sensors for coal dust are characterized by several limitations. The limitations include factors such as the calibration method, environment, and dust concentrations. Some studies reported the impact of coal dust on low-cost sensors, but the response of these sensors was not evaluated using the MSHA-certified coal dust monitors for underground mines (Ghamari *et al* 2022) (Mahdavipour *et al* 2015). As such, the findings of this study cannot be generalized to the measurement of coal dust in underground mine environments. In another study, low-cost sensors, PMS 1003 and Alphasense CO–B4, have been evaluated for long-term air quality monitoring in Australia and China. The PMS1003 represents a digital universal sensor for quantifying suspended particle concentrations in the air. It accurately counts and measures particle concentrations, providing data through a digital interface (Zhou and Haoxin 2016). Alphasense CO–B4 is a general environment and monitoring sensor which can detect carbon monoxide in both PPM and PPM variants (Alphasense 2017). The studies included the assessment of various sources of pollution, including coal dust. However, it is essential to note that the studies were not designed explicitly for coal dust measurement, and as such, the results cannot be used to conclude the accuracy of coal dust measurements (Liu *et al* 2020). A recent study developed and evaluated an optical sensor for measuring coal dust particles with higher precision (Zhang *et al* 2021a). The results indicated that the sensor demonstrated considerable precision and stability while measuring coal dust particles. However, the dust concentration used to evaluate was excessively high, ranging from 200–800 mg m^{-3}, more than 100 times higher than the safe exposure limit. This raises the question of how the sensor performs when measuring coal dust particles at concentrations close to the exposure limit.

Wind velocity and sensor direction were also shown to have an impact on the PM sensor's response, but how it impacts coal dust measurement is unknown. A few studies have reported the impact of low wind velocities of 0.5 m s^{-1} on the performance of low-cost PM sensors (Zikova *et al* 2017, Alfano *et al* 2020). However, the underground airflow velocity ranges from zero up to 4 m s^{-1} (Christensen *et al* 1984, Fobelets 1987, Roghanchi *et al* 2016). This makes it necessary to study the impact of wind velocity in this range to provide a more reliable basis for assessing the accuracy of low-cost sensors in measuring coal dust levels and their suitability for use in coal mining regions. Additionally, *a prior* study has reported some preliminary results suggesting that wind direction may impact the performance of PM sensors (Bulot *et al* 2019, Liu *et al* 2020). In underground mining environments, air typically flows in one direction, which may have different implications for the performance of PM sensors. Therefore, the impact of sensor position on wind direction needs to be investigated to understand better how this factor affects the accuracy and reliability of PM sensors in measuring coal dust particles in underground mining environments.

To address the gaps mentioned above, this paper aims to evaluate the impact of wind velocity and sensor direction on the performance of low-cost PM sensors. Evaluation will also be performed using ISO 12103-1, A2 Fine Test Dust to analyze the level of impact when measuring Arizona dust and coal dust. As demonstrated in figure 1, the factorial design of experiments will be performed at three dust concentration levels. At each level, there will be two factors (wind velocity and sensor direction) with three levels for each factor: wind velocities of 0.5 m s^{-1}, 1.5 m s^{-1} and 3 m s^{-1}; and sensor directions towards the stream, perpendicular to the stream, and opposite to the stream. The response of each low-cost sensor will be compared to two-reference instruments (PDM 3700 and APS). This study investigates the factors commonly encountered in an underground mining environment, which provides valuable information on the feasibility of using these low-cost sensors in the mining industry where coal dust is a concern.

2. Experimental methods

2.1. Experimental instruments

Four low-cost PM sensors were evaluated, including the Gaslab, CM-505 (referred Gaslab) multi-gas sensors (GasLab 2022), the Airtrek sensor (LLC 2023) by aerosol works, SPS30 sensor batch# 227C66FD7F30 FA2A (Sensiron 2018), and Plantower PMS5003 batch#2020 061 903 541 (Yong and Haoxin 2023), referred to as, (PMS) low-cost PM sensor. Two sensors of each type except Airtrek sensor were evaluated in this study to achieve a more accurate assessment of sensor response. By evaluating multiple sensors of each type, the study provided a more comprehensive and reliable assessment

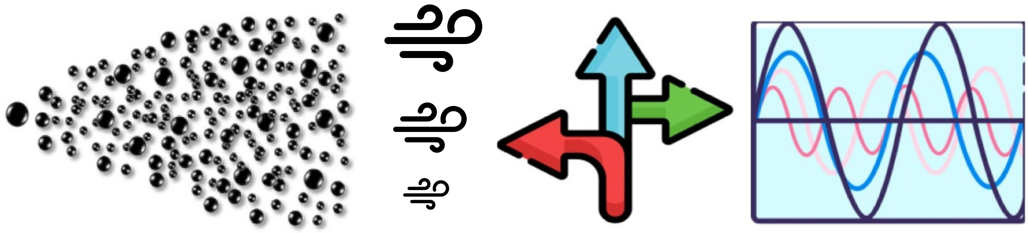


Figure 1. Low-cost PM sensor flow-chart.

of sensor performance in measuring coal dust particles. The working principle of the Gaslab sensor is that it uses a combination of NDIR, fluorescent, and electrochemical sensors to measure PM concentration and gas concentration. These sensors can measure PM2.5 and PM 10 together with other gases such as carbon dioxide (CO_2), carbon monoxide (CO) and oxygen (O_2) concentration. The PMS and SPS30 works on the light scattering principle. It uses a fan to draw ambient air into the sensing area. When the particles reach the sensing area, LED light hits the particles. The light scattered by the particles is detected by a photodiode detector, which sends the electrical signals to the in-built processor.

The microprocessor then converts the intensity of the electrical signals to the number and mass of the particles. These PMS sensors characterize PM by size into PM1, PM2.5 and PM10. The manufacturers of the PMS sensors state that PM1 is measured for particles in the size range of 0.3 μm–1 μm, PM2.5 for particles in the size range of 1 μm–2.5 μm and PM10 for particles in the size range of 2.5 μm–10 μm. The low-cost PM monitor is continuously powered using 5 V USB cables. For data analysis, the PM monitor is interfaced with ThingSpeak MATLAB-based online IOT platform, which serves as a cloud where all data is transmitted through Wi-Fi. SPS30 sensors work on the same principle as PMS5003. The data is stored locally on the computer.

Two reference monitors, PDM 3700 and Aerodynamic Particle sizer (APS) model 3321 are utilized in this study. Personal dust monitor (PDM) and APS are known for their high accuracy in measuring aerosol properties. They provide precise data, making them suitable as references for validating and calibrating other aerosol monitoring instruments. APS measures aerosol particle size distributions with high resolution, providing data on the aerodynamic diameter of particles. This detailed size information is crucial for understanding how different particles behave and their potential impacts on health and the environment. Both APS and PDM3700 offer real-time or near-real-time monitoring capabilities. This real-time data is valuable for tracking changes in aerosol characteristics over time, helping researchers capture fluctuations and trends by using APS and PDM3700 as standards or references, researchers can maintain consistency in their studies and compare data across different experiments or locations. The first reference monitor is a PDM3700. MSHA has approved this equipment as the regulatory compliance monitoring device, and also The National Institute for Occupational Safety and Health has authenticated the precision and accuracy of this instrument (Volkwein *et al* 2006). This instrument uses the principle of tapered element oscillation microbalance (TEOM). The cutoff diameter of the coal dust particle which can enter this instrument is 4.5 μm which is insured by an impactor installed near the inlet. The second reference monitor used in this study is the APS 3321 manufactured by TSI. This instrument uses the principle of inertia to classify the particle into different sizes. The size range of APS is 0.5–20 μm. As an aerosol particle traverses this overlapping beam geometry, it elicits a unique signal characterized by two maxima. The temporal duration between these maxima yields pertinent aerodynamic particle sizing data. The particles are then classified based on their aerodynamic diameter (TSI incorporated 2022). The APS also records the height of the peaks, which means it also records instantaneous values like sudden jumps in concentration, unlike PDM, which gives an average concentration, allowing a secondary calculation of particle size based on optical scattering (Peters and Leith 2003).

The particle generation setup and the wind tunnel used in this study are shown in figure 2. The wind tunnel used in this study is a custom-built wind tunnel made with metal frames and acrylic glass panels. The wind tunnel has a U shape with a cross-sectional dimension of the tunnel is 0.5 m × 0.5 m. The entire dimension of the U shape is 4.5 m long and 2 m wide. The wind tunnel has a particle generator consisting of an air blower connected to the venturi feeder. A vibratory feeder is used to feed the coal to the venturi feeder. This venturi feeder uses the venturi effect to draw the dust into the outlet pipe of the blower, which then blows dust into the wind tunnel. The outlet of the wind tunnel is connected to a dust collector, which collects dust exiting the tunnel and provides airflow through the wind tunnel. The wind tunnel has a platform built at the monitoring location, which is 25 cm from the top of the tunnel on which the sensors and the nozzles for the monitors are installed.

