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Title: Performance Assessment of Low-Cost PM Sensors under Diverse Exposure and Meteorological Conditions

Abstract

Air pollution remains one of the leading environmental factors responsible for adverse health outcomes, contributing to cardiovascular and respiratory diseases, impaired cognitive development, and premature mortality. Addressing this public health burden requires reliable, high-resolution monitoring systems capable of capturing the spatial and temporal variability of complex pollutant mixtures. While these mixtures encompass both particulate matter (PM) and gaseous compounds, PM exposure is a primary driver of these health impacts and forms the core focus of this research. In recent years, low-cost sensors (LCS) have emerged as a promising design intervention to bridge critical gaps in conventional regulatory monitoring; their affordability, compact form factor, and low-power requirements enable the development of dense sensor networks and portable systems. However, the application of LCS introduces a complex product design challenge. Sensor reliability under diverse meteorological conditions, high PM loading, varying aerosol composition, and long-term field exposure remains uncertain. These environmental extremes are especially prevalent across South Asia, particularly within the Indo-Gangetic plain, where they directly compromise LCS accuracy, durability, and overall life cycle performance.

This thesis approaches air quality monitoring as a design for environmental problems by integrating product design, embedded electronics, aerosol science, and exposure assessment to systematically evaluate the performance of commercially available particulate matter sensors. Their performance was assessed against reference-grade beta attenuation monitor (BAM) and GRIMM optical particle counter instruments through four collocated field investigations conducted under diverse environmental conditions representative of India.

The first study consisted of a four-month winter deployment in New Delhi, during which the reference BAM recorded $PM_{2.5}$ concentrations ranging from 6 to 611 $\mu g/m^3$, with a four-month average of 137 $\mu g/m^3$. While the evaluated LCS successfully captured the temporal variation in $PM_{2.5}$ concentrations under moderate conditions, their accuracy deteriorated substantially when relative humidity exceeded 80% and $PM_{2.5}$ concentrations surpassed approximately 100 $\mu g/m^3$.

Hygroscopic growth of aerosol particles was identified as the primary mechanism responsible for this degradation, and none of the evaluated sensors satisfied the United States Environmental Protection Agency (US EPA) recommended intercept criterion of 0 ± 5 μg/m^3, highlighting the limitations of factory calibration under highly polluted and humid environments.

The second study evaluated sensor performance in the arid, dust-dominated environment of Jodhpur using a collocated BAM, GRIMM 11-D optical particle counter, and elemental characterization by inductively coupled plasma mass spectrometry (ICP-MS). The results demonstrated excellent agreement between the LCS and the GRIMM for fine particulate matter (R^2 > 0.9 for PM_1 and $PM_{2.5}$), whereas performance deteriorated considerably for coarse particles (R^2 < 0.4 for PM_{10}). Elemental analysis revealed that crustal components, primarily calcium, potassium, aluminium, and iron, collectively accounted for approximately 90% of the measured elemental $PM_{2.5}$ mass, confirming that aerosol composition plays a critical role in influencing optical sensor response.

The third study examined the influence of sampling frequency on sensor performance in a highly polluted urban environment with hourly $PM_{2.5}$ concentrations ranging from 11.7 to 303.3 μg/m^3. Sampling intervals from 15 s to 60 min produced only minor differences in conventional hourly performance metrics. However, analysis of high-temporal-resolution measurements showed that only sub-minute sampling reliably detected short-duration pollution plumes, demonstrating that sampling frequency should be selected according to the intended monitoring objective rather than solely on conventional statistical performance indicators.

The final study assessed long-term sensor stability by comparing newly deployed sensors, sensors operated continuously for more than one year, and cleaned sensors following routine maintenance. The study demonstrated that measurement drift emerging after approximately 6-12 months of field deployment was primarily caused by airflow-path obstruction resulting from dust accumulation rather than irreversible degradation of the sensing element. Routine cleaning restored sensor performance to levels comparable with new units, establishing that long-term drift in these sensors is largely reversible and can be effectively mitigated through periodic maintenance.

Collectively, this research provides a comprehensive design-oriented evaluation of low-cost particulate matter sensors under the diverse environmental conditions encountered across India. To the best of our knowledge, this is the first study to evaluate a consistent set of LCS against the same reference instrumentation across both humid, high-pollution conditions in

Delhi and arid, dust-dominated conditions in Jodhpur within a unified framework. The work further validates an approximately 100 μg/m^3 $PM_{2.5}$ threshold beyond which sensor performance degrades under humid conditions, corroborating independent findings reported from India, and presents the first evidence that long-term performance drift of LCS operating under sustained high-PM conditions is predominantly maintenance-related rather than an inevitable consequence of sensor aging. Overall, this thesis demonstrates that the performance of low-cost particulate matter sensors is inherently context-dependent and provides evidence-based design recommendations for their calibration, deployment, sampling strategy, and maintenance, thereby supporting the development of reliable, scalable, and cost-effective air quality monitoring systems for India and other resource-constrained regions facing similar environmental challenges.