Reply to the comments of Referee # 1

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Title: Sustaining Low-Cost PM2.5 Monitoring Networks in South Asia: Technical Challenges and Solutions

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Authors Acknowledgment:

The authors sincerely thank the referees for their thorough reviews and insightful comments. We have carefully addressed each comment by acknowledging the constructive feedback and incorporating it into the revised manuscript to enhance its quality and clarity.

Referee # 1 Comments:

This manuscript provides an examination of the technical and logistical challenges in deploying and maintaining low-cost $PM_{2.5}$ sensor networks across South Asia (excluding India). It addresses region-specific issues such as power outages, environmental stressors, and maintenance demands, and offers strategies to mitigate these challenges. The work contributes insights into air quality monitoring in low-resource settings, with a focus on practical solutions for scaling low-cost sensors (LCS). However, there are fundamental concerns related to sensor calibration that would require more than analysis and writing adjustments to address.

Specific comments:

1. The authors assert that maintenance strategies can "debunk the myth" of limited sensor lifespan. However, broader literature indicates that while proactive maintenance can improve sensor performance, low-cost sensors still face durability constraints, particularly in high-dust, high-temperature, and humid environments. Addressing these limitations more directly would help set realistic expectations for LCS durability. Additionally, the lack of discussion on calibration raises questions about the study's claims regarding sensor lifespan.

Reply: The paper addressed the limitation by presenting the results of low-cost sensors installed at locations with heavy pollution load and extremely hot temperature in South-Asian countries. Regular maintenance includes calibration of the sensor in a calibration chamber every 1 year after following cleaning and maintenance protocols. The paper is meant to serve as a maintenance protocol for low-cost sensors as the low-cost sensors manufacturing company claims only 1 year for the sensor lifetime, but the network is sustained for more than 3 years in several South-Asian countries due to consistent maintenance protocols on a regular basis. For instance, Figure 10 depicts one sensor in Pakistan (NUST-Pk4) which was exposed to severe dust episode caused by construction activity in the proximity of it (after cleaning NRMSE=0.033), and it has been successfully restored by following rigorous quality control, maintenance and calibration procedure as mentioned in section 2 (Methodology). Calibration and collocation are described in other companion manuscripts Jain et al (2024); Madhwal et al. (2024); Khaleel et al. (2024); Shabbir et al. (in review); Shrestha et al. (in review); Zaman et al. (in preparation); Senarathna et al. (in review).

2. While the study is presented as covering South Asia, it does not include India—the region's largest country. Providing a rationale for excluding India would be valuable for readers, helping clarify the study's scope. Referring to this work as a "South Asia-wide study" might create an impression of broader coverage than is provided, so revising this framing would improve accuracy.

Reply: This is a very good point. Although India was part of the overall project funded by the US Department of State (PI M. Bergin) due to geo-political issues with Pakistan, the Indian team could unfortunately not participate in this publication. It is worthwhile to point out that the Indian team did roll out a network of ~70 BlueSky sensors in urban Lucknow that collected data over a 3-year period that is described by Madhwal et al. 2024 (Atmos. Environ.) and Jain et al. 2024 (Atmos. Environ.). The context is still focused on South-Asian countries having Nepal, Maldives, Sri Lanka, Bhutan, Bangladesh, and Pakistan that in essence surround India and represent the broad range of meteorology and particulate matter sources and concentrations experienced in India. With this said we have replaced "South Asia" with "South Asian countries" in the title.

3. Although the manuscript details maintenance protocols, it lacks information on the costs associated with these activities. A cost-benefit analysis comparing the maintenance of LCS with that of traditional regulatory monitors would offer policymakers clearer insights into the economic feasibility of implementing LCS networks at scale.

Reply: The cost of a low-cost sensor Blue Sky from TSI is 800 USD in addition to a paid subscription to data services while traditional monitors cost around 25,000-30,000 USD so that is why it is called low-cost sensors. The procedure was not costly as the instrument was shipped back to the supersite lab through shipment, here we have a calibration chamber for the maintenance. It costs between 10 to 15 dollars for each for one maintenance cycle. In addition, regulatory monitoring stations require air-conditioned environments along with routine maintenance and calibration, which significantly increase operational costs. As a result, government agencies in South Asian countries often find these systems financially unfeasible. Moreover, the cost-benefit analysis point will be added to table 2 of revised manuscript (Section 3 Results & Discussion).