2.2. Experimental design

A complete factorial experimental design was used to determine the accuracy of the low-cost sensors. Table 1 shows one experiment set with one concentration level of 0–1.0 mg m^{-3}. Most of the pollutants are commonly diluted at a wind velocity

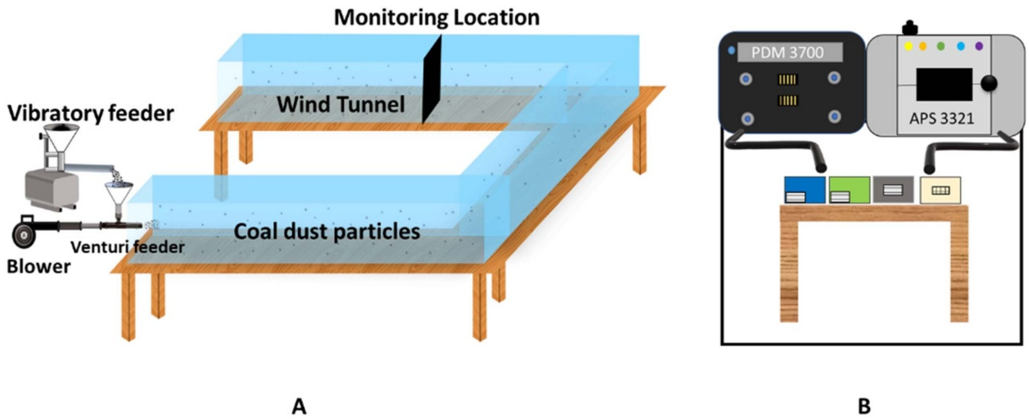


Figure 2. (A) Wind tunnel and particle generation setup used in this study. (B) Location of sensor inlets and reference monitor inlets at the monitoring location.

Table 1. Experimental scheme for day 1 at coal dust concentration between 0 and 1.0 mg m^{-3}.

Run order	Dust concentration (mg m^{-3})	Wind velocity (m s^{-1})	Sensor direction
1	0–1.0	3	Towards the stream
2	0–1.0	0.5	Perpendicular to the stream
3	0–1.0	1.5	Perpendicular to the stream
4	0–1.0	1.5	Towards the stream
5	0–1.0	3	Perpendicular to the stream
6	0–1.0	1.5	Opposite the stream
7	0–1.0	0.5	Opposite the stream
8	0–1.0	0.5	Towards the stream
9	0–1.0	3	Opposite the stream

Table 2. Experimental scheme for Arizona road test dust.

Run order	Dust concentration (mg m^{-3})	Wind velocity (m s^{-1})	Sensor direction
1	0–3	1.5	Towards the stream
2	0–3	1.5	Perpendicular to the stream
3	0–3	1.5	Opposite the stream

of 0.3 m s^{-1} (Mcpherson *et al* 2009). Nevertheless, within the operational zones dedicated to production activities, airflow rates typically exhibit a broader range, fluctuating between 1 and 3 m s^{-1}. It is worth noting that surpassing this upper threshold may lead to notable discomfort among subterranean laborers. This discomfort primarily arises from the disruptive influence of larger dust particles transported by the intensified airflow (Nevins 1971, Fanger 1977, Berglund and Fobelets 1987, Zhou 1999, Toftum 2002). The author decided to use three wind velocity levels as 0.5, 1.5 and 3 m s^{-1}, and the three direction levels are towards the stream, perpendicular to the stream and opposite. Thus, each set of experiments has nine test runs. Since the PEL for coal dust is 1.5 mg m^{-3}, the author decided to test these sensor on lower and upper side of PEL. A similar experimental design was used for the other concentration levels of 1.0–2.0 mg m^{-3} and 2.0–3.0 mg m^{-3}. Therefore, a total of 27 experiments were performed. Each set of experiments was completed on the same day. The response of low-cost sensors will be compared to two reference monitors, i.e. PDM 3700 and APS.

To investigate the response of the sensors to various types of dust, an additional set of experiments was conducted using Arizona road test dust as the test material. A comparison will be drawn between the sensor responses to coal mine dust and Arizona road test dust. The experimental protocol includes three tests with different sensor directions, but the dust concentration level was maintained within the range of 0–3 mg m^{-3}, and the wind velocity was held constant at 1.5 m s^{-1} for all runs. The duration of each test run will be 60 min. The experimental scheme for Arizona road test dust is shown in table 2.

3. Results

Before the low-cost sensor evaluation, the response of these two reference monitors was compared to see their degree of

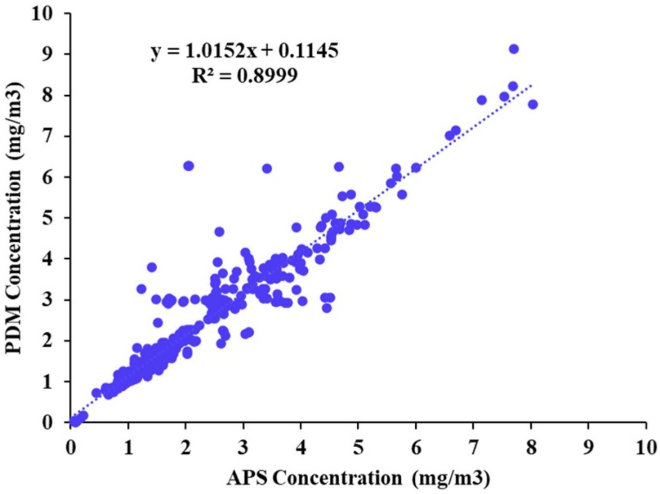


Figure 3. Correlation between PDM reference monitor and APS reference monitor.

disagreement, which may affect the low-cost sensors' calibration model. The PDM utilizes the BGI HD cyclone with a precise D_{50} cutoff point of 4.37 µm. For APS, the concentration of the particles within 4.37 µm is used in this analysis (Belle 2017). As shown in figure 3, when the data from PDM and APS for all coal dust experiments was compared, a very high linearity was observed between their response. In assessing the strength of the linear relationship, we calculated R-squared in conjunction with Pearson correlation coefficients (r)p. The Pearson correlation coefficient, often referred to as Pearson's *r*, is commonly used to measure the linear relationship or correlation between two variables. A 0.94 value of *r* signifies a strong positive correlation. The *R*-squared value of 0.89, shown in figure 3, showed a very high correlation between these two reference monitors. It is mentioned in earlier studies that an *R*-squared value above 0.8 is considered highly correlated, an *R*-squared value of 0.6–0.8 shows moderate correlation and an *R*-squared value below 0.6 is considered a low correlation (Kelly *et al* 2017, Sayahi *et al* 2019a). The high correlation between these two monitors shows they can be used as reference monitors to calibrate low-cost PM sensors. Even though APS has not been recognized as a reference monitor for coal dust monitoring, its high accuracy shows that it can be utilized as a reference monitor for coal dust monitoring.

The clock settings for all sensors and monitors were standardized to ensure synchronized time stamps. Various monitors have varying data recording intervals: the APS and PMS sensors were configured to record real-time concentrations every 15.0 s, Airtrek reported concentrations every 30.0 s, SPS30 and Gaslab reported concentrations every 1.0 s and 2.0 s respectively. To facilitate comparability with the PDM, which records multiple data points within a minute, the readings from sensors and monitors that do so were averaged within each minute. This minute-by-minute concentration data is subsequently employed in the assessment and calibration procedures.

The PDM's reported time-weighted average (TWA) concentration data were transformed into minute-by-minute real-time concentrations using equation (1) to maintain consistency with the data from all other sensors. In this equation, TWAn represents the TWA at each time step, Cn denotes the measured real-time concentration, T indicates the time interval between consecutive measurements, and Tn signifies the total number of minutes at time n

$$C = \frac{\mathrm{TWA}n\ X\ Tn}{T} - (C_1 + C_2 + C_3 \ldots.\ C_{n-1})\,. \quad (1)$$

3.1. Precision

The results of the precision test are displayed in figure 4. Intramode correlation between two models of each sensor type (a) PMS5003 (b) SPS30 (c) Gaslab sensors. The correlation coefficient values and *R* squared values for sensors w.r.t reference monitors are given in table 3.

It can be seen from figure 4(b) that SPS30 sensors have shown the highest degree of precision with an *R*-squared value of 0.94 and Pearson's *r* value of 0.97. The manufacturer datasheet suggests that SPS30 sensors can effectively read concentrations up to 1 mg m^{-3}, but the sensors in this study reported higher concentrations. It can be depicted that most of the points are congested near or a little beyond the effective range. Beyond this range, the points started to scatter more, and SPS30 read up to 20 mg m^{-3} showing the overestimation as the actual concentration during all experiments went up to 9 mg m^{-3}.

