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Performance Evaluation of Particulate Matter Low-Cost Sensors under Power Supply Variations

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***Abstract*—The deployment of mobile stations is a growing trend in air quality monitoring due to their ability to increase data spatial resolution. In this context, the use of low-cost platforms is a solution often considered for data collection and sensor powering. Among these platforms, power management can be quite different, but in any case it is worth noting that a low quality supply voltage can lead to sensor data degradation. This paper examines the behavior of low-cost particulate matter sensors under varying power supply voltage conditions. Laboratory tests were carried out under controlled conditions to assess the response of various sensors to changes in voltage. The results reveal a manufacturer-dependent variation in sensor performance that affects the accuracy of air quality monitoring.**

***Index Terms*—Air quality monitoring, low-cost sensors, laboratory characterization, power supply fluctuations**

I. INTRODUCTION

Among low-cost monitoring systems, particulate matter (PM) sensors based on the laser scattering principle have allowed increasing the spatial and temporal resolution of specific measurement applications for air quality monitoring [1]. In fact, due to the low cost and the presence of several manufacturers, measurement platforms can be installed at different points of interest to increase the spatial resolution of the monitoring application. In addition, due to the low power consumption and small size, the sensor installation process is simple and unobtrusive compared to traditional monitoring stations. The high temporal resolution allows for the capture of rapid changes in pollutant levels, increasing awareness of air quality at a given time [2].

The emergence of these sensors has been accompanied by the development of platforms for collecting, processing, and transmitting data at low cost, taking advantage of the concept of the Internet of Things. Systems based on single-board computers (SBCs), such as Raspberry Pi, Beaglebone, and Arduino, enable the management of multiple sensors, optimizing space and power consumption and making it possible to create a cost-effective monitoring platform [2], [3].

Several projects have taken advantage of the possibility of using low-cost platforms for air quality assessment, often considering also other quantities that can influence low-cost PM sensors, such as relative air humidity [4]. Other projects have developed specific platforms with the intention of increasing the efficiency of the power supply to reduce power consumption [5] and increase the duration of batteries. In fact, low-cost monitoring systems can be installed in locations without a power supply available from the grid and can be powered by a photovoltaic panel and batteries, in an off-grid system.

Reducing power consumption is indeed an important aspect; even if the single monitoring platform has low power consumption, in the context of increasing spatial resolution, a large number of monitoring stations has a higher impact to be considered appropriately [5].

Recently, PM monitoring platforms have implemented two equal sensors on the same platform, see for instance [6], to increase data reliability by allowing bad data identification and acquisition system backup in case one sensor fails. However, a deeper redundancy should consider different power supplies for each sensor; moreover, bad data in the presence of power supply issues would propagate to both sensors, not allowing the identification of a reference for comparison.

In addition to the normal variations expected in the amplitude and frequency of the voltage, power systems can be affected by power quality issues such as harmonics, interharmonics, and voltage fluctuations [7], [8]. In island systems, powered by a system consisting, in general, of a photovoltaic panel, battery, and voltage regulator, voltage fluctuations can be high and, if not carefully monitored, can lead to sensors working outside of the specification, affecting PM measurements [9]. For example, in [10], a power supply issue was the cause of abnormal values of PM measurements in the collected data. In [9], a battery lack of capacity caused issues in the data provided by the PM sensor. Very high PM values can be measured in real cases and cannot be considered as bad data without evaluating the context in which the sensors operated. For example, in [11], due to fireworks, the $PM_{2.5}$ measured had extremely high values like those obtained under power supply issues.

Several factors affecting PM measurements, such as humidity and temperature, are well documented in the literature, but in-depth studies on the impact of power supply on the behavior of low-cost PM sensors are yet to be done. Not monitoring the power supply exposes to the risk of unwittingly using

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degraded measurements that can lead to incorrect evaluation of air quality indices. Conversely, proper monitoring could allow discarding any bad data or implementing ad-hoc compensation processes, and would represent a cost-effective and easy-to-implement procedure in low-cost SBC platforms.

In this context, this paper investigates the metrological behavior of three low-cost PM sensors when exposed to changes in power supply voltage and the effect that such changes have on the quality of the data produced by the measurement process. In particular, taking into account possible issues on power supply reported in the scientific literature, the basic idea is to correlate the variable conditions of the power supply with the outputs of three of the most common low-cost PM sensors in a controlled laboratory environment. An analysis focused on identifying distinct behaviors in the considered sensors is provided, aimed at investigating the varied impact of supply voltage fluctuations on PM measurements.

