$WWSDI = CR_1 \cdot S_1 + CR_2 \cdot S_2 + ... + CR_n \cdot S_n$ (2)

Evaluating the quality of a locally-developed PM2.5 sensor system under Ethiopian ambient and indoor air quality circumstances

Johannes Dirk Dingemanse[1],Afework Tademe[2] and Wegene Negesse Debele[3]

[1]Faculty of Water Supply and Environmental Engineering, Arba Minch Water Technology Institute, Arba Minch University, Ethiopia

[2] Faculty of Electrical and Computer Engineering, Institute of Technology, Arba Minch University, Ethiopia

[3]Ethiopian Meteorology Institute, Jimma Branch, Ethiopia

Principal author email: johannesdirk.dingemanse@amu.edu.et

1. Introduction

1.1 Background

Air pollution is amongst the top risk factors for the global disease burden (Shaddick et al., 2018). This burden is relatively higher in low-income countries under both ambient and indoor circumstances (World Health Organization, 2021, 2022), but resources for measurements are lowest in those countries. A primary indicator for air pollution in indoor and ambient situations is particulate matter with a diameter smaller than 2.5 µm (PM2.5) (World Health Organization, 2021). Recently, for PM2.5 various low-cost sensor systems (LCS) are being developed. Commercial LCS prices range from $200-$500, and a sensor system can be self-built for approximately $60. LCS have the potential to increase data collection in Ethiopia. It is important to evaluate the quality of an LCS under the conditions where it will be used (Karagulian et al., 2019), but LCS have so far been barely validated in low-income countries (Dingemanse and Tademe, 2023). To use an LCS in Ethiopia, its quality should be evaluated under circumstances encountered in Ethiopia.

1.2 Objectives

To evaluate the quality of a locally assembled low-cost PM2.5 sensor system in Ethiopia:

- Under ambient concentration circumstances;
- Under indoor (high concentration) circumstances.

2. Methods

2.1 Instrument development

Within Arba Minch, a low-cost sensor system (SPSA) was developed (Dingemanse and Tademe, 2023). It consists of a Sensirion SPS30 sensor for PM2.5 measurements, a DS3231 Real Time Clock for keeping track of time, an SD Module for data storage, optionally a BME280 relative humidity and temperature sensor, and an LED for control light. All components are connected to an Arduino microprocessor and put in a plastic box. The Sensirion SPS30 measures the PM2.5 concentration based on scattered IR light (Sousan et al., 2021). Figure 1 shows an overview of the sensor system.