PMS 5003 sensors also showed excellent precision, with Pearson's *r* value of 0.81 and *R*-squared value 0.72 in figure 4(a). Unlike SPS30 sensors, these sensors have shown that they can read any concentration with excellent accuracy and good precision without overreporting the concentration above a particular range. Figure 4(a) also shows that these sensors did not experience excessive peaks and reported the concentration in good agreement with each other. As mentioned earlier, the maximum concentration reported during all the experiments went up to 9 mg m^{-3}, and these sensors read a maximum of 7 mg m^{-3}, which is slightly under-reporting but still very near to the actual concentration read by the reference monitors.

The Gaslab sensors have shown the worst precision among all sensors tested in this study which is evident from its *R*-squared value of 0.3 figure 4(c). The *r* value was found to be 0.5, an *r* of 0.5 suggests a moderate relationship. It is not a perfect correlation. Their readings were capped at 1.2 mg m^{-3}, and the two sensors did not exhibit good agreement with each other. The Pearson's *r* and *R*-squared values for reference monitors and sensors are given in table 3.

3.2. Impact of coal dust concentration

To evaluate the effect of coal dust concentration on the performance of low-cost PM sensors, we checked the linearity of each sensor by comparing the sensor response to the actual concentration when the sensors' inlets were facing the

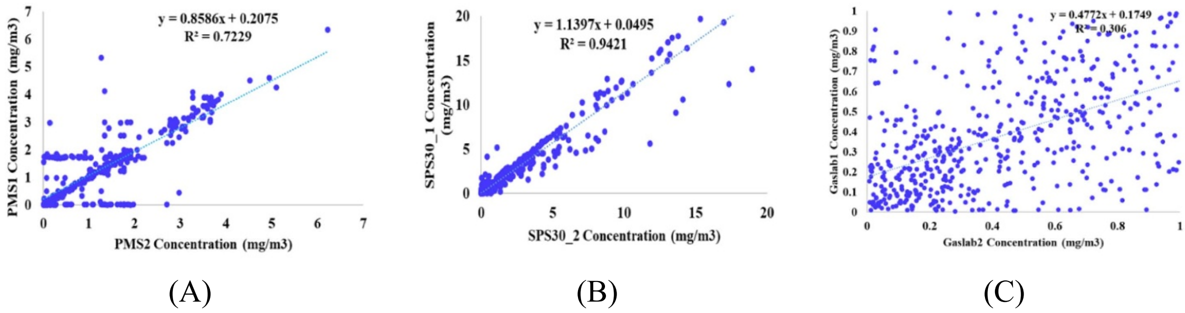


Figure 4. Intra-mode correlation between two models of each sensor type (a) PMS5003 (b) SPS30 (c) Gaslab sensors.

Table 3. Correlation coefficient and R-squared values for reference monitor and sensors.

Sensor	Sensor	Pearson's *r*	*R*-squared
PDM	APS	0.94	0.89
Gaslab	Gaslab	0.306	0.5
SPS30	SPS30	0.94	0.97
PMS5003	PMS5003	0.72	0.81

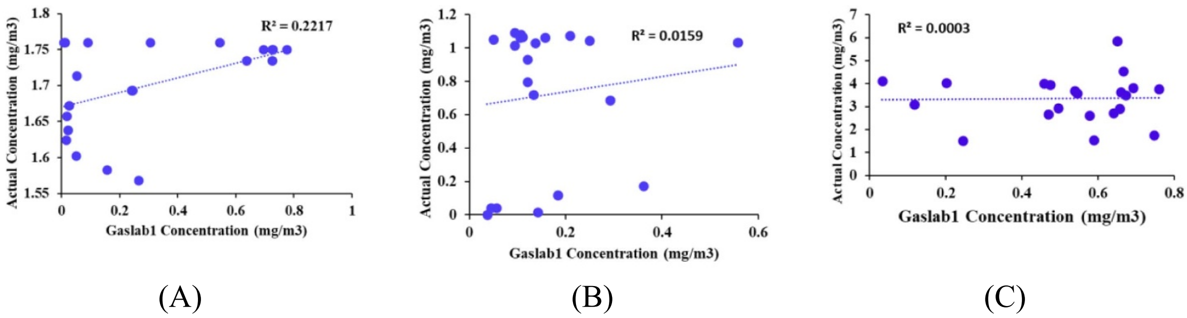


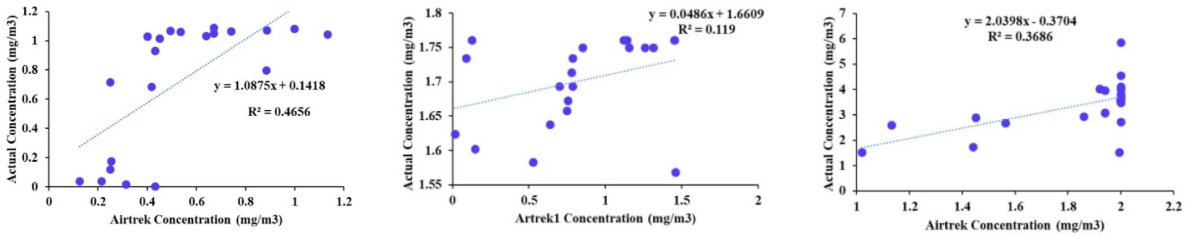
Figure 5. Gaslab sensor at (A) 2.0–3.0 concentration, (B) 1.0–2.0 concentration, (C) 0–0.1 concentration.

airflow direction. The *R*-squared value is a statistical measure that assesses the association level between two or more variables in a linear regression model. It provides information on the degree to which the variation in the dependent variable is attributable to the independent variable(s). It is a widely used metric in statistical analysis to determine the strength and quality of the relationship between variables. In prior research, it has been noted that a coefficient of determination (*R*-squared) exceeding 0.8 is indicative of a strong correlation, while an *R*-squared value ranging from 0.6 to 0.8 suggests a moderate correlation. An *R*-squared value below 0.6 indicates a weak correlation (Kelly *et al* 2017, Sayahi *et al* 2019a).

Figure 5 presents the linearity analysis of Gaslab sensor outputs compared to actual concentrations, whereby PDM was used as the reference monitor. As can be seen, it has abysmal performance at all concentration levels, with *R*-squared values of 0.2217, 0.0159, and 0.0003, at high, medium, and low concentration levels, respectively. It also showed very low values for *r* as 0.47. 0.12 and 0.017. These very low values of Pearson's *r* show that there is almost low to no relationship between reference monitors and Gaslab sensors. Additionally, it only reports a maximum value of 1.0 mg m^{-3} even when the actual concentration exceeds that level. As can be seen in figures 5(a) and (b), where the actual concentrations were up to 6.0 mg m^{-3} and 1.75 mg m^{-3}, respectively, the Gaslab readings were below 1.0 mg m^{-3}. Because of the poor performance of this monitor, we decided not to evaluate it for any further analysis of other sensor directions and velocities.

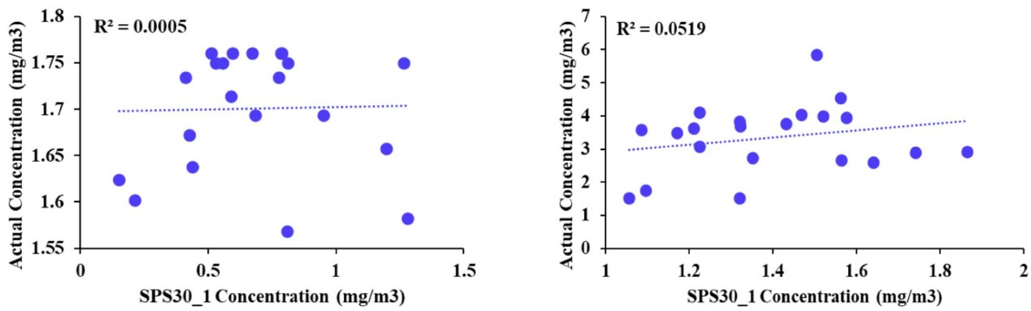
The Airtrek sensor (figure 6) demonstrated marginally better linearity but still a weak correlation with the reference monitor when positioned toward the direction of the stream. A moderate relationship was shown by Airtrek sensors as indicated by *r* value of 0.56 and 0.52 at low and intermediate concentration. However, a very low *r* value of 0.22 was observed at high concentration showing very low correlation. According to the manufacturer's datasheet, Airtrek is designed to measure concentrations up to 2.0 mg m^{-3}. As can be seen in figure 6(c), it gave a constant reading of 2.0 mg m^{-3} when the actual concentration was higher.

The response of SPS30 sensors significantly deteriorated beyond a concentration of 1.0 mg m^{-3}, aligning with the manufacturer's datasheet specifications (Sensiron 2018).