II. SYSTEM COMPONENTS FOR LOW-COST PM SENSOR ANALYSIS

The experimental evaluation of the behavior of three models of low-cost PM sensors affected by power supply voltage disturbances was conducted in the Instrumentation and Measurement laboratory of the University of Cagliari, in Italy. Different tests were carried out under similar humidity and temperature conditions, minimizing the variability associated with these factors and thus focusing on the effects of power supply voltage variations in the $PM_{2.5}$ and PM_{10} sensor output data. Since sensor accuracy is a function of its estimated PM concentration, the effects induced by abnormal behaviors of the power supply voltage were investigated over a wide range of PM concentrations.

The three considered low-cost PM sensor models are Honeywell HPMA115S0-XXX [12], Plantower PMS5003 [13] and Nova Fitness SDS011 [14] (from now on S1, S2 and S3, respectively), coming from three different manufacturers; their specifications are discussed in Section II-A. In Section II-B, the TSI DustTrak II Aerosol Monitor [15] station, employed as reference device, is also presented.

A. Low-Cost PM sensors

Table I summarizes the specifications of interest of the three low-cost PM sensor models under investigation. Each of them bases its operation on the light scattering principle, in which the effects of the interaction between light and PM particles are leveraged. A laser installed in the device package produces a light signal, and a photodiode is in charge of translating the information associated with its received light intensity into an electrical signal. A fan makes the PM particles flow inside the measuring cavity, where they trigger a light scattering phenomenon which influences the amount of light radiation incident on the photodiode. This mechanism causes the captured light intensity to be inversely proportional to the PM concentration within the chamber, and PM concentration in the surrounding air is estimated by proprietary algorithms running in the microcontroller unit.

TABLE I
LOW-COST PM SENSOR SPECIFICATIONS

Parameter	Sensor		
	S1	**S2**	**S3**
PM Resolution [μg/m³]	1	1	0.3
PM Concentration Range [μg/m³]	0 to 1000	0 to 1000	0 to 999
PM Accuracy Range I [μg/m³] Range II [%]	 ±15@[0-100] ±15	 ±10@[0-100] ±10	 ±10@[0-67] ±15
Supply Voltage [V]	5 ± 0.2	5 ± 0.5	5 ± 0.3
Supply Current [mA]	< 80	≤ 100	90 ± 10

The three considered sensor models estimate both $PM_{2.5}$ and PM_{10} concentrations, and they are characterized by wide input ranges up to $1000\,\mu g/m^3$. Sensor measurement performances are provided in terms of accuracy of PM concentration measurements, and are separately specified for two different ranges (reported as Range I and Range II in Table I).

Given the aim of this work, it is essential to pay special attention to the variation range of the supply voltage, outside of which deviations of the sensor from the normal behavior can be expected. In these terms, S1 sensor is the most restrictive, since it allows a maximum excursion of $0.2\,V$ from the $5\,V$ nominal value. S3 admits a variability of $0.3\,V$, while input voltage of the S2 sensor can vary $\pm 10\,\%$ around the nominal value.

A suitable choice must be made for the device in charge of powering the sensors, as it must be able to provide an adequate power to allow the devices to work properly. This can be done by the evaluation of the current absorbed by sensors when they operate in nominal conditions: product specifications report similar upper limits in the devices under examination, with values ranging from a minimum current of $80\,mA$ absorbed by S1 to a maximum current of $100\,mA$ absorbed by S2.

B. Reference Station

Reference station plays a central role, since it can provide accurate PM concentration estimates in the air environment where low-cost sensors operate. The DustTrak™ II Aerosol Monitor 8530 made by TSI Incorporated is the selected reference instrument [15].

DustTrak DRX II is an aerosol monitor suite based on the 90° light scattering technology which measures concentration of particle size between 0.1 and $10\,\mu m$. The selected DustTrak model can measure PM concentration in the $0.001 - 400\,mg/m^3$ interval, achieving a $1\,\mu g/m^3$ resolution when values below 1 mg/m^3 are read. No accuracy information is explicitly reported in the specification document, but manufacturer categorizes the device as a "near-reference" instrument, capable of providing data of sufficient accuracy to complement existing air pollution monitors and networks

[16]. Furthermore, several literature papers use this device as reference station to characterize low-cost PM sensors. In [17], a DustTrak DRX desktop monitor was used to calibrate a low-cost air quality station including a Nova Fitness SDS011 sensor for $PM_{2.5}$ and PM_{10} measurements. A calibration chamber capable of providing uniform concentrations to multiple PM sensors was developed in [18]: DustTrak 8350 desktop model was used to evaluate the performance of Plantower PMS 3003 sensors in the presence of $PM_{2.5}$ pollutant provided by the chamber. In [19], linearity of several PM sensors was evaluated against a DustTrak DRX II device, considering $PM_{2.5}$ measurements.

