# Best Practices for Deploying and Maintaining a Low-Cost $PM_{2.5}$ Sensor Network

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# Best Practices for Deploying and Maintaining a Low-Cost PM2.5 Sensor Network

Center for Study of Science, Technology and Policy (CSTEP)

July 2022

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Designed and edited by CSTEP



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## Abbreviations and Acronyms

| | |
|---|---|
| µg | Microgram |
| BAM | Beta attenuation monitor |
| CSTEP | Center for Study of Science, Technology and Policy |
| FAQs | Frequently asked questions |
| FEM | Federal equivalent method |
| FRM | Federal reference method |
| GPS | Global Positioning System |
| IoT | Internet of Things |
| LCS | Low-cost sensor |
| MAB | Mean absolute bias |
| NRMSE | Normalised root mean square error |
| PM | Particulate matter |
| $PM_{2.5}$ | Particulate matter with a size less than 2.5 microns |
| $R^2$ | Coefficient of determination |
| RMSE | Root mean square error |
| TEOM | Tapered element oscillating microbalance |

## 1. Background and Context

Strategically placed sensors can monitor air pollution and provide a detailed picture of air quality and its variability within a region. Low-cost sensors (LCSs) that measure $PM_{2.5}$ are becoming increasingly popular because of their low cost, ease of use, and portability. However, the portability and low cost come with trade-offs on data quality, reliability, and shelf life. The typical shelf life of LCSs is around a year to two. Also, the raw data from these LCSs need to be calibrated. This report documents the best practices for establishing and maintaining an LCS network.

It is intended for regulatory authorities and research and policy organisations that are keen on establishing LCS networks for air quality monitoring. It lays out key considerations and challenges for different stages of project planning. While the technical details are universally applicable, some context-specific guidance may be more relevant for resource-limited settings. The best practices suggested are expected to help stakeholders set up and maintain LCS networks efficiently. The points put forth are based on our experience in establishing a city-wide PurpleAir LCS network in Bengaluru and maintaining it for 2 years.

Establishing a city-wide network often involves installing sensors across a range of host sites that qualify certain criteria. For example, in the Bengaluru project, we have hosts from residences, offices, schools, colleges, and other institutions. Therefore, it is important to consider certain logistical aspects and infrastructural requirements, in addition to the monitoring objectives, during the planning and implementation of an LCS network.

Network characteristics such as number of sensors, expanse of the network, measurement tenure, and sensor locations are determined by the objectives of establishing the sensor network. Some common objectives for establishing an air pollution LCS network are as follows:

- Identifying pollution hotspots
- Understanding inequities in air pollution (are some populations more exposed than others?)
- Supplementing regulatory data to better inform citizens on local air pollution
- Understanding air pollution issues in regions where no regulatory monitoring is available (e.g., rural and peri-urban areas in India)
- Informing policies for pollution prevention
- Developing and training spatial prediction models with adequate ground-level data

Figure 1 summarises the key points to be considered at different stages of LCS network deployment. Each key point is elaborated in the document, and an FAQs section is provided at the end.