(A) (B) (C)

Figure 6. Airtrek sensor at (A) 2.0–3.0 mg $^{-3}$ concentration, (B) 1.0–2.0 mg $^{-3}$ concentration, (C) 0–0.1 concentration.



(A) (B)

Figure 7. SPS30 sensor at (a) concentration 1.0–2.0 mg m^{-3} and (b) concentration 2.0–3.0 mg m^{-3}.

According to the datasheet, the mass concentration range for the SPS30 sensor is 0–1 mg m^{-3}. Although the sensors can still measure concentrations beyond this limit, their accuracy diminishes substantially. As depicted in figures 7(a) and (b), when the actual concentration ranged between 1.0–2.0 mg m^{-3} and 2.0–3.0 mg m^{-3}, the corresponding *R*-squared values were 0.0005 and 0.0519, respectively. These low *R*-squared values demonstrate the sensor's low accuracy in reading concentrations above 1.0 mg m^{-3}, making it unsuitable for monitoring coal dust at higher concentrations. Additionally, very low *r* values of 0.02 and 0.22 were measured which also indicated the poor response of SPS30 sensor with the reference monitor beyond their effective concentration range.

The *R*-squared and Pearson's *r* values for Gaslab, Airtrek and SPS30 are given in table 4.

Table 4. The R-squared and Pearson's r values for Gaslab, Airtrek and SPS30 at high concentrations.

Sensor	Monitor	Concentration	Pearson's *r*	*R*-squared
Gaslab	Reference monitor	Low	0.47	0.22
		Intermediate	0.12	0.015
		High	0.017	0.0003
Airtrek	Reference monitor	Low	0.46	0.56
		Intermediate	0.119	0.52
		High	0.3686	0.22
SPS30	Reference monitor	Intermediate	0.005	0.2
		High	0.0519	0.22

3.3. Impact of sensor direction

Sensor direction considerably affects the linearity of SPS30 sensor response within their effective range of concentration. As seen in figure 8(a), when the sensor inlet is toward the flow direction, it showed moderate linearity with the *R*-squared value of 0.71. However, the *R*-squared value decreased to 0.36 and 0.18 when the senor direction was changed to perpendicular and opposite, respectively. Similarly, an *r* value of 0.84 suggest a very strong relationship with SPS30 and reference monitor when the sensor inlet direction is towards the stream. The *r* values were dropped to 0.6 and 0.4 when the inlet direction was altered to particular and opposite. Figures 8(b) and (c) illustrates that a similar trend was observed for the sensor response concerning sensor direction at a wind velocity of 1.5 m s^{-1} and 0.5 m s^{-1}.

Statistical analysis was conducted to investigate two-way interactions of sensor direction and wind velocity on the sensor response. The ANOVA analysis revealed that sensor direction and wind velocity significantly affect the sensor response ($p = 0.0001$). The Tukey HSD statistical test assessed the impact of sensor directions, specifically towards, perpendicular, and opposite. This post hoc test compares all possible pairs of least square (LS) mean differences to identify which differences are significant. Results indicated that the opposite sensor direction had the most significant impact, with an LS mean value of 1.5. Meanwhile, the LS mean

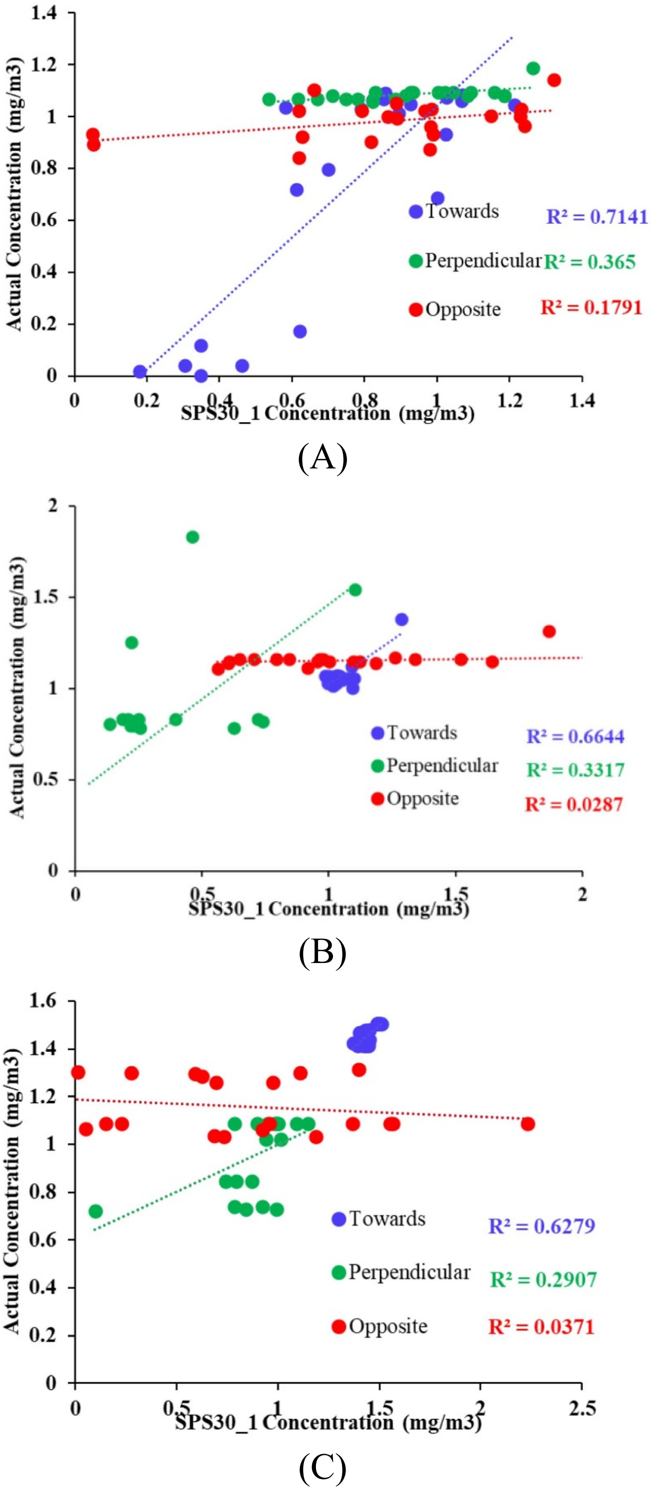


Figure 8. SPS30 response at concentration 0–1.0 mg m^{-3} (a) velocity 3.0 m s^{-1}, (b) velocity 1.5 m s^{-1}, (c) velocity 0.5 m s^{-1}.

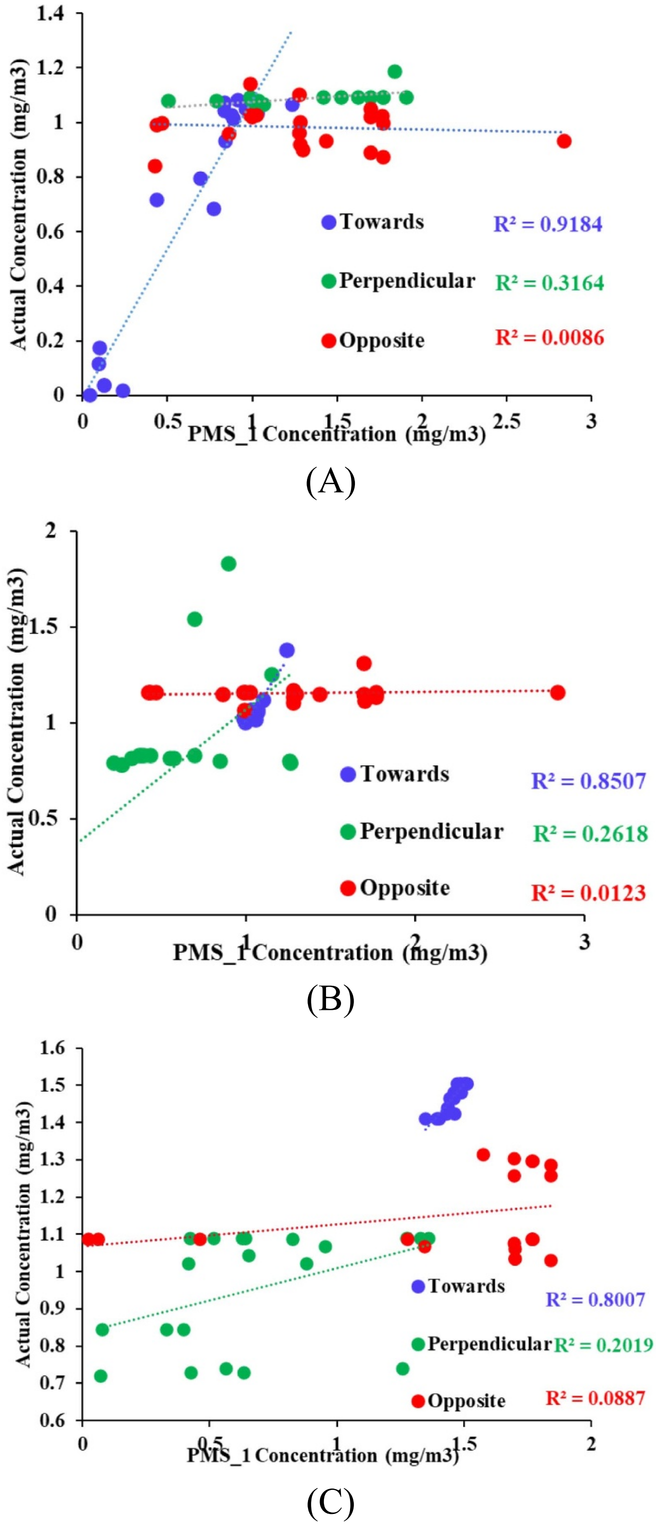


Figure 9. PMS5003 response at concentration 0–1.0 mg m^{-3} (a) velocity 3.0 m s^{-1}, (b) velocity 1.5 m s^{-1}, (c) velocity 0.5 m s^{-1}.