DustTrak measurements can thus be considered as the reference values of PM concentration in low-cost sensor performance evaluation.

C. Data Acquisition Platform

The myRIO-1900 platform (from now on myRIO) made by National Instruments (NI) [20] is the base element of the data acquisition system used during the tests. It is a compact embedded hardware that includes a real-time processor, a field-programmable gate array (FPGA), analog and digital I/O, and wireless communication. The Xilinx Zynq-7010 FPGA and dual-core ARM Cortex-A9 processor are the core components of the myRIO platform.

MyRIO is usually powered by an external power adapter. This power supply usually works in a range of 6 to 16 V, giving flexibility in laboratory and field settings. The on-board power management system ensures that the processor, FPGA, and I/O lines are stable by regulating voltages. This management also includes overcurrent protection, which ensures platform safety during experimentation.

D. Test Setup

Figure 1 shows the laboratory test setup developed to characterize the low-cost PM sensors. For each model, a pair of sensors is employed, each of which is connected to a different myRIO device. The purpose of this approach, projected onto a real-world application context, is to always have a low-cost term of comparison available for measurements in case one of the two sensors fails. Previous works have adopted this approach, aimed at increasing redundancy in monitoring stations based on low-cost sensors [2], [21]. In this experimental analysis, problems are artificially induced on one of the two sensors in the form of supply voltage variations.

The schematic shows how "A" sensor of each pair is powered through the myRIO 5 V output, while "B" sensor power supply is provided by an external device, the Digilent Analog Discovery 2 [22]. The programmable power generation functionality of this device is exploited to feed B sensors with different voltage waveforms chosen to simulate problems in the power supply. Analog Discovery 2 is capable of providing a 700 mA output current, sufficient for the three sensors, which require, in normal operation, a total current of about 270 mA when connected in parallel (see the specifications in Table I).

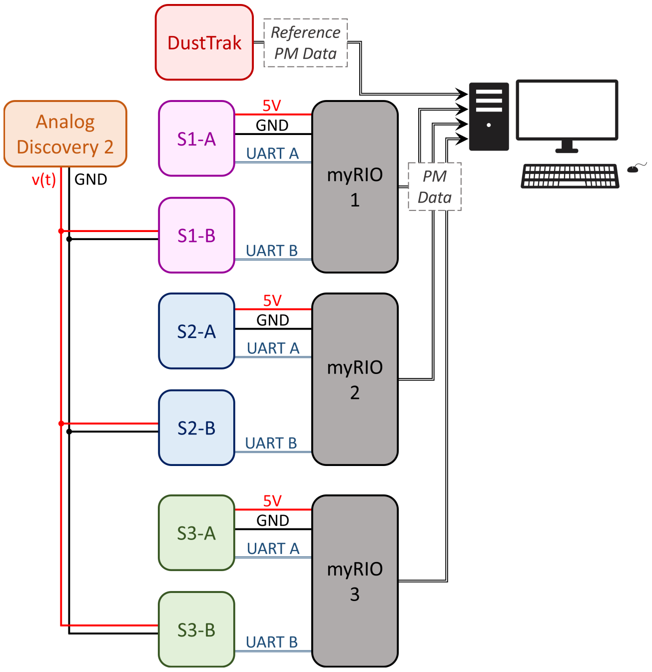

Fig. 1. Test architecture.

Sensors under test send their output data via UART protocol, exploiting the dual communication interface of myRIOs. These collect data by means of a software developed in LabVIEW, and send them to a central computer unit, where they are cleaned up in post-processing and then analyzed.

Test architecture also includes the TSI DustTrak DRX II monitoring station, used as reference, which stores measurements into its internal memory, only readable when the device is not in test mode. The reference station and low-cost sensors were placed in a flat area, within an overall volume lower than $1\,m^3$, thus ensuring the similar pollutant concentration entering the measuring chambers of all devices.

Measurements are reported by all instruments with a rate of 1 Hz, and tests were conducted under constant monitored temperature and relative humidity of 23 °C and 50 %, respectively.