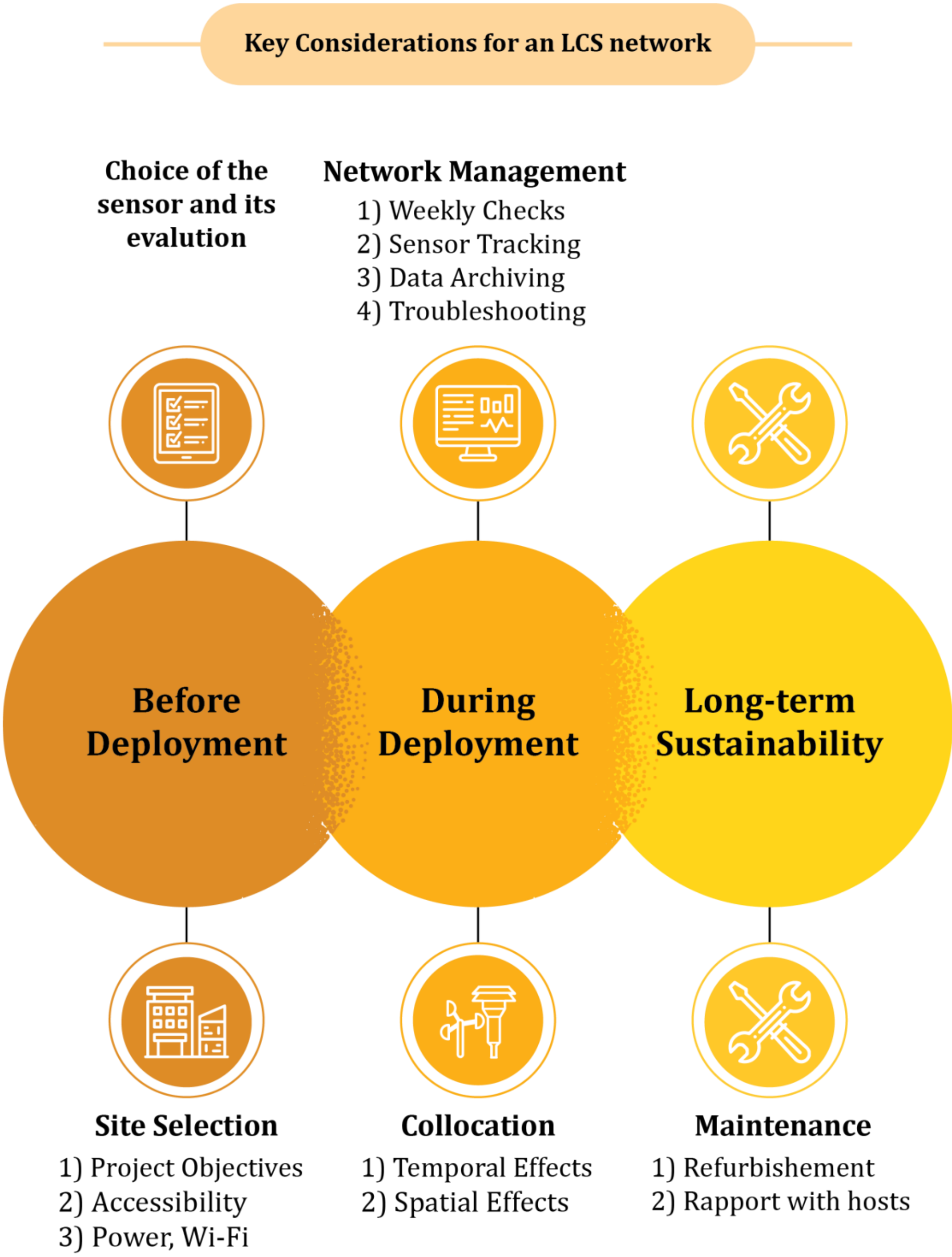



Figure 1: Key considerations

# 2. Sensor Selection, Evaluation, and Calibration

## 2.1 Choosing an LCS

There are several LCSs available in the market. Sensor selection is determined by the objectives of the project, field conditions, and the following factors:

- Cost
- Ease of installation
- Portability
- Precision and accuracy of the sensor measurements
- Temporal resolution of the output data by the LCS
- Wi-Fi/cellular module availability
- Meteorological sensor availability
- Solar panel availability
- Online dashboard facility
- Global Positioning System (GPS) module availability
- Battery backup
- Dual laser counters
- Internal storage (SD card) facility
- Lifetime of the sensors
- Back-end and technical support by the vendor

Detailed guidance on selecting a sensor for air quality management in Indian cities can also be found here[1]. Investigators planning for LCS networks in rural areas need to consider network coverage of various cellular/internet service providers to ensure uninterrupted cloud server connectivity of the Internet of Things–based LCSs.

## 2.2 Sensor Evaluation and Calibration

Most LCSs quantify $PM_{2.5}$ based on the light scattering technique, which is sensitive to various factors (humidity and aerosol optical and microphysical properties) in addition to the particle concentration. $PM_{2.5}$ measurements often require evaluation followed by calibration. The procedure of evaluating sensor accuracy (the level of agreement between sensor-measured and reference-grade $PM_{2.5}$) and deriving calibration equations is termed field calibration. In addition to accuracy testing, precision (the level of agreement between $PM_{2.5}$ measurements by sensors of the same type and make) testing is also recommended. Precision testing informs whether a calibration factor/equation derived for an LCS can be used to calibrate $PM_{2.5}$ measurements from another LCS of the same make/type or not (Giordano et al., 2021).

Sensors can be evaluated in the laboratory and in the field. Most LCSs are evaluated in the laboratory by the manufacturer (as part of factory calibration) for a known type of aerosol. The ambient $PM_{2.5}$ is a mixture of various chemical species, and the $PM_{2.5}$ composition varies across regions; therefore, local field evaluation/calibration under atmospheric conditions that the network LCSs will be deployed in is desirable. For field calibration, the most common procedure is the collocation of LCSs and Federal Reference Method (FRM) or Federal Equivalent Method (FEM) grade $PM_{2.5}$ instrumentation. Reference-grade methods for $PM_{2.5}$ measurements—

[1] https://www.vitalstrategies.org/resources/integrated-use-of-low-cost-sensors-to-strengthen-air-quality-management-in-indian-cities/

approved by the United States Environmental Protection Agency (USEPA)—include beta attenuation monitor (BAM), tapered element oscillating microbalance (TEOM), and gravimetric analysis. Gravimetric analysis is a time-integrated measurement and is less preferred for calibrating LCSs. Near real-time $PM_{2.5}$ measurements (hourly data from BAM/TEOM) are more suitable for deriving calibration factors for $PM_{2.5}$ measured by LCSs (Zusman et al., 2020).

## 2.3 Collocation and Its Frequency

Figure 2 shows a typical collocation set-up where LCSs are installed next to a BAM-1022 (FEM) monitor, which is a USEPA-approved instrument for hourly averaged $PM_{2.5}$. A distance of one metre between the reference-grade monitor inlet and any other monitor/LCSs should be maintained as the high flow rate of the reference monitor can create a low-pressure zone around its inlet. It is important to regularly maintain the FRM/FEM instruments as per their operational manuals. Flow check or calibration of reference instruments should be performed at regular intervals. Similarly, leak tests, zero tests, and span checks need to be performed for the FRM/FEM devices according to the frequency prescribed by the manufacturer.

Figure 2: Collocation set-up

The agreement between $PM_{2.5}$ measurements from LCSs and reference-grade monitors can change with time and space. Therefore, when an LCS network is deployed, it is recommended that LCSs be collocated with reference-grade monitors for periodically (covering different seasons) capturing the seasonality/temporality in the relationship. Ideally, collocation should cover the range of PM concentrations and atmospheric conditions that LCSs are expected to encounter while they are deployed in the field. This can be done by conducting collocation experiments in various study regions (urban background, sites with specific dominant pollution sources, etc.). If the network consists of *n* number of sensors, it is recommended to collocate all the *n* sensors with the reference instrument before the start of the campaign. A strategically selected (Zamora et al., 2022) window of a minimum of 10–14 days of collocation is desirable to derive calibration equations. It is also recommended to collocate at least three LCSs with the reference-grade instrument for the entire duration of the monitoring campaign. This will help in the following aspects:

(i) Better understanding the temporal variations in the relationship between LCS $PM_{2.5}$ and reference $PM_{2.5}$ measurements
(ii) Investigating degradation in LCSs performance (if any)

(iii) Evaluating the long-term stability of LCSs precision

Giordano et al. (2021) have more details on collocation and calibration. In situations where continuous or frequent collocation exercises are not feasible throughout the measurement campaign, the collocation exercises can be conducted before and after the monitoring campaign.