values for towards and perpendicular were 1.06 and 0.83, respectively.

It can be seen in figures 9 and 10 that sensor direction showed a similar impact as the SPS30 sensor on the linearity of PMS sensors. It is shown in figure 9 that at actual coal concentrations between 0 and 1.0 mg m^{-3}, when the sensor inlet direction is towards the stream, the PMS sensor showed very high linearity with an *R*-squared value of 0.91, 0.85 and 0.8 at a wind velocity of 3.0 m s^{-1}, 1.5 m s^{-1} and 0.5 m s^{-1},

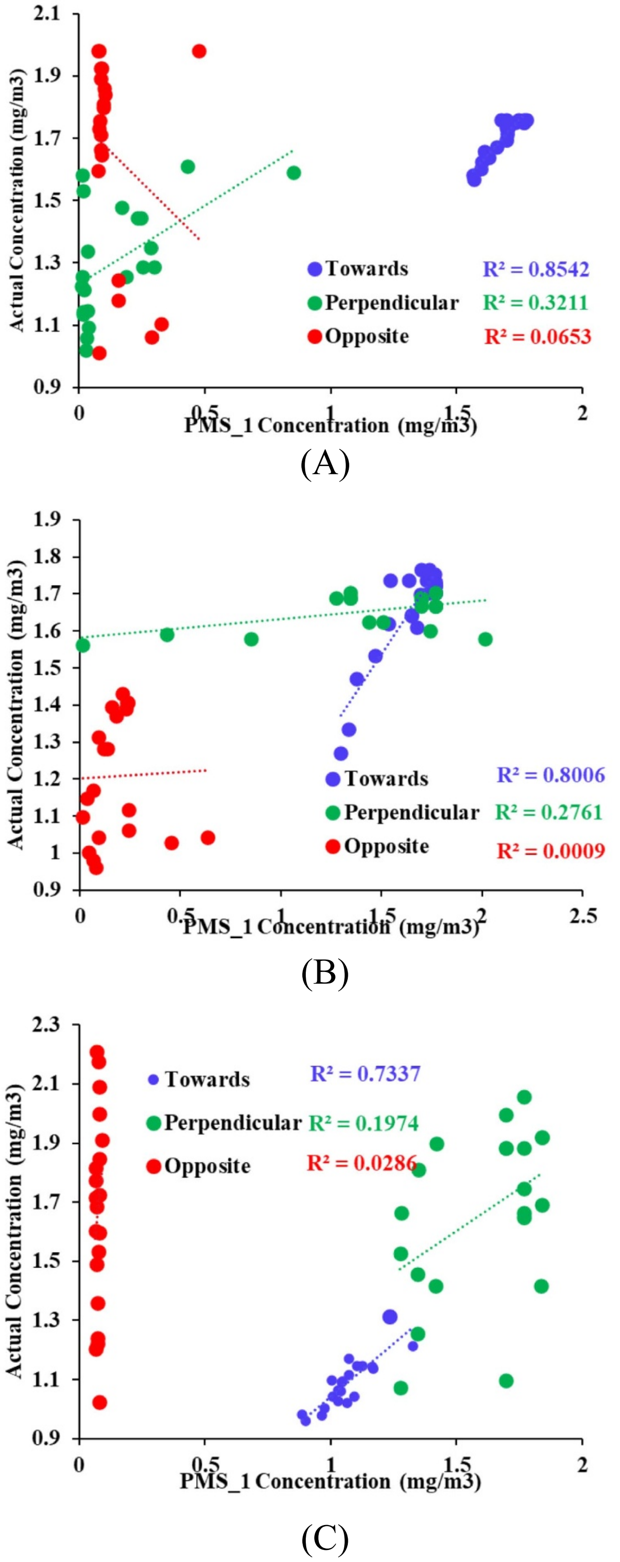


Figure 10. PMS5003 response at concentration 1.0–2.0 mg m^{-3} (a) velocity 3.0 m s^{-1}, (b) velocity 1.5 m s^{-1}, (c) velocity 0.5 m s^{-1}.

respectively. These high correlation values agree with previous studies that also obtained high PMS sensor linearity values (Wang *et al* 2015, Sayahi *et al* 2019a, Amoah *et al* 2023, Zaid *et al* 2023). The Pearson's r also showed a strong linear relationship with an r values of 0.95, 0.92 and 0.89. It is surprising to see in figures 9(a)–(c) that an R-squared value of 0.31, 0.26 and 0.21 is observed when the direction of the sensor is changed to perpendicular to the stream. Similarly, for the sensor direction opposite to the air stream, an R-square value of 0.008, 0.0123 and 0.08 is recorded for a wind velocity of 3.0, 1.5 and 0.5 m s^{-1}. It is displayed in figure 10 that a similar effect of direction is observed for a concentration between 2.0 and 3.0 mg m^{-3}. When the inlet sensor direction is toward the stream, high R-squared values of 0.85 and 0.8 of 0.73 are observed. In the perpendicular direction, R-squared values decreased to 0.32, 0.26 and 0.20 and shallow R-squared values of 0.0653, 0.009 and 0.02 are observed at opposite inlet sensor direction at a wind velocity of 3 m s^{-1}, 1.5 m s^{-1} and 0.5 m s^{-1}. Likewise manifested in figure 11, at higher concentrations (2.0–3.0 mg m^{-3}) PMS sensor revealed a reasonably high R-squared value of 0.74 in (A) and portrayed a meagre R-squared value of 0.29 and 0.38 in figures (b) and (c). When the inlet sensor direction is towards the stream, these low linearity values are due to the coincidence error. A summary for Pearson's r and R-squared for SPS 30 sensor at low concentration and PMS5003 sensors for low, intermediate, and high concentration is give in table 5.

Coincidence error is a common issue that can arise in sensor measurements, particularly when the sensor is exposed to high concentrations of particles. When the concentration of particles in the sensing area is high, the sensor can sometimes interpret multiple particles as a single, more prominent, and heavier particle. This can result in an incorrect interpretation of the mass concentration of particles in the air compared to measurements taken by a reference monitor. The phenomenon of coincidence error occurs when the probability of two or more particles entering the sensor at the same time is high. When this happens, the sensor can only detect a single signal from the group of particles rather than detecting individual particles. This is due to the sensor's limited sampling rate and resolution, which can lead to an inaccurate measurement of particle concentration. Through ANOVA analysis, it was found that a two-way interaction exists between sensor direction and wind velocity ($p = 0.0001$). This result is consistent with that observed for the SPS30 sensor, where different sensor directions were also found to impact the sensor response significantly.