III. TEST RESULTS

In the following, a preliminary study on the capability of the most common SBCs to provide a stable power supply to the sensors during variations in the DC power input is firstly reported. This analysis aims at demonstrating that, depending on the specific SBC used to feed PM sensors (as often done in practical applications), the guaranteed input voltage strongly depends in turn on the board supply.

Then, performances of low-cost PM sensors during power supply voltage fluctuations are analyzed using the setup of Section II-D. A first test was conducted to assess sensor behavior in nominal voltage supply conditions (Steady State Test), then three different types of voltage supply variations were applied: a ramp of 2 hours in the $5 - 2\,V$ range (Ramp Test), a 30-min period sawtooth waveform and a 60-min period

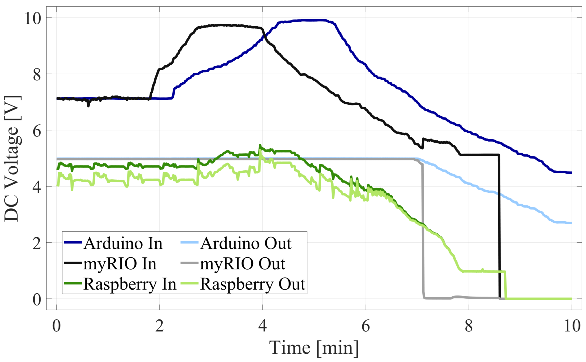

Fig. 2. Different behavior of voltage supply output (light color) in SBCs when fluctuations affect DC voltage input (dark color).

sinusoidal waveform (these last two tests are referred to as Voltage Fluctuations Tests).

A. *Power Supply Evaluation*

In what follows, the output voltage stability of the power supply pins of some common SBCs is analyzed. Three platforms commonly used to interface with low-cost PM sensors are considered [23], [24]: Arduino Uno R3, Raspberry Pi 3B+, and NI myRIO. Power supply management may actually vary among different devices, depending on their characteristics and cost, therefore it was decided to investigate different SBC platforms. An adjustable $0 - 15\,\mathrm{V}$ direct current (DC) bench power supply, with a dispatchable current up to $2\,\mathrm{A}$, is used for the SBCs.

In particular, the test is carried out by varying the DC input power supply inside and outside the range of the nominal voltages suggested by the sensors manufacturers, and the stability of the $5\,\mathrm{V}$ output is assessed.

The results are reported in Fig. 2, where the input and output voltages from three platforms are shown. The Raspberry PI platform, the only one with a nominal voltage input of $5\,\mathrm{V}$ (Raspberry In), can provide a $5\,\mathrm{V}$ output (Raspberry Out) for generic peripherals. This device exhibits a decrease in the voltage output when the voltage input drops below the nominal value, and is characterized by noisy input and output power supply voltages in comparison to the other devices. The Arduino platform can be powered with a voltage input in the range of $7 - 12\,\mathrm{V}$ (Arduino In) and the $5\,\mathrm{V}$ outputs (Arduino Out), dedicated to supplying the sensors, appear stable during the voltage variation inside the nominal range; however, if the voltage input goes below the nominal voltage, it is possible to observe a different behavior in the $5\,\mathrm{V}$ output, which follows the same trend of the input voltage. In this particular condition, the platform continues to operate, powering the sensor with a voltage below the $5\,\mathrm{V}$ nominal level. The myRIO platform can be powered with a voltage of 6 to $16\,\mathrm{V}$ (myRIO In) and the $5\,\mathrm{V}$ output (myRIO Out) provided by the board appears stable during the whole voltage input variation, whereas the device stops providing the voltage output when the input is below $5.5\,\mathrm{V}$, causing the sensor to switch off.

TABLE II
STEADY-STATE TEST RMSE RESULTS

RMSE [μg/m^3]			
Devices	**Sensor**		
	S1	**S2**	**S3**
A vs Reference	61.8	8.8	71.9
B vs Reference	59.0	6.5	74.1
A vs B	3.2	6.7	2.4

In this scenario, Raspberry Pi and Arduino platforms experience voltage output drops during decrements in the input DC voltage values. On the contrary, the NI myRIO board reacts to voltage input drops by stopping the supply of the $5\,\mathrm{V}$ voltage output, keeping otherwise excellent stability. However, it is essential to recall that the cost of myRIO is around ten times higher than that of the other platforms.

B. *Steady-State Test*

The aim of this test was to assess the performance of the sensors under nominal power supply conditions and to determine any discrepancy between sensors from the same manufacturer. Before the test, the air was polluted with the use of an incense stick (often used as a source of pollution [23]), and then data were collected for 10 hours, during the natural extinguishment of the pollutant. Both the low-cost sensors and the reference station recorded $\mathrm{PM}_{2.5}$ and PM_{10} measurements, but for the sake of brevity only $\mathrm{PM}_{2.5}$ data are reported, since similar considerations can be obtained for the PM_{10}.