## 2.4 Meteorological Measurements

In addition to $PM_{2.5}$, many LCSs measure meteorological parameters such as relative humidity (RH) and temperature (T). RH measurements help in correcting bias introduced by the effect of humidity on $PM_{2.5}$ measurements by LCSs. Earlier studies (e.g., Chakrabarti et al., 2004) have provided methods to correct light scattering–based $PM_{2.5}$ measurements for RH effects. However, before using RH values measured by LCSs, it is advisable to evaluate their performance. Studies (e.g., Liu et al., 2019; Kumar et al., 2022) have indicated that LCS measurements of RH and T often underestimate or overestimate ambient levels. In such cases, one can also rely on a nearby weather station to correct the bias in RH and T measurements made by LCSs.

## 2.5 Calibration Models

Simultaneous data ($PM_{2.5}$, RH, and T from LCSs and reference-grade monitors) collected during collocation experiments can be used to build calibration models. The linearity in the LCSs $PM_{2.5}$ concentrations can also be verified using this data. If all the *n* sensors do not agree with each other (imprecise), then it is recommended to have a sensor-specific calibration model. It is possible that there exists a small bias in the PM measurements between LCSs. The most commonly used models are based on statistical and machine learning (ML) approaches. Statistical models include linear, non-linear, univariate, multivariate, segmented, and Gaussian regression methods, while ML models include random forest, neural networks, and deep learning (e.g., Feenstra et al., 2019; Barkjohn et al., 2020; deSouza et al., 2022). It is advisable to train a set of models and select one that better calibrates raw LCS $PM_{2.5}$ concentrations. Most of the calibration models include RH and T as predictors in addition to $PM_{2.5}$. As pollution sources and their strengths can change seasonally, aerosol optical and microphysical properties can also change seasonally. Therefore, different calibration models can be trained for different seasons (subject to availability of seasonal data). If the difference in seasonal regression coefficients is more than the uncertainty/error in the regression coefficient, it is advised to calibrate LCS $PM_{2.5}$ concentrations using seasonal calibration models. The accuracy of raw and calibrated LCS $PM_{2.5}$ measurements can be assessed using a set of performance metrics.

## 2.6 Performance Metrics

The following metrics can be used to evaluate the accuracy of $PM_{2.5}$ concentrations measured by LCSs: coefficient of determination ($R^2$), root mean square error (RMSE), mean absolute bias (MAB), and normalised root mean square error (NRMSE).

$$R^2 = \left( \frac{\sum_{i=1}^{n} L_i R_i - \frac{1}{n} \sum_{i=1}^{n} L_i \sum_{i=1}^{n} R_i}{\sqrt{\sum_{i=1}^{n} L_i^2 - \frac{1}{n} \left(\sum_{i=1}^{n} L_i\right)^2} \sqrt{\sum_{i=1}^{n} R_i^2 - \frac{1}{n} \left(\sum_{i=1}^{n} R_i\right)^2}} \right)^2 \quad \text{.................. (1)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (L_i - R_i)^2}{n}} \quad \text{.................. (2)}$$

$$MAB = \frac{\sum_{i=1}^{n} |L_i - R_i|}{n} \quad \text{.................. (3)}$$

$$NRMSE = \frac{RMSE}{\frac{1}{n} \sum_{i=1}^{n} R_i} \quad \text{.................. (4)}$$

*L* and *R* are hourly LCS $PM_{2.5}$ and reference $PM_{2.5}$ concentrations, respectively, and *n* is the number of paired data points. If the raw $PM_{2.5}$ from LCSs are considered *L*, then these metrics assess sensor performance in terms of raw $PM_{2.5}$ concentrations. If *L* is considered calibrated $PM_{2.5}$ (raw LCS $PM_{2.5}$ corrected using a calibration model), then these metrics assess the performance of the calibration model. The model performance can then be validated using the k-fold cross-validation method. The model-adjusted $R^2$ will help in understanding how much of the variance in data is being explained by the model. A linear fit to the scatter plot between calibrated LCS $PM_{2.5}$ and reference $PM_{2.5}$ concentrations also yields an $R^2$, which can be used to check the linearity in the calibrated data. MAB and RMSE are scale-dependent metrics, which are sensitive to the range of $PM_{2.5}$. The normalised RMSE (NRMSE) is a relevant metric to compare the performance of the calibration models developed for different geographies/seasons. The USEPA-recommended performance metrics and their target value ranges can be found in Duvall et al. (2021).

# 3. Site Selection and Installation

In most cases, the site selection process is driven by objectives of the study. If the objective is to train/build a land-use regression using the network data, the sensors need to be installed in locations covering various land-use types. If the goal of the study is to examine the impact of the socio-economic status on pollution exposure, sensors need to be installed in neighbourhoods characterised by a range of income slabs (e.g., low, middle, and high). If the objective is to estimate population-weighted mean $PM_{2.5}$, then sensors need to be installed based on the spatial resolution of the population data. In addition to objectives, other site requirements to install LCSs are explained in subsequent sections.

## 3.1 Infrastructural Requirements

Typically, LCSs require power, Wi-Fi, and protection from weather elements such as sunlight and rain. A few LCS monitors are integrated with solar panels, which have dual purposes of providing electric power and shade. LCSs with solar panels can be pole-mounted and are useful in public areas (parks, traffic junctions, streets, etc.), but adding a solar panel can increase the cost of an LCS unit. For sensors without a solar panel, a host is required to provide infrastructure. During the establishment of an LCS network, some sites might require minor modifications (electrical/civil) during installation, which might not be possible in all locations (for instance, rental apartments). In such instances, we need to look for alternative host locations that satisfy the intended objective.

Figure 3: Typical installation

## 3.2 Power Supply

Typically, power consumption of an LCS unit is equivalent to a mobile phone adapter. The cost of electricity needed to run an LCS unit for a month in a residential location can vary between INR 10 and INR 50. Ensuring an uninterrupted power supply to the LCS unit is critical. In residential sites, placing a marker/sticker alerting not to turn off the switch might prevent accidental power interruption. In an institutional or office setting, it is recommended that the sensor be directly connected (without a switch) to the power supply.