The influence of the sensor's orientation on its response can be clarified in two ways. Firstly, a relatively high R-squared value for the sensor directed towards the airflow indicates that particles are more likely to enter the sensor's inlet, resulting in a more accurate response. In our study, we used an exhaust wind tunnel, which means the air flows in only one direction. At higher velocities, smaller particles, especially those with a size of less than 5 µm, tend to move with the wind only in the direction of the flow. When the sensor's inlet direction is parallel to the airflow, it reduces the likelihood of particles entering through the inlet and reaching the sensing area, leading to lower measured concentration. Conversely, when the sensor direction is perpendicular or opposite to the stream,

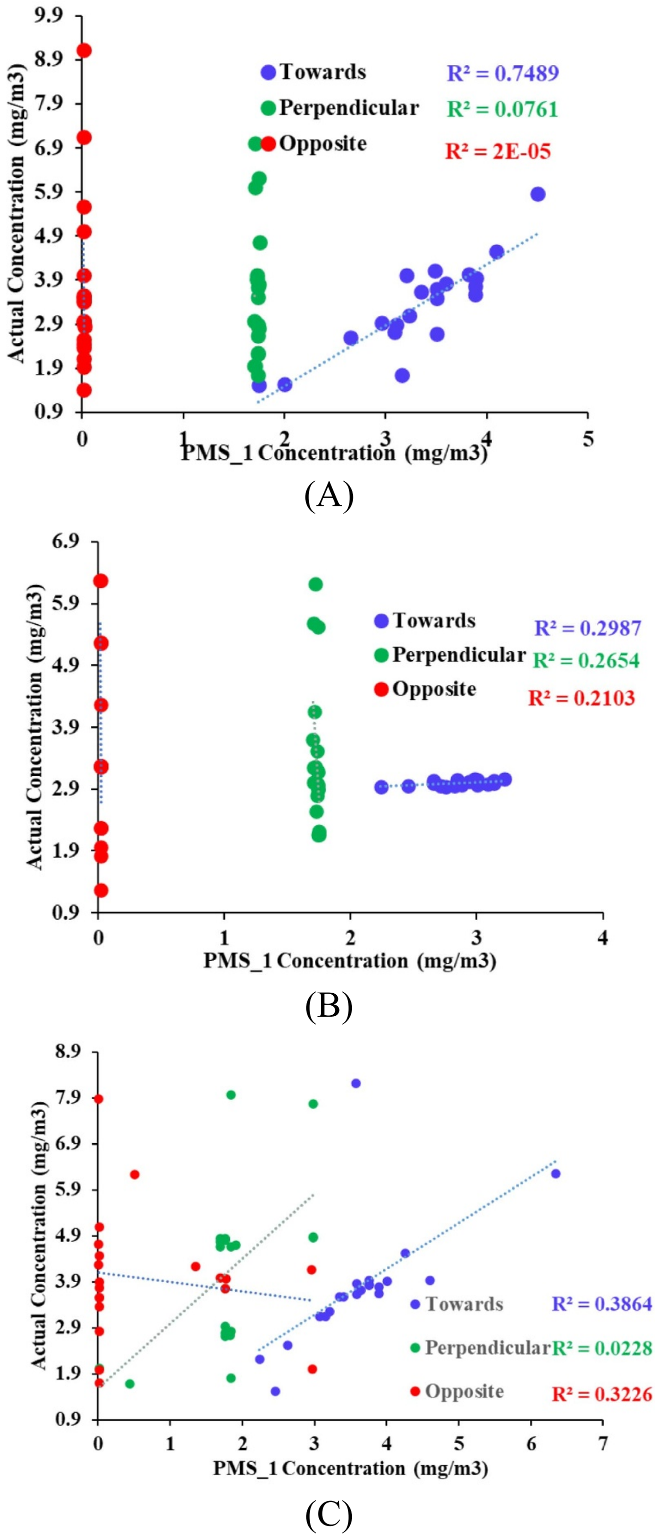


Figure 11. PMS5003 response at concentration 2.0–3.0 mg m^{-3} (a) velocity 3.0 m s^{-1}, (b) velocity 1.5 m s^{-1}, (c) velocity 0.5 m s^{-1}.

coal particles are less likely to enter the inlet, mainly when the sensor direction is opposite to the stream. Furthermore, the low *R*-squared value for the perpendicular and opposite sensor directions suggests that the fan at the sensor inlet is not powerful enough to draw in the same number of particles when facing the stream. This could be a result of the low to poor linearity of the sensor when changing the direction, even when the concentration in the tunnel is within the same range as the sensor direction towards the stream.

3.4. Impact of wind velocity

The impact of wind velocity on the performance of low-cost sensors was investigated and found to be significant.

Test results have shown that the sensors performed better at a higher velocity of 3 m s^{-1}, regardless of dust concentration and sensor direction. For example, for the SPS30 sensor, when the position is toward the airflow (figure 8), the *R*-squared value was 0.7141 at a velocity of 3 m s^{-1}, but this value was only 0.66 and 0.62 when the velocity was 1.5 m s^{-1} and 0.5 m s^{-1}, respectively. This finding also applies to the PMS sensor, as shown in figure 9.

A better correlation at the highest velocities indicates that the fan inlet velocity of the sensor is very near to 3 m s^{-1}. This can be explained by the concept of non-isokinetic sampling, as shown in figure 12 . When the wind tunnel velocity is the same as the fan inlet (3 m s^{-1}), the particles will follow their streamlines and enter the sensor inlet without much deviation. However, in the case of wind tunnel velocity of 1.5 and 0.5 m s^{-1}, the particles will not follow the streamlines and will deviate from their path at the fan inlet, resulting in incorrect sampling entering the sensor and hence lower sensor response. Therefore, the author concluded that wind velocity significantly impacts the performance of low-cost sensors. Furthermore, it should be considered while conducting air pollution monitoring.

3.5. Impact of Arizona road dust

Low-cost PM sensors showed inferior results when challenged with ARD compared to coal dust, as illustrated in figures 13 and 14. It has been observed in much previous research that lights scattering-based sensors behave differently when challenged with different types of particles (Kelly *et al* 2017, Of and Using 2019).

Figure 13 demonstrates the PMS 5003 response when challenged with ARD and coal dust. The PMS5003 sensor responded better to coal dust than ARD, as indicated by the higher *R*-square value of 0.93 for coal dust with the reference monitor compared to 0.6 for ARD. The *r* value for 0.96 and 0.78 was observed for coal dust and ARD. Figure 14 exhibits the SPS30 response for ARD and coal dust. SPS30 sensor Illustrated inadequate response with ARD with an *R*-squared value of 0.0011 and responded somewhat to coal dust as evident from an *R*-squared value of 0.7. Similarly an *r* value of 0.85 shows very high response for coal and an *r* value of 0.03 shows extremely poor response for ARD, this comparison shows that this low-cost sensor responded well when challenged with coal dust and inadequate response when challenged with ARD.The particle size (PM1, PM2.5, PM5 and

Table 5. A summary for Pearson's r and R-squared for SPS 30 sensor at low concentration and PMS5003 sensors for low, intermediate, and high concentration.

Sensor	Monitor	Concentration	Wind velocity	Sensor direction	Pearson's *r*	*R*-squared
SPS30	Reference monitor	Low	High	Towards	0.84	0.7141
				Perpendicular	0.6	0.365
				Opposite	0.42	0.1791
			Intermediate	Towards	0.81	0.6644
				Perpendicular	0.57	0.3317
				Opposite	0.16	0.0287
			Low	Towards	0.79	0.6279
				Perpendicular	0.51	0.2907
				Opposite	−0.02	0.0371
PMS5003	Reference monitor	Low	High	Towards	0.95	0.9184
				Perpendicular	0.56	0.3164
				Opposite	−0.09	0.0086
			Intermediate	Towards	0.92	0.8507
				Perpendicular	0.51	0.2618
				Opposite	0.09	0.0123
			Low	Towards	0.89	0.8007
				Perpendicular	0.45	0.2019
				Opposite	0.29	0.0887
PMS5003	Reference monitor	Intermediate	High	Towards	0.92	0.8542
				Perpendicular	0.56	0.3211
				Opposite	−0.02	0.0653
			Intermediate	Towards	0.89	0.8006
				Perpendicular	0.52	0.2761
				Opposite	0.03	0.0009
			Low	Towards	0.85	0.7337
				Perpendicular	0.44	0.1974
				Opposite	0.23	0.0286
PMS5003	Reference monitor	Intermediate	High	Towards	0.86	0.7489
				Perpendicular	−0.004	0.0761
				Opposite	−0.27	0.00005
			Intermediate	Towards	0.54	0.2987
				Perpendicular	−0.45	0.2654
				Opposite	−0.51	0.2103
			Low	Towards	0.62	0.3684
				Perpendicular	0.43	0.0228
				Opposite	−0.17	0.3226

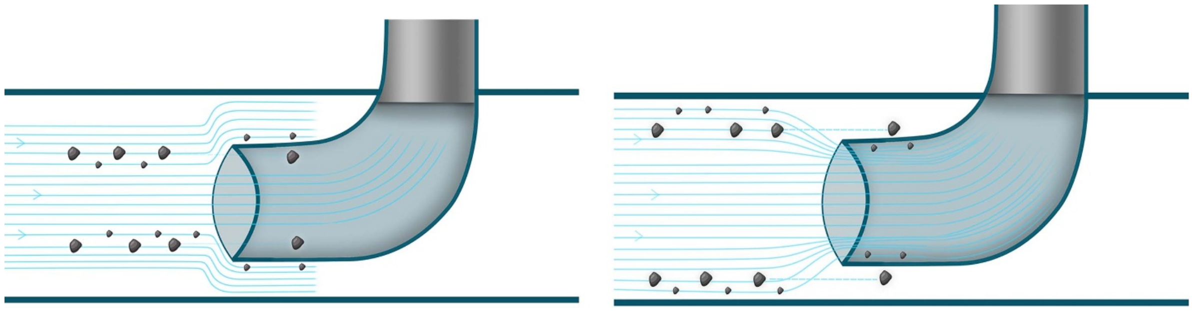


Figure 12. A visual illustration of non-isokinetic sampling.