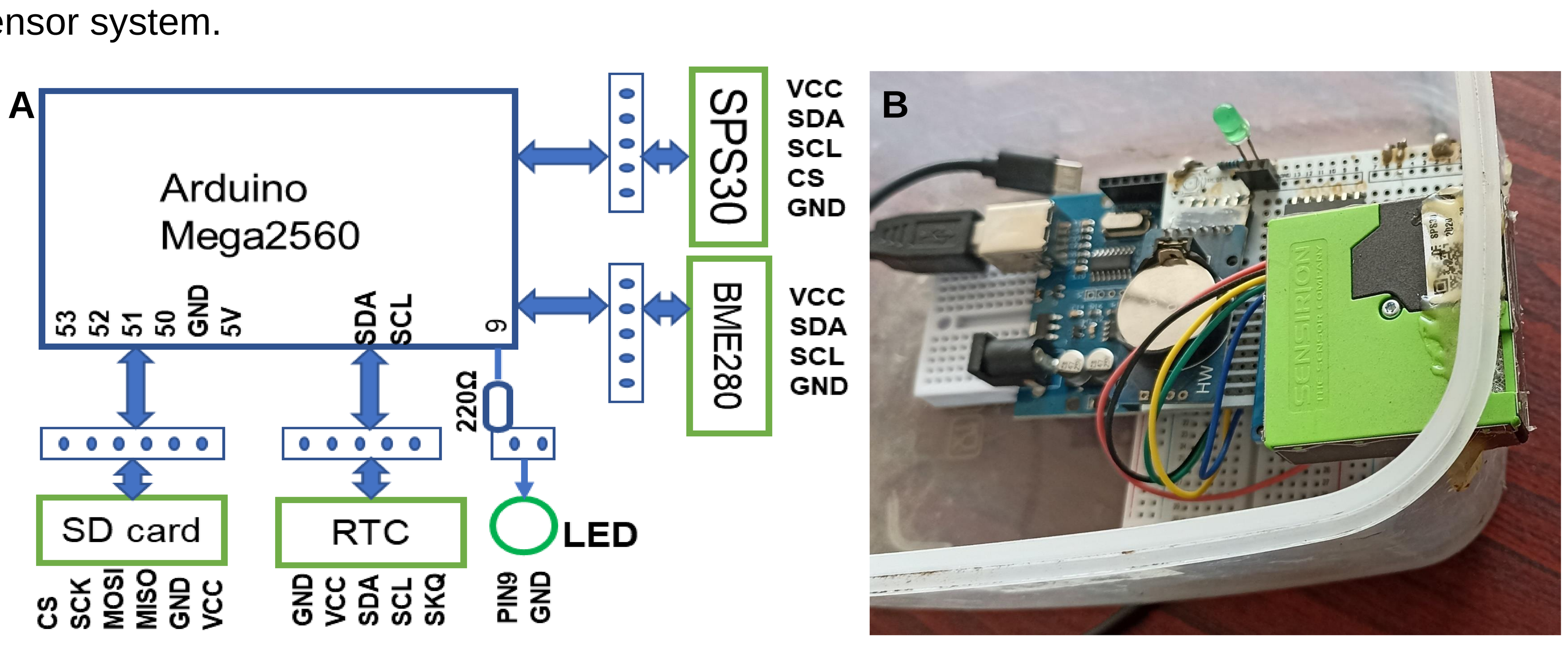

Fig. 1: Sketch of the SPSA circuit (A) and photo of the insides of an SPSA sensor system (B).

2.2 Instrument comparisons

The quality of the SPSA data was evaluated through collocation with itself, a reference instrument, and two commercial LCS. The reference method for PM2.5 data collection is gravimetry. As gravimetric instrument, we used the Ultrasonic Personal Aerosol Sampler (UPAS). We conducted gravimetric analysis of the filters with a Mettler AE240 Dual Range balance. The two commercial LCS used were the IQAir Airvisual (IQAV) and the UCB-PATS+ (PATS). Both IQAV and PATS estimate the PM2.5 concentration based on scattering of infrared light (Pillarisetti et al., 2017; Zamora et al., 2020). The PATS is designed for personal sampling and (high) indoor concentrations, but not for low ambient concentrations (lower detection limit is 10 µg/m3). Hence, we only used the PATS at indoor locations.

2.3 Measurements

Instruments were collocated at four ambient locations (two in Arba Minch, one in both Addis Ababa and Adama) and four indoor locations. For the ambient locations, sources of PM2.5 are traffic and neighborhood biomass burning. The four ambient locations represented four assumable distinct concentration levels. The indoor locations were selected for their use of biomass fuel, to represent (extremely) high and variable concentrations. All indoor locations were in Arba Minch kitchens. Table 1 presents a summary of all measurements.

Table 1: Summary of collocated measurements of two SPSA (INTRA), other LCS (IQAV, PATS), and a gravimetric instrument (UPAS).

Type	Location	INTRA [hours]	IQAV | PATS [hours]	UPAS [samples]
Ambient	Arba Minch, quiet area	1,825	7,164	
Ambient	Arba Minch, center	2,905	1,015	3
Ambient	Addis Ababa, EMI station	8,663	5,295	7
Ambient	Adama, EMI station	1,093	1,268	12
Indoor	Inside wood cooking kitchens	442	2,157 | 546	10

2.4 Data analysis

For comparing two SPSA, the coefficient of variation (CV) is calculated with Equation 1:

$$CV = \frac{1}{n}\sum \frac{\sigma_i}{\mu_i} \quad \textbf{(Eq. 1)}$$

where σ_i is the standard deviation and μ_i is the mean of measurements of identical LCS during time period i, and n is the number of time periods. The CV reflects the variation amongst two identical instruments and should be lower than 10% (EPA, 2006; NIOSH, 2012). CV was calculated based on 10-minute averaged data. Another metric we used is the Pearson correlation (r).

Metrics for comparing SPSA with the UPAS are slope (S) and coefficient of determination (R^2) from Ordinary Least Squares regression. Furthermore, accuracy is calculated as the upper value of the confidence interval at 90% of all $\frac{x_i}{y_i}$, where x_i is the concentration of the LCS and y_i the concentration of the reference instrument for time period i. Accuracy reflects how close the SPSA is to the UPAS and should be below 25% after bias correction (NIOSH, 2012).

3. Results

3.1 Concentration levels

Daily averages across the ambient locations ranged from 3 to 82 µg/m³, with an interquartile range (IQR) of 12 to 22 µg/m³. Under indoor circumstances, hourly averaged concentrations ranged from 6 to 4,799 µg/m³, with an IQR of 59 to 360 µg/m³.

3.2 Comparison of two collocated SPSA

Figure 2 shows all daily and hourly averages for two collocated SPSA. The similarity between two SPSA was strong (r≥0.96). Across the different ambient and indoor locations, the CV varied from 3.2 to 9.2%. It was in all cases lower than the required 10%.