## 3.3 Internet Connection

As most LCSs work on the IoT principle, an active internet connection is required to establish the link between the sensor and its cloud server. Some international makers of LCSs (such as PurpleAir and TSI BlueSky) are Wi-Fi-based. This becomes challenging in low- and middle-income countries while deploying sensors in public areas as public Wi-Fi may not always be available. The host Wi-Fi connection can be requested and used (possible in urban areas) to configure LCSs, or a SIM-based portable dongle can be installed along with the LCSs. It is good practice to use an exclusive dongle for the LCS configuration rather than using the hosts' Wi-Fi. Using hosts' Wi-Fi might save expenditure, but the downside is that if the hosts change their Wi-Fi password, the sensor gets disconnected from its cloud server until it is reconfigured. If a dongle is used, the field team should be aware of its sleep settings; otherwise, after a stipulated time, the dongle will enter the sleep mode and the LCS will get disconnected from its cloud server. Even though a site is selected based on objectives of the study, the infrastructural demands of LCSs can influence the selection of installation locations.

## 3.4 Installation

LCSs can be used for both indoor and ambient air pollution monitoring. If the objective is to measure indoor air pollution, it is recommended to install the monitor at breathing height and in a room where residents spend most of their time (or as per the objectives of the study). If the objective is to measure outdoor/ambient air pollution, LCSs need to be installed away from indoor pollution sources (cookstoves, burning incense, etc.) and the sensor should sample unobstructed/well-mixed air. The installation height may vary between 3 metres and 10 metres from ground level. To rule out any possible impact of winds/gusts, LCSs should be installed with inlets facing down. It is not recommended to install sensors close to any surface; otherwise, LCS can sample the dust settled on the surface.

Figure 4: Installed LCSs

## 3.5 Hosts

To establish a network of LCSs, volunteers are needed to host sensors. A call for volunteers on social media (such as Twitter and Facebook) or institutional mailing lists can help in finding interested/suitable hosts. For many people, knowing that hosting LCSs allows them to learn about the real-time status of air quality in their homes and the immediate neighbourhoods is empowering. For the Bengaluru project, we circulated a brief project description along with a Google form where volunteers could sign up and enter information about location characteristics. Collaborating with educational organisations (colleges and schools) for hosting sensors is another sustainable arrangement. This will also help create awareness and interest in the topic of air pollution among students. When reaching out to educational institutions, contacting specific departments (e.g., environmental sciences) or faculty involved in air pollution research is recommended. Beyond the technical aspects of LCSs, the enthusiasm and cooperation of participating hosts are critical for the successful deployment of an LCS network.

# 4. Network Maintenance

## 4.1 Troubleshooting

As part of network maintenance, it is necessary to perform daily checks to ensure all sensors are online. We do daily checks for the Bengaluru project via the publicly available PurpleAir map. LCSs can be offline for multiple reasons, including internet disconnection, power failure, and accidental device disconnection. In case of a power outage, an LCS with internal battery backup will continue to record data for a certain period. Because of internet signal/connectivity issues in particular areas, LCSs can toggle between online and offline statuses. In such instances, it is advised to wait for a day or two before contacting the concerned host. If the LCS continues to be offline even after a day, the first step is to troubleshoot remotely by asking the host to check for possible loose connections or accidental switching off of the power supply. The host can be asked to reset/restart the LCS if all else fails. If the LCS is still not online, an in-person visit according to the host's availability is warranted. During the in-person visit, in addition to what has been done during the remote troubleshooting, the field team can try replacing/reconfiguring the LCS. If the on-site troubleshooting fails, the field team can replace the sensor with a spare sensor to avoid data loss. If the issue is with the network and the LCS continues to record data on the SD card, the data can be used for analysis.