Results in terms of root mean square error (RMSE), computed according to

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{\rho}_i^X - \hat{\rho}_i^Y)^2}, \tag{1}$$

are shown in Table II. In (1), N is the number of considered measurements, $\hat{\rho}_i^X$ and $\hat{\rho}_i^Y$ are the ith PM values measured by generic devices X and Y, respectively, expressed in $\mu\mathrm{g/m}^3$. RMSE values are reported for each sensor with respect to the reference station (A vs Reference and B vs Reference), and with respect to its counterpart of the same model (A vs B). It is possible to observe a low level of error, with respect to the reference station, for S2 sensors. S1 and S3 sensors, both A and B, underestimate the PM concentration, and this results in higher levels of RMSE. The differences among all the A and B sensors are low, which means that similar behaviors characterize the sensors from the same vendor. It is important to recall that the low-cost sensors are not calibrated, and the mismatch with the reference station should be compensated before the installation process.

For each sensor, to prevent the variation of PM concentration with time from influencing significantly the analysis, 1-minute portions of data were considered, and the standard

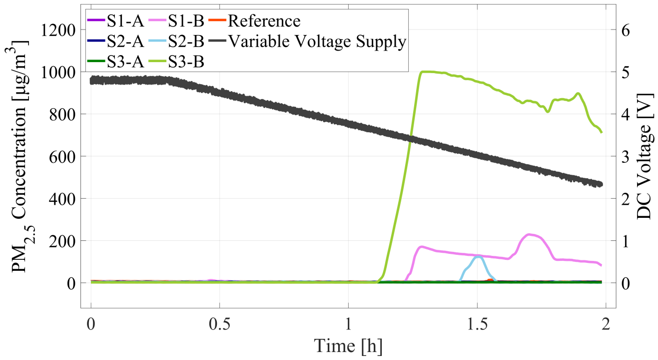

Fig. 3. $\mathrm{PM}_{2.5}$ concentration trends during the ramp test.

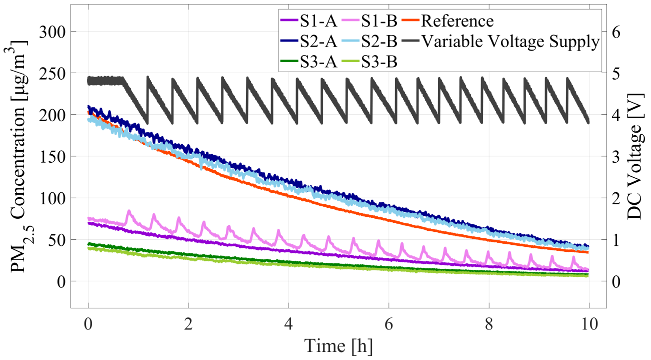

Fig. 4. $\mathrm{PM}_{2.5}$ concentration time trends during sawtooth fluctuation test.

deviations of the measured values in each portion were estimated. Their average is less than $1.1\ \mu g/m^3$ for S1 and S3, and less than $2.7\ \mu g/m^3$ for S2, i.e., lower than all RMSE values in Table II.

C. Ramp Test

The second test considers a significant degradation of the voltage supply in input to the three B low-cost sensors. In particular, to simulate an issue in the power supply voltage provided to the sensor, a slowly decreasing voltage ramp from the nominal voltage down to 2 V is generated by the Analog Discovery 2. The test is conducted in normal laboratory conditions, without external pollutants, with reference values of $\mathrm{PM}_{2.5}$ within the $10 - 30\ \mu g/m^3$ interval.

Fig. 3 shows the trend of the $\mathrm{PM}_{2.5}$ concentration measurements over around 2.5 hours correlated with the supplied voltage. The test starts from the nominal voltage (a slight load effect appears from the acquired voltage), and after 15 minutes, the voltage starts to decrease slowly. From the 3.5 V level, it is possible to observe for all the sensors an increment of the evaluated concentration of PM; in particular, the behavior of sensor S3-B is similar to the results described in [9] and [10] where, due to generic power supply issues, sensor measurements reached high values of concentration (up to $1000\ \mu g/m^3$). The same behavior but with limited concentration values is obtained from sensors S1-B (over $200\ \mu g/m^3$) and S2-B (over $100\ \mu g/m^3$).