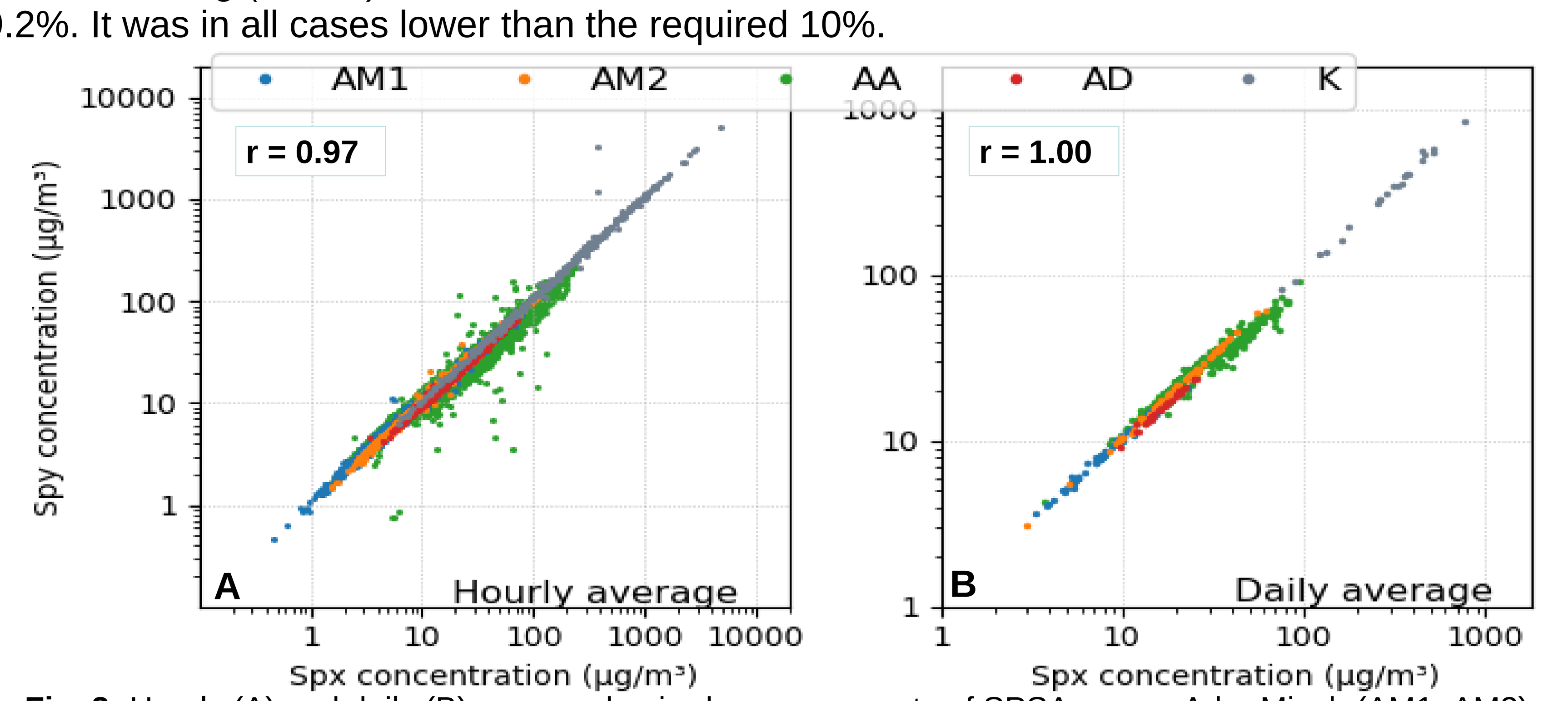

Fig. 2: Hourly (A) and daily (B) averaged paired measurements of SPSA across Arba Minch (AM1, AM2), Addis Ababa (AA), Adama (AD) and kitchens (K).

3.3 Comparison of SPSA and other sensors with reference

Figure 3 show the comparisons of SPSA as well as the two commercial LCS collocated with the UPAS.