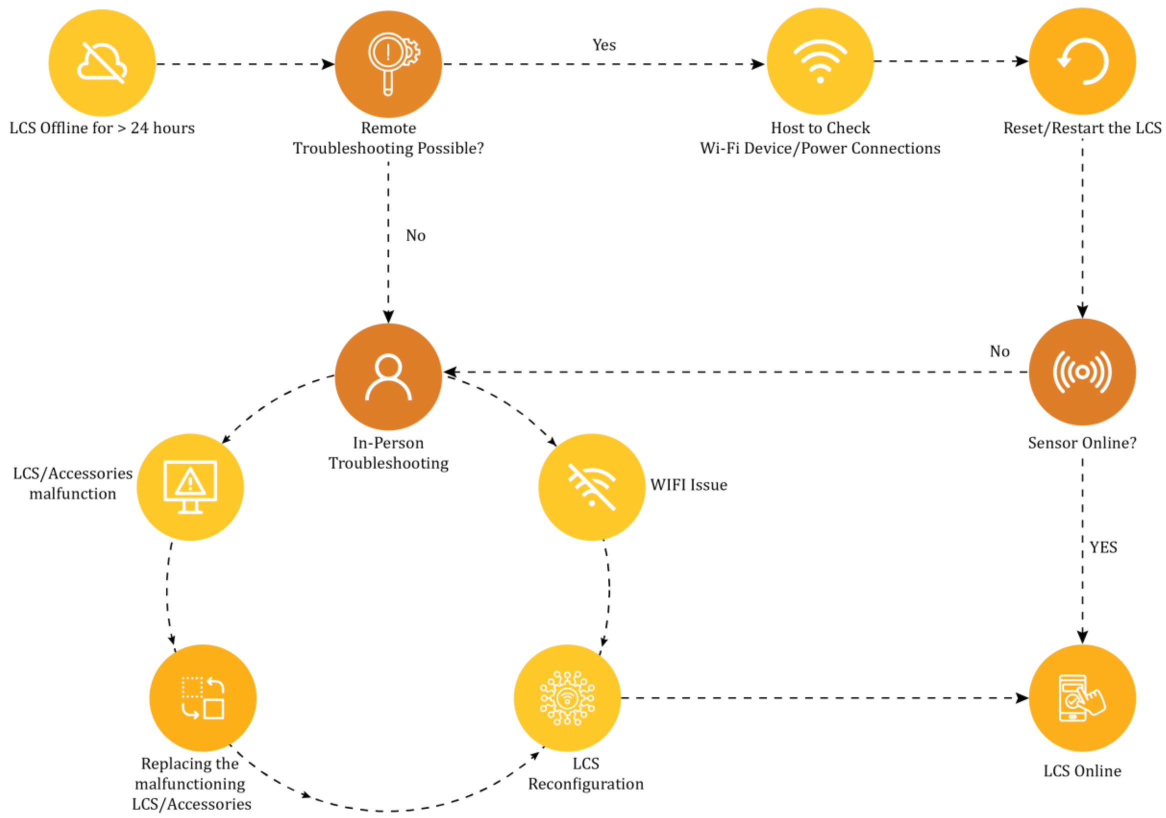



Figure 5: LCS troubleshooting flow chart

## 4.2 Data Quality Checks

Quality checks and post-processing of LCS data are required because of the following reasons:

- Possible inherent noise in high-frequency data
- Occurrence of spikes and zero values, which is uncharacteristic of ambient pollution
- Unequal intervals of data logging/averaging
- Possible baseline shift in data
- Intermittent data loss due to power and network issues

Some of these issues can be addressed by removing outliers and averaging for longer periods, for example, by computing 1-hour averages from 1-minute data (or whatever the maximum time resolution is). In LCSs that have dual laser counters (e.g., PurpleAir), the difference in concentrations between the counters can be monitored (Barkjohn et al., 2021) to investigate the malfunctioning of any of the laser counters. LCSs typically have a lifespan of 1 to 2 years, and their response can slowly drift over time. To detect any possible long-term deterioration, regular collocation of LCSs with reference-grade instruments is recommended. These protocols should ideally be predefined, and routine data checks should be conducted to replace/repair malfunctioning units with minimal data loss.

## 4.3 Sensor and Data Management

While implementing an LCS network project, keeping track of all the monitors is very important. LCSs may be moved from one location to another during the project tenure for a variety of reasons, including (i) conducting collocation experiments, (ii) refurbishment, and (iii) repair and replacement. A unique identification number should be given to each sensor and the measurement site. When an LCS is refurbished, it is important to collocate with a reference-grade instrument and check its performance before deployment. An Excel sheet–based searchable database or an offline desktop application can be used to record maintenance logs, status, and the location history of each LCS.

The network data should be downloaded regularly (fortnightly or monthly) from the cloud server. The highest temporal resolution data available should be downloaded and plotted (e.g., time-series plots) to detect issues such as abrupt shifts, degradation, and polluting sources operating close to the LCSs. The downloaded files should be renamed in machine-readable formats.

# 5. Long-Term Sustainability

## 5.1 Rapport with Hosts

Establishing a good rapport with hosts is critical for the long-term sustainability of an LCS network. Hosts are typically donating their time and space to a measurement campaign and may need to be contacted from time to time for troubleshooting and maintenance. Having one point of contact at each location helps in remote troubleshooting and reduces data losses by keeping the device downtime to a minimum. Taking the time to create awareness on air quality, introducing project goals, demonstrating how to check air pollution levels in their locality using sensors and online dashboards, and answering their questions or concerns help get buy-in from hosts. For in-person visits, being mindful of time constraints for site accessibility is essential as host availability may differ depending on the location (residential, office, or institution). If educational institutions are interested in becoming hosts, integrating the LCS network project with school projects via workshops or tutorials will go a long way in creating a sustainable network.

## 5.2 Cost Reduction Strategies

### *5.2.1 Refurbishment*

To sustain the network for a long term (beyond one year or so), a few cost-cutting strategies can be implemented. Given the relatively shorter shelf/field life of LCSs, replacement costs can be multiplicative. The laser counter is the most vulnerable part of an LCS. Instead of replacing the whole LCS, laser counters can be replaced at a fraction of the cost of a new LCS. For example, in the Bengaluru project, after some technical training, PurpleAir laser counters (Plantower) were replaced by the field team when they malfunctioned at one-sixth the cost of a new sensor.

A match between the PurpleAir $PM_{2.5}$ concentrations from the A and B channels before and after the refurbishment is shown below. After replacing the faulty laser counters, a clear difference could be observed in the time series. The BEFORE panel shows a malfunctioning LCS with a noticeable bias between A (purple) and B (blue) channel data. After refurbishing (replacing both Plantowers) the PurpleAir LCS with a pair of new laser counters, A and B readings aligned with each other (as shown in the AFTER panel). See Appendix for a step-by-step guide for replacing the laser counters in PurpleAir LCSs. For an LCS with not easily accessible replacement parts, we might need to contact the vendor for refurbishment. Vendor support may also be needed if other parts of the LCS are malfunctioning (such as the internet module or the microprocessor).

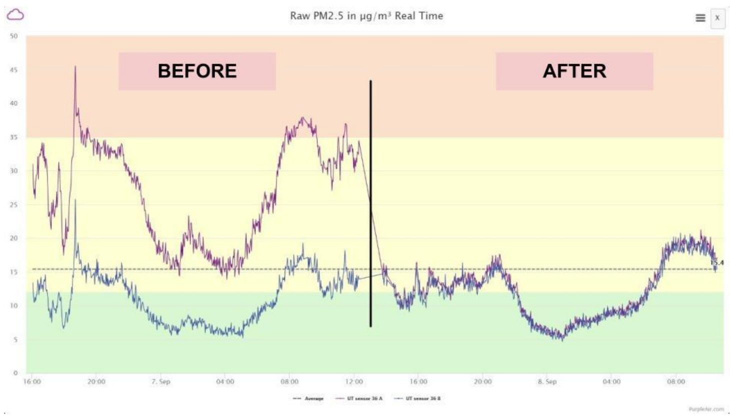



Figure 6: A snip of $PM_{2.5}$ time series from A and B channels of a PurpleAir LCS before and after the replacement of the Plantower set

### 5.2.2 Use of Application-Based Delivery

To avoid frequent visits to an LCS site, new/refurbished/replacement sensors can be delivered using application-based delivery agents (e.g., Dunzo in Bengaluru). As shown in the figure below, a do-it-yourself (DIY) kit with a configured LCS unit along with all the peripherals and an instruction guide can be prepared. For the Bengaluru study, the set-up includes a PurpleAir monitor, a Wi-Fi hotspot device (JioFi dongle), a powerbank (10,000 mAh) for battery backup, and micro-USB cables to connect the devices (Figure 7). The set-up also includes zip ties to hang the PurpleAir LCS at the installation location. The PurpleAir device will be pre-registered for the installation location and configured to the JioFi device before it is delivered to the host. The final set-up is plug and play so that the host can power it without further modifications. The installation procedure can also be explained to the host over a video call.