It is important to highlight that the overestimation of $\mathrm{PM}_{2.5}$ concentration starts when the input voltage is close to 3.5 V, far from the nominal value of the datasheet. In this scenario, an appropriate monitoring of the voltage supplying the sensor can help to evaluate the state of the PM monitoring process and increase the trustworthiness of the PM data output.

D. Voltage Fluctuations Tests

Last tests are aimed to evaluate if the sensors deviation from normal behavior can also be detected for voltage fluctuations limited with respect to the nominal voltage level. Fig. 4 shows a series of voltage ramps over 10 hours with a voltage variation from 5 V to 4 V. $\mathrm{PM}_{2.5}$ values start from $200\ \mu g/m^3$, then slowly decrease to concentrations close to $40\ \mu g/m^3$ (red line in Fig. 4). It is possible to observe the behavior of S1-B: the PM concentration starts to be overestimated when the voltage supply value exits from the nominal variation band, and it restarts to follow the expected behavior when the voltage comes back inside. A different behavior, but less evident, for sensor S3-B shows a slight underestimation under voltage variation. Also sensor S2-B appears influenced, and it is possible to observe a trend related to the variable voltage during the higher PM concentration levels.

In a subsequent test, a sinusoidal variation in the power supply voltage is introduced, keeping the same range as before, from 5 to 4 V (see Fig. 5). This test confirmed that the sensors response to limited voltage fluctuations (up to 80 % of nominal voltage) is different from that found in nominal voltage conditions. From Fig. 5, it can be seen that the sensors most affected by voltage fluctuations, S1-B and S3-B, behave in an opposite way, as the former overestimates while the latter underestimates the PM concentration. The analysis of different sensors permits detecting a variety of behaviors, as it shows type-based effects on PM measurements.

Furthermore, these two tests resulted in PM measurements trends having the same timing of voltage fluctuations, confirming the causal relationship between the two processes.

Table III shows the PM concentration RMSE results, where it is possible to observe a slight difference, in the comparison with the reference, between sensors of the same manufacturer. This aspect appears clearer when considering RMSE of homologous A and B sensors, where values are higher compared to the Steady-State Test results reported in Table II. The growth of RMSE between sensors of the same model exceeds, in the case of S1 and S3, the intrinsic variability of PM values reported in Section III-B.

These findings are consistent for both $\mathrm{PM}_{2.5}$ and PM_{10} measurements, highlighting the sensors sensitivity to significant and minor voltage variations. Consequently, real-time monitoring of the power supply voltage could be important for assessing the accuracy of PM measurements and identifying bad data.

IV. CONCLUSIONS

The evaluation of PM measurements based on low-cost sensors offers enhanced spatial and temporal resolution in air

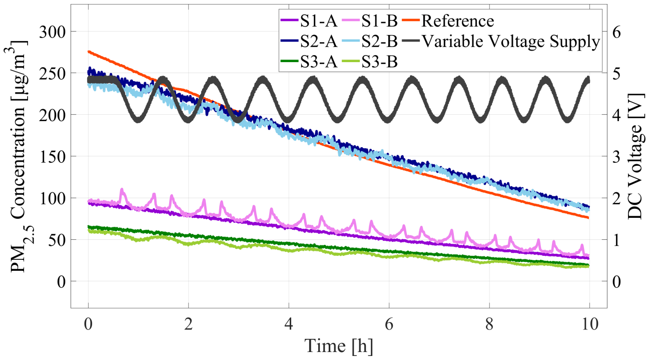

Fig. 5. PM$_{2.5}$ concentration time trends during sinusoidal fluctuation test.

TABLE III
SINUSOIDAL FLUCTUATION TEST RMSE RESULTS

RMSE [μg/m^3]			
Devices	**Sensor**		
	S1	**S2**	**S3**
A vs Reference	109.6	11.2	127.6
B vs Reference	103.6	12.6	133.1
A vs B	8.1	7.9	5.8

quality monitoring, owing to their ease of installation and high reporting rate. These sensors, however, are subject to external influences such as relative humidity and temperature. Moreover, an aspect often overlooked in scientific literature is the impact of power supply issues on sensor accuracy. The laboratory characterization of three low-cost PM sensor models under different voltage fluctuations has revealed a manufacturer-dependent variability in sensor response. This finding underscores the need to consider real-time power supply voltage monitoring in low-cost air quality systems, which could significantly enhance the trustworthiness and accuracy of the collected measurements, ensuring a more robust understanding of environmental air quality.

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