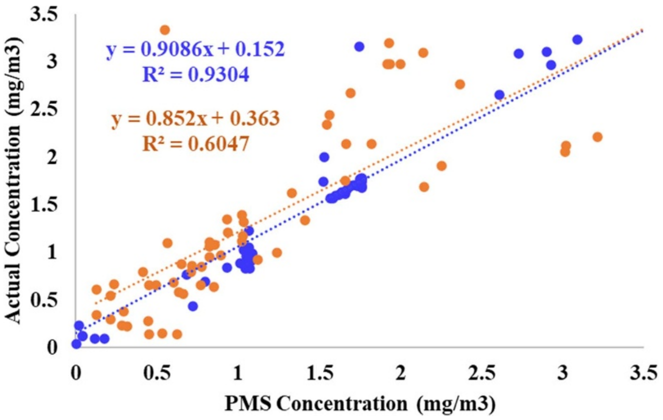


Figure 13. PMS5003 response for (orange) Arizona road dust and (blue) coal dust.

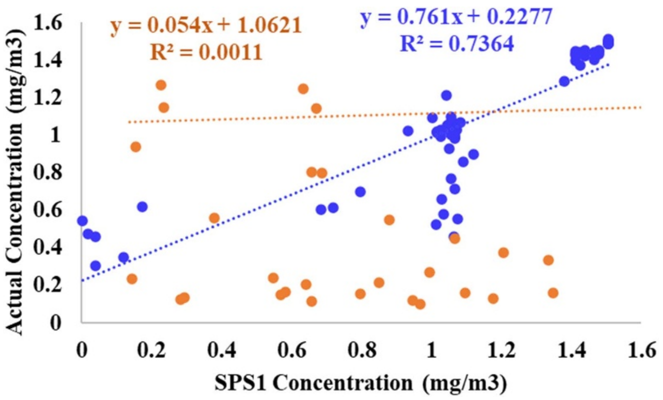


Figure 14. SPS30 response for (orange) Arizona road dust and (blue) coal dust.

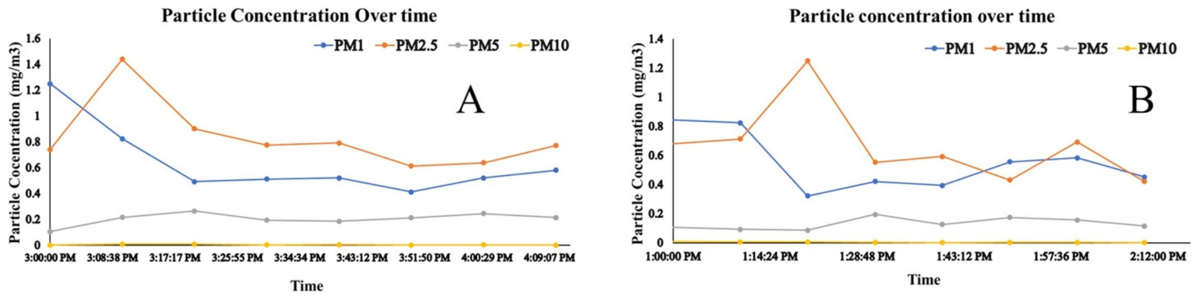


Figure 15. Dynamic particle concentration over time with particle sizes of (a) coal and (b) ARD.

PM10) and their respective concentration is shown for coal and ARD during run of experiments in figures 15(a) and (b). The particle concentration for each size is averaged after every 10 min. This shows that smaller size particles had more concentration over the time as compared to big size particles. Since the PMS5003 sensor is designed to measure particle sizes in this range, it is expected to respond better to coal dust, which has a higher concentration of particles in the target size range. Therefore, the particle size distribution in the two types of dust is a likely explanation for the difference in the performance of the PMS5003 sensor when measuring this dust.

4. Conclusion

Accurate personal monitoring is paramount for detecting overexposures of miners working in underground coal mines and recommending appropriate control measures. Unfortunately, the high cost and size constraints of PDMs restrict their utilization to a limited number of miners, thereby exposing most miners to potential unknown overexposures. In contrast, low-cost PM sensors offer a viable alternative due to their affordability, small size, and portability, enabling real-time personal exposure measurements for all miners. Previous studies have highlighted the potential of low-cost PM sensors as a practical means of monitoring PM levels. Nevertheless, the impact of environmental factors such as wind velocity and sensor direction on the performance of these sensors remains largely unexplored. Therefore, this study aimed to evaluate the performance of low-cost PM sensors in measuring coal dust and assess the influence of wind velocity and sensor direction on their performance. The results were also analyzed to investigate the impact of different types of dust: coal dust and ARD. While these cost-effective sensors may occasionally be affected by relative humidity, our recent study, as conducted by our research group using the same sensor type, has established that the influence of relative humidity is statistically insignificant (Amoah *et al* 2023). Consequently, this paper does not address the impact of relative humidity due to our findings. This study found that the air trek and Gaslab sensors cannot be used for coal dust monitoring as they have shown a very poor correlation with reference monitors. This study showcased that SPS30 has portrayed an encouraging response while measuring the coal dust, but these sensors have limited capability as this sensor can only be utilized in low-concentration environments (0–1.0 mg m^{-3}). SPS30 sensors may experience a sudden jump in concentration beyond the effective range. PMS 5003 sensor exhibited promising result in coal dust monitoring and have displayed that this sensor can be utilized very effectively up to a concentration of 3.0 mg m^{-3}. These sensors may experience coincidence errors at high concentrations over 3.0 mg m^{-3}.

Sensor direction affects the performance of these low-cost PM sensors significantly. This study depicted that when the senor direction was changed from towards to perpendicular to the opposite, a significant drop in R^2 values was noted in SPS30 and PMS5003 sensors. Tukey HSD further evidenced that different sensor direction significantly impacts the sensor response.

The effect of varying wind velocity was also found to be impacting the sensor response. It was observed that these sensors produce better results at high wind velocity, i.e. 3 m s^{-1}, as compared to 1.5 s^{-1} and 0.5 m s^{-1}. Statistical analysis also confirmed that a wind velocity of 3 m s^{-1} had more effect on the sensor response, while wind velocities of 1.5 and 0.5 m s^{-1} had the same effect on the sensor response. These results are consistent for both SPS30 and PMS5003. Further statistical analysis validated that a two-way interaction between sensor direction and velocity influences the sensor response.

The investigation has elucidated that these low-cost sensors demonstrate a better response when challenged with coal dust and manifest an inferior response to ARD. These results are consistent for both SPS30 and PMS5003.

In this study, we have presented experimental results that shed light on the performance of low-cost sensors in coal dust monitoring. The results indicate significant variations among these sensors, which warrant further discussion and considerations for future sensor design and optimization. The observed disparities in sensor performance can be attributed to several factors. First and foremost, it is crucial to acknowledge the inherent limitations of low-cost sensors, which are often designed for specific applications and may not perform optimally in all scenarios. The differences among these sensors can be attributed to variations in sensor design, calibration, and sensitivity. The results of this study underscore the importance of comprehensively assessing low-cost sensor performance and understanding the factors that influence their accuracy. It is evident that sensor direction and wind velocity have significant impacts on sensor response. These findings provide valuable insights for sensor design and optimization in the context of coal dust monitoring and beyond. Future research should delve deeper into the intricacies of these factors and explore strategies to enhance sensor reliability in diverse environmental conditions.

This study has certain limitations that can be summarized as follows. Firstly, the limited number of data points used in each test, conducted over a 20-minute duration, may have restricted the depth and comprehensiveness of the analysis. To ensure a more robust understanding, having a minimum of 60 data points for each test would have been preferable. Secondly, concentration clustering was observed in some tests due to constraints in the dust generation setup. Ideally, a more even distribution of concentration data points within the range would have provided a more representative sensor performance assessment across different concentration levels. These limitations should be considered when interpreting the study's results and conclusions. Future research endeavors could address these limitations by increasing the data points and enhancing the dust generation setup to achieve a broader and more diverse concentration range.

Data availability statements

All data that support the findings of this study are included within the article (and any supplementary files).

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Authors' contributions

Dr Guang Xu:
Dr Guang Xu provided funding, generated idea, supervised and verified the findings.
Mirza Muhammad Zaid:
Mirza Muhammad Zaid fabricated the setup for experimental work, performed all the requisite experiments, analyzed the results, written and edited the manuscript.