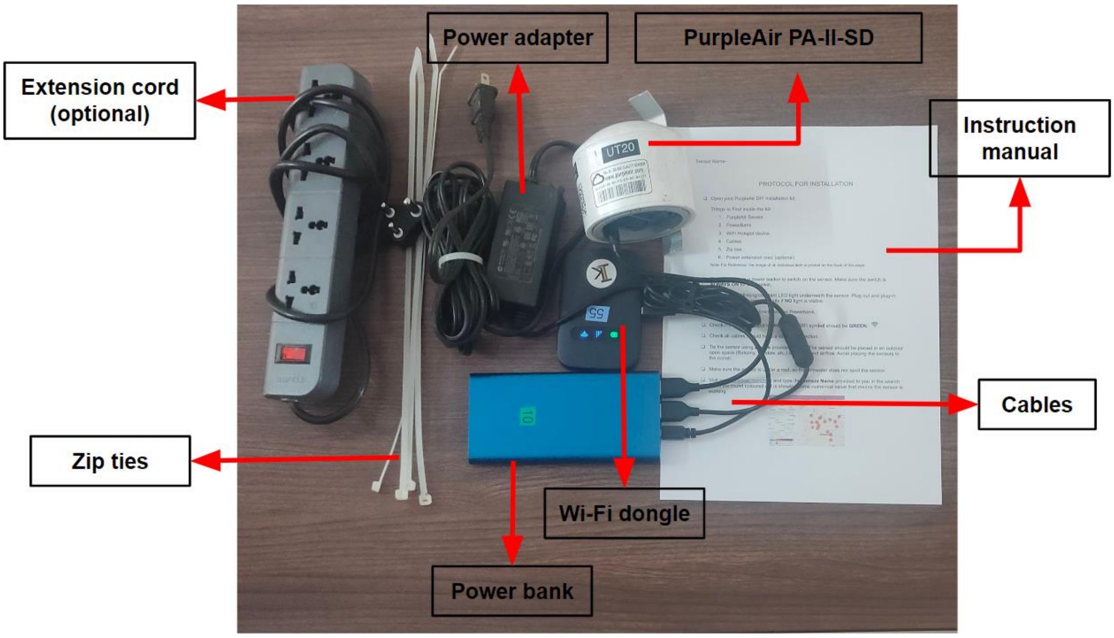



Figure 7: A do-it-yourself kit of a PurpleAir device consisting of an external powerbank, Wi-Fi dongle, and other essentials

### 5.2.3 Using the Host Wi-Fi

In sites with cooperative hosts, a host Wi-Fi connection can be used for configuring the LCS. While this reduces the overall cost of LCS installation, over-reliance on hosts may lead to data interruptions in certain situations.

## 6. Conclusion

The affordability, portability, and availability of LCSs make air quality data accessible to the general public. They are crucial to air quality monitoring systems because isolated regulatory sensors fail to capture local hotspots and spatial patterns. Developing countries, such as India, have extreme burdens of air pollution and require sustainable networks to monitor air pollution in cities and rural areas.

In areas with absent or limited monitoring, spatial patterns from LCS networks can inform decision-makers in deciding whether a reference-grade monitor is required in a particular area. LCS networks can also be used to identify pollution hotspots and evaluate geographically targeted mitigation policies. However, network projects designed to answer research or policy questions require careful planning beyond the plug-and-play modality of LCSs.

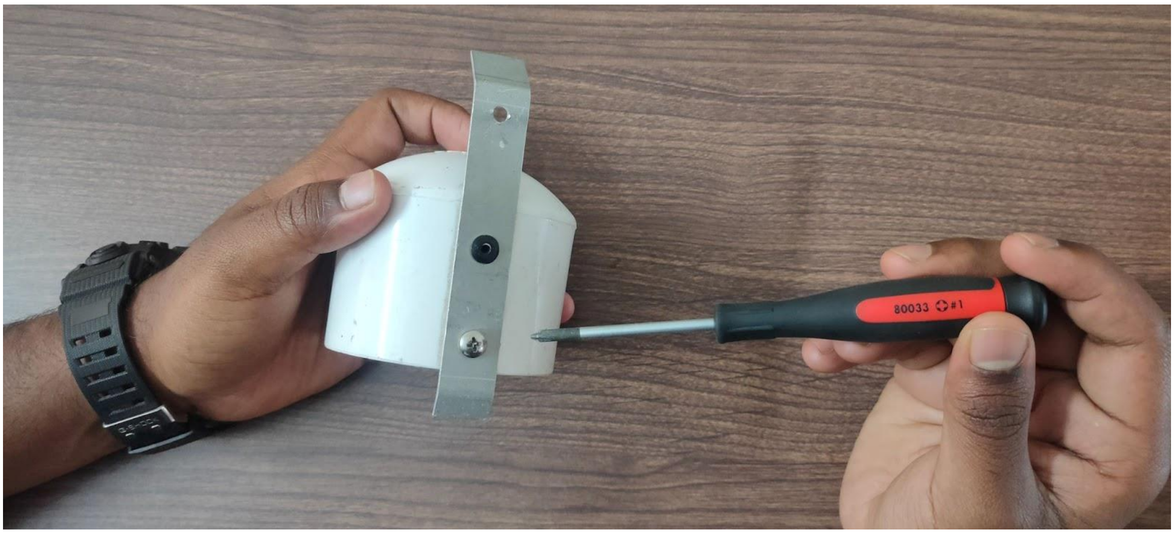
The trade-off of the low cost of LCS is the variable performance under different environmental conditions. Evaluating LCSs in the field is, therefore, critical to ensure data quality from network projects. We hope that best practices suggested in the document will help users establish low-cost sensor networks efficiently.