The updated table with estimated costs is given below:

Country	**Issues Faced**	**Proposed Solutions / Trouble shootings**	**Frequency of occurrence**	***Estimated -Costs (USD/unit)**
Sri Lanka	a) Power supply issues	a) Installing dedicated power outlets and opting solar powered backups	a) 10	15$
	b) Network connectivity	b) using Wi-Fi dongles	b) 8	10$

	c) clogged mesh due to salinity	c) regular maintenance	c) 4	~8-10$
	d) firmware updates	d) manual firmware update	d) 1	-
	e) Malfunctioning sensors (PM2.5 = 0 for more than 1 Day)	e) cleansing, troubleshooting and replacement	e) 1	~20-25$
Nepal	a) Power supply disruptions	a) Coordination with local partners, and physical field visits	a) 4	-
	b) Wi-Fi connectivity (Change in Wi-Fi password)	b) Opting for the solar-powered backup with independent internet sources	b) 1	~15-20$
	c) PM2.5 Monitor defects	c) Downloading data from SD card	c) 1	-
	d) Dead Power Supplies	d) Replacing malfunction adapters	d) 1	~10-15$
	e) Firmware updates	e) manually updating firmware	e) 1	-
	f) reconfiguration button issue	f) applying WD-40 spray (anti-rust)	f) 1	-
Maldives	a) Continuous Wi-Fi and power supply outages	a) Using external modems, downloading data from SD cards and securing power switches	a) 14	10$
	b) sensor maintenance due to dust and salinity	b) cleaning sensors regularly	b) 12	-
	c) sensor deployment and logistic issues	c) Raising awareness and site visits for sensors installation	-	-
	d) Lack of reference stations for calibration	d) Calibration against regional reference stations	-	-
Bhutan	a) Wi-Fi connectivity	a) Verifying internet and sensor connections	a) 2	~15-20$
	b) firmware upgrades	b) exploring firmware upgrade solutions	b) 1	-
	c) data recording intervals	c) cleansing and maintenance	c) 2	-
	d) Electricity outages	d) new power supply	d) 1	~10-15$
	e) remote area access and road obstructions	e) efficient logistics for remote access and collaborating with local	e) 1	-

		authorities for road clearance		
Bangladesh	a) Wi-Fi access (Frequent change in Wi-Fi password)	a) Using cellular modems	a) ~10-15	15$
	b) Electricity disruptions	b) Replacing malfunctioning adapters	b) 2	10$
	c) Sensor defects (PM2.5 = 0 for more than 1 Day)	c) Regular physical inspection and constant communication with hosts	c) 1	10$
	d) Firmware updates	d) manufacturer coordination for manually upgradation of firmware	d) 1	-
	e) Security breaches	e) Involving the public and ensuring security concerns while selecting the areas/locations to deploy the sensors	e) 1	-
Pakistan	a) Bad Electronic Board	a) Replacement with locally assembled board	a) 5	10$
	b) Sensirion Malfunctioning (PM2.5 = 0 for more than 1 Day)	b) Cleansing & replacement of component if dust clogged goes inside the sensirion.	b) 6	25$
	c) Dead Power Supplies	c) Locally available same specifications power adapter with little modifications	c) 10	10$
	d) Webs & Bugs inside the sensor box	d) Monthly cleaning, maintenance, and check ups	d) ~5-10	10$
	e) Internet Disruptions	e) Wi-Fi dongles for internet provision	e) 10	12$
	f) harsh weather conditions (reconfiguration button issues)	f) applying WD-40 (anti-rust) to setting up sensors	f) 3	5$

**The rectification costs were estimated based on the expenses reported by each collaborator. However, the costs are expected to fall within a similar range across all South Asian countries, as detailed records of expenses have not been maintained.*

4. Some content in the Introduction would be more appropriate in the Methods section. Reorganizing the manuscript to clarify methods and improve flow would make it easier for readers to follow the study's approach and findings.

Reply: Noted and changes will be incorporated in the revised manuscript. Authors revised the manuscript by restructuring moving headings 1.4 and heading 1.6 under Section 2 Methodology.

5. Table 2 summarizes technical challenges and solutions but does not specify whether this information is based solely on the authors' observations or if it includes input from formal surveys or consultations. If surveys were conducted, please include details on the methodology (including any ethics statement), respondent demographics, survey methods, and response rates to enhance transparency.

Reply: The observations summarized in Table 2 are based on the issues and challenges shared by the network operators from each country, who are also co-authors of this study. Beyond these contributions, no formal surveys or consultations were conducted. To enhance clarity, we will include a detailed description of authors' observations in the methodology section of the revised manuscript.

6. The introduction specifically and the manuscript more generally would benefit from additional context on the scientific basis for low-cost sensors, particularly around sensor accuracy, limitations, and typical calibration challenges in the field. This would provide readers with a stronger foundation for understanding the study's objectives and limitations.

Reply: This is a good point. There has been a great deal of work on low-cost sensors, particularly those measuring PM2.5, that has added greatly to our understanding of their accuracy and precision. For example, Zheng et al. (Atmos. Meas. Tech., 2018) found that with proper calibration the accuracy of low-cost PM2.5 sensors in both high and low concentration environments can be ~10%. In addition, there are community wide approaches to calibration and quality control that have greatly increased our ability to manage and maintain low-cost sensor networks to ensure accuracy and precision (Barkjohn et al., EST Air, 2024). Furthermore, the introduction of the manuscript will be revised to address objectives and limitations of the study.

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