Nana Amoah:
Nana Amoah contributed to the experimental work and helped the interpretation of the results.
Dr Ashish Kakoria:
Dr Ashish Kakoria contributed to the analysis of the results and the writing of the manuscript.
Dr Yang Wang:
Dr Yang wang provided requisite apparatus from his lab for the experimental work, contributed to the design of the experiments and the analysis of the results.

Conflict of interest

There is no competing interest to be disclosed.

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References

Alfano B, Barretta L, Del Giudice A, De Vito S, Francia G D, Esposito E, Formisano F, Massera E, Miglietta M L and Polichetti T 2020 A review of low-cost particulate matter sensors from the developers' perspectives *Sensors* **20** 1–56
Alphasense 2017 CO-B4 carbon monoxide sensor technical specification 44 p 1 (available at: www.alphasense.com/wp-content/uploads/2019/09/CO-B4.pdf)
Amoah N A, Guang X, Kumar A and Wang Y 2023 Calibration of low-cost particulate matter sensors for coal dust monitoring *Sci. Total Environ.* **859** 160336
Belle B 2017 Pairwise evaluation of PDM3700 and traditional gravimetric sampler for personal dust exposure assessment *Mine Ventilation Conf.* (*Brisbane*) pp 28–30
Berglund L G and Fobelets A P R 1987 Subjective human response to low-level air currents and asymmetric radiation *ASHRAE Trans.* **93** 497–523
Blackley D J *et al* 2022 Progressive massive fibrosis in coal miners from 3 clinics in Virginia pp 2017–8
Blackley D J, Halldin C N and Scott Laney A 2018 Continued increase in prevalence of coal workers' pneumoconiosis in the United States, 1970–2017 *Am. J. Public Health* **108** 2017–9
Bulot F M J, Johnston S J, Basford P J, Easton N H C, Apetroaie-Cristea M, Foster G L, Morris A K R, Cox S J and Loxham M 2019 Long-term field comparison of multiple low-cost particulate matter sensors in an outdoor urban environment *Sci. Rep.* **9** 1–13
Christensen N K, Albrechtsen O, Fanger P O and Trzeciakiewicz A 1984 Air movement and draught *Indoor Air. Proc. 3rd Int. Conf. on Indoor Air Quality and Climate* vol 5 pp 301–8
Chung A, Chang D P Y, Kleeman M J, Perry K D, Cahill T A, Dutcher D, McDougall E M and Stroud K 2001 Comparison of real-time instruments used to monitor airborne particulate matter *J. Air Waste Manage. Assoc.* **51** 109–20
DFRobot 2013 Air quality sesnor SEN0177 p 6
Dos S, Antao V C, Petsonk E L, Sokolow L Z, Wolfe A L, Pinheiro G A, Hale J M and Attfield M D 2005 Rapidly progressive coal workers' pneumoconiosis in the United States: geographic clustering and other factors *Occup. Environ. Med.* **62** 670–4
Dylos corporation 2017 Dylos air quality monitors DC1700 p 21 (available at: https://lib.store.turbify.net/lib/yhst-16473542037836/DylosLoggerUsersGuidev30.pdf)
Fanger P O 1977 Discomfort due to air velocities in spaces *Proc. of Meeting of Commission B1, B2, E1, of Instit. Refrig* vol 4
Fobelets A P R 1987 Subjective human response to low-level air currents and asymmetric radiation *ASHRAE Trans.* **93** 497–523
GasLab 2022 Handheld multi gas detector operating instructions pp 2–3
Ghamari M, Soltanpur C, Rangel P, Groves W A and Kecojevic V 2022 Laboratory and field evaluation of three low-cost particulate matter sensors *IET Wirel. Sens. Syst.* **12** 21–32
Ishtiaq M, Jehan N, Khan S A, Muhammad S, Saddique U, Iftikhar B and Zahidullah 2018 Potential harmful elements in coal dust and human health risk assessment near the mining areas in Cherat, Pakistan *Environ. Sci. Pollut. Res.* **25** 14666–73
Kelly K E, Whitaker J, Petty A, Widmer C, Dybwad A, Sleeth D, Martin R and Butterfield A 2017 Ambient and laboratory evaluation of a low-cost particulate matter sensor *Environ. Pollut.* **221** 491–500
Liu X *et al* 2020 Low-cost sensors as an alternative for long-term air quality monitoring *Environ. Res.* **185** 109438
LLC, AerosolWorks 2023 AerosolWorks LLC (available at: https://aerosolworks.com/) (Accessed 3 July 2023)
Mahdavipour O *et al* 2015 Wireless sensors for automated control of total incombustible content (TIC) of dust deposited in underground coal mines *2015 IEEE Sensors—Proc.* pp 3–6
Mcpherson M J, Eng C, Aime M and Ashrae M 2009 *Subsurface Ventilation and Environmental Engineering* (Springer)
Nevins R G 1971 Thermal comfort and drafts *J. Physiol.* **63** 356–8
Northcross A L, Edwards R J, Johnson M A, Wang Z M, Zhu K, Allen T and Smith K R 2013 A low-cost particle counter as a realtime fine-particle mass monitor *Environ. Sci. Process. Impacts* **15** 433–9
Of, Valuation, and Orrection Using 2019 L e l—p a Pm m i—c c—p f S pp 1–34
Peters T M and Leith D 2003 Concentration measurement and counting efficiency of the aerodynamic particle sizer 3321 *J. Aerosol Sci.* **34** 627–34
Potera C 2019 Black lung disease resurges in appalachian coal miners *Am. J. Nurs.* **119** 14
Roghanchi P, Kocsis K C and Sunkpal M 2016 Sensitivity analysis of the effect of airflow velocity on the thermal comfort in underground mines *J. Sustain. Min.* **15** 175–80
Sayahi T, Kaufman D, Becnel T, Kaur K, Butterfield A E, Collingwood S, Zhang Y, Gaillardon P-E and Kelly K E 2019a Development of a calibration chamber to evaluate the performance of low-cost particulate matter sensors *Environ. Pollut.* **255** 113131
Sensiron 2018 Datasheet SPS30 particulate matter sensor for air quality monitoring and control pp 1–20 (available at: www.sensirion.com)
Sensiron 2018 SPS30 (available at: https://sensirion.com/products/catalog/SPS30/) (Accessed 3 July 2023)
Sharp 2013 Application note of sharp dust sensor GP2Y1010AU0F p 6 (available at: www.sharp-world.com/products/device-china/lineup/data/pdf/datasheet/gp2y1010au_appl_e.pdf)
Shniyei 2023 Particle sensor unit PPD42NK (available at: www.shinyei.co.jp/stc/eng/products/optical/ppd42nj.html)
Thermo Scientific 2014 *Model PDM3700*
Toftum J 2002 Human response to combined indoor environment exposures *Energy Build.* **34** 601–6
TSI incorporated 2022 Aerodynamic particle sizer model 3321
van den Bossche M, Rose N T and De Wekker S F J 2017 Potential of a low-cost gas sensor for atmospheric methane monitoring *Sens. Actuators* B **238** 501–9

Volkwein J C, Vinson R P, Page S J, McWilliams L J, Joy G J, Mischler S E and Tuchman D P 2006 Laboratory and field performance of a continuously measuring personal respirable dust monitor

Wang Y, Li J, Jing H, Zhang Q, Jiang J and Biswas P 2015 Laboratory evaluation and calibration of three low-cost particle sensors for particulate matter measurement *Aerosol Sci. Technol.* **49** 1063–77

Wang Z *et al* 2016 Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building *J. Air Waste Manage. Assoc.* **66** 1109–20

Yong Z and Haoxin Z 2023 *PMS5003 Particulate Matter Sensor with Cable*

Zaid M M, Guang X and Amoah N A 2023 Accuracy of low-cost particulate matter sensor in measuring coal mine dust-a wind tunnel evaluation *Underground Ventilation* (CRC Press) pp 274–84

Zhang H, Nie W, Liang Y, Chen J and Peng H 2021a Development and performance detection of higher precision optical sensor for coal dust concentration measurement based on MIE scattering theory *Opt. Lasers Eng.* **144** 106642

Zhang R, Guohui L, Fan J, Wu D L and Molina M J 2007 Intensification of Pacific storm track linked to Asian pollution *Proc. Natl Acad. Sci.* **104** 5295–9

Zhou G 1999 Human perception of air movement: impact of frequency and airflow direction on sensation of draught

Zhou Y and Zheng H 2016 Digital universal particle concentration sensor PMS1003. Data sheet c:15 (available at: www.aqmd.gov/docs/default-source/aq-spec/resources-page/plantower-pms5003-manual_v2-3.pdf)

Zikova N, Masiol M, Chalupa D, Rich D, Ferro A and Hopke P 2017 Estimating hourly concentrations of PM2.5 across a metropolitan area using low-cost particle monitors *Sensors* **17** 1–19