# APPENDIX.

# 7. Appendix: Replacement of Plantower Sensors in PurpleAir

A PurpleAir device can be refurbished by replacing the Plantower laser counters, as long as the meteorological sensor and other electronics are working well. Follow the steps listed below to replace the faulty Plantower set:

1. Unscrew the outer shell.

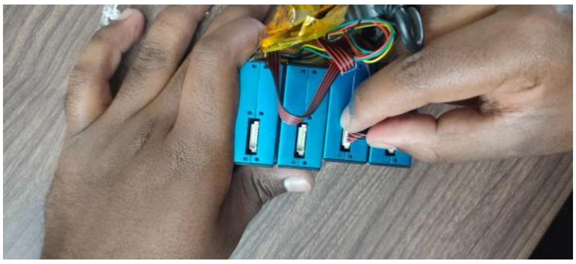


2. Pull the Plantower assembly out by pulling the ring.

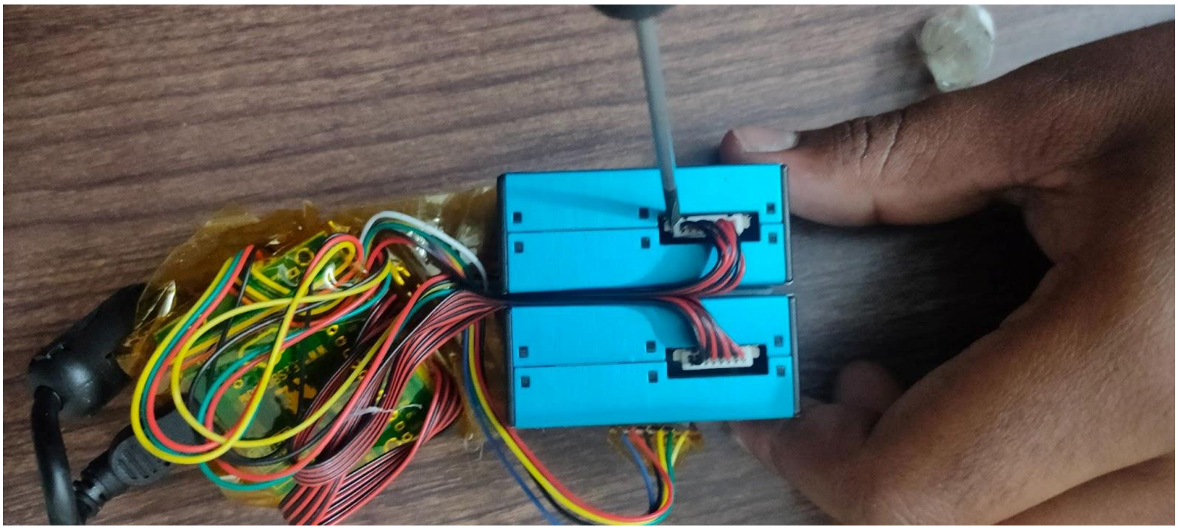
3. Remove the sensor unit from the ring and remove the adhesive tape wrapped around the sensor.

4. Remove the SD card unit, the RH and temperature sensor, and the power socket assembly, which are glued around the Plantower set.

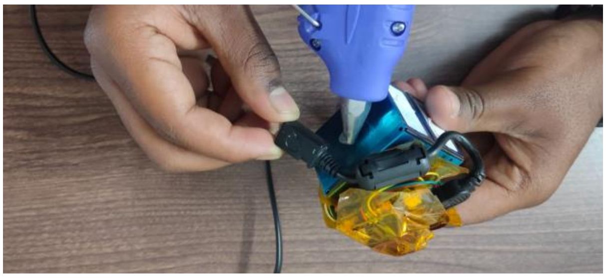

5. Disconnect the Plantower sensors from the microprocessor unit, and connect them to the new Plantower set.

6. Use a flathead screwdriver to gently push the connector socket inside the Plantower.



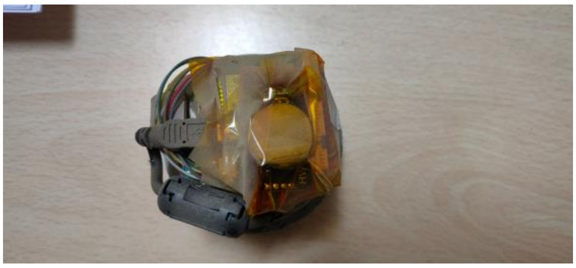
7. Stick the SD card unit, RH and temperature sensor, and the power socket assembly to the new Plantower set.



Note: You can use hot glue to stick the power socket again.

8. Wrap the whole assembly back with the adhesive tape and place it inside the ring. Then, push the whole assembly inside the white shell and screw it again.

9. Plantower unit before and after refurbishment



## 8. FAQs

**1. Why is local calibration important?**

As most of the PM LCSs use the light scattering technique, which is sensitive to aerosol microphysical and optical properties and weather conditions (which vary in space and time), a local calibration exercise is recommended. This is to ensure that the LCS response is corrected for optical properties of the local PM.

**2. Can we use the nearest Central Pollution Control Board (CPCB) station to build the calibration model?**

In urban areas, PM levels can vary rapidly. The LCS should ideally be installed as close as possible to the CPCB reference-grade monitor for the collocation exercise to ensure both instruments sample the same air mixture.

**3. Is a meteorological sensor mandatory for an LCS?**

PM measurements from LCSs often need a humidity correction. Meteorological sensors measure the ambient humidity levels, which subsequently can be used to compensate for the effect of humidity on PM measurements.

**4. What are the deciding factors for replacing a laser counter?**

The deciding factors are the sudden shift in PM measurements (in the absence of a known pollution event) and the gradual deterioration in the LCS's performance. In LCSs with dual laser counters (as in PurpleAir), one of the deciding factors is the observable difference between measurements from the two counters—channels A and B in PurpleAir.

**5. Can we use the raw data from LCSs directly for research?**

Direct data from LCSs can be biased when compared to reference-grade monitors; therefore, it is recommended to use data from LCSs after correcting them using a local calibration model.

**6. What is the lifespan of an LCS?**

The lifespan of an LCS varies from a few months to a couple of years. In general, LCSs installed in highly polluted environments deteriorate faster.

**7. Do all low-cost monitors require internet connectivity?**

Most of the LCSs are IoT-based and require internet connectivity to configure and push the data to their online servers. A few LCSs give the option of storing data in local storage (SD card) also.

**8. Can we rely on SD cards alone to collect data?**

LCSs equipped with SD cards can be relied upon to collect data. However, ensure that the LCSs are always powered on and collect pollution data continuously. The SD card data format could also differ from the format in which data is collected and presented by online servers. Therefore, there might be certain deviations in how the collected data is presented in the SD card format. SD cards are also prone to get corrupted. Periodic monitoring of SD cards is, therefore, essential to ensure that they are not corrupted and collect data as intended.

**9. Do all LCSs have a bias compared to reference-grade monitors?**

The key functional unit inside an LCS is the laser counter. The design, laser intensity, optics construction, and laboratory calibration of the laser counter will have an impact on measurements. The bias observed in LCS-measured PM values compared to reference-grade monitors varies across LCSs.

**10. What kind of calibration model is suitable for correcting LCS PM data?**

Various forms of calibration models are available in the literature, including statistical and machine learning models. Beyond model fit, the choice of calibration model can be based on the desired level of simplicity and availability of data on predictor variables.

## 9. References and Suggested Reading


Barkjohn, K. K., Gantt, B., & Clements, A. L. (2021). Development and application of a United States-wide correction for $PM_{2.5}$ data collected with the PurpleAir sensor. *Atmospheric Measurement Techniques, 14(6)*, 4617–4637. https://doi.org/10.5194/amt-14-4617-2021

Chakrabarti, B., Fine, P. M., Delfino, R., & Sioutas, C. (2004). Performance evaluation of the active-flow personal DataRAM $PM_{2.5}$ mass monitor (Thermo Anderson pDR-1200) designed for continuous personal exposure measurements. *Atmospheric Environment, 38(20)*, 3329–3340. https://doi.org/10.1016/j.atmosenv.2004.03.007

deSouza, P., Kahn, R., Stockman, T., Obermann, W., Crawford, B., Wang, A., . . . & Kinney, P. (2022). Calibrating networks of low-cost air quality sensors. *Atmospheric Measurement Techniques Discussions*, 1–34. https://doi.org/10.5194/amt-2022-65

Duvall, R., Clements, A., Hagler, G., Kamal, A., Kilaru, V., Goodman, L., ... & Dye, T. (2021). Performance testing protocols, metrics, and target values for fine particulate matter air sensors: Use in ambient, outdoor, fixed sites, non-regulatory supplemental and informational monitoring applications. *US EPA Office of Research and Development Washington, DC*. EPA/600/R20/280. https://cfpub.epa.gov/si/si_public_record_Report.cfm?dirEntryId=350785&Lab=CEMM

Feenstra, B., Papapostolou, V., Hasheminassab, S., Zhang, H., Der Boghossian, B., Cocker, D., & Polidori, A. (2019). Performance evaluation of twelve low-cost $PM_{2.5}$ sensors at an ambient air monitoring site. *Atmospheric Environment, 216*, 116946. https://doi.org/10.1016/j.atmosenv.2019.116946

Giordano, M. R., Malings, C., Pandis, S. N., Presto, A. A., McNeill, V. F., Westervelt, D. M., ... & Subramanian, R. (2021). From low-cost sensors to high-quality data: A summary of challenges and best practices for effectively calibrating low-cost particulate matter mass sensors. *Journal of Aerosol Science, 158*, 105833. https://doi.org/10.1016/j.jaerosci.2021.105833

Kumar, V., Malyan, V., & Sahu, M. (2022). Significance of Meteorological Feature Selection and Seasonal Variation on Performance and Calibration of a Low-Cost Particle Sensor. *Atmosphere, 13(4)*, 587. https://doi.org/10.3390/atmos13040587

Liu, H. Y., Schneider, P., Haugen, R., & Vogt, M. (2019). Performance assessment of a low-cost PM2. 5 sensor for a near four-month period in Oslo, Norway. *Atmosphere, 10(2)*, 41. https://doi.org/10.3390/atmos10020041

Public Lab (2018, September 17). How to open and clean a PMS 5003 air sensor. https://publiclab.org/notes/kkoerner/09-17-2018/how-to-open-and-clean-a-pms-5003-air-sensor

Zimmerman, N. (2022). Tutorial: Guidelines for implementing low-cost sensor networks for aerosol monitoring. *Journal of Aerosol Science, 159*, 105872. https://doi.org/10.1016/j.jaerosci.2021.105872

Zusman, M., Schumacher, C. S., Gassett, A. J., Spalt, E. W., Austin, E., Larson, T. V., ... & Sheppard, L. (2020). Calibration of low-cost particulate matter sensors: Model development for a multi-city epidemiological study. *Environment International, 134*, 105329. https://doi.org/10.1016/j.envint.2019.105329

Zamora, M. L., Buehler, C., Datta, A., Gentner, D, R., & Koehler, K. (2022). Optimizing co-location calibration periods for low-cost sensors. *EGUsphere,* 1-20. https://doi.org/10.5194/egusphere-2022-200

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