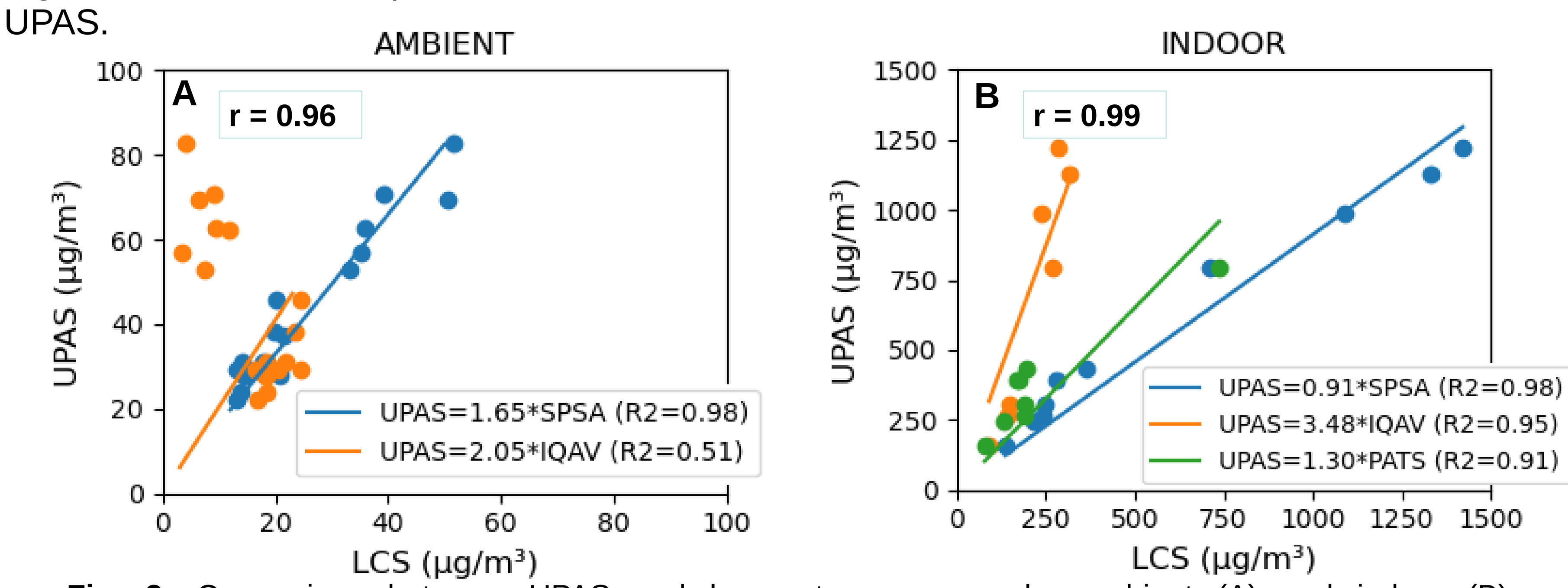

Fig. 3: Comparison between UPAS and low-cost sensors under ambient (A) and indoor (B) circumstances.

Both under ambient and indoor circumstances, the correlation between SPSA and UPAS was strong (R^2=0.98, r≥0.96). Under ambient concentration, bias correction was required: linear regression resulted in a slope of 1.65, implying that the SPSA reported too low concentrations. For indoor circumstances, the bias was less than 10% (slope 0.91). After bias correction, the SPSA accuracy was lower than the required 25% (15% and 18% under ambient and indoor circumstances, respectively). In comparison, the IQAV under ambient circumstances did not result in a strong linear relationship with the UPAS (R^2=0.51). Under indoor circumstances, R^2s of IQAV and PATS were lower (0.95 and 0.91, respectively), and the bias was larger (slopes of 3.48 and 1.30, respectively).

4. Conclusions

The locally developed low-cost PM2.5 sensor system SPSA was tested across ambient and indoor concentration circumstances common for Ethiopia. The coefficient of variation between two collocated SPSA was lower than 10% under all concentration levels. Furthermore, the accuracy with respect to the gravimetric reference method was under both ambient and indoor circumstances lower than the threshold of 25%. While under ambient concentration, a correction is required, both under ambient and indoor circumstances the linear relation to the gravimetric method is strong (R^2=0.98). Data quality results for the SPSA were competitive with two commercial low-cost sensors. Local development of a PM2.5 sensor system resulted in local expertise building, lower costs, and a sensor with good data quality for Ethiopian air quality circumstances. It is strongly recommended to similarly build, test and develop low-cost sensors in other environmental fields. This will increase both the expertise and research capacity of the Ethiopian scientific community.

Bibliography

Dingemanse, J. D., & Tademe, A. (2023). Developing and testing a PM2.5 low-cost sensor in Ethiopia under ambient and indoor air pollution conditions . Clean Air Journal, 33(2). https://doi.org/10.17159/caj/2023/33/2.16488

EPA (2006) General requirements of an equivalent method determination (Subchapter C). 40 CFR Parts 53. Available at: https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-53/subpart-C.

Karagulian, F., Barbiere, M., Kotsev, A., Spinelle, L., Gerboles, M., Lagler, F., Redon, N., Crunaire, S. and Borowiak, A. (2019) 'Review of the Performance of Low-Cost Sensors for Air Quality Monitoring', Atmosphere, 10(9), p. 506. Available at: https://doi.org/10.3390/atmos10090506.

NIOSH (2012) Components for Evaluation of Direct-Reading Monitors for Gases and Vapors. 2021–162. Cincinnati, OH: National Institute for Occupational Safety and Health. Available at: https://stacks.cdc.gov/view/cdc/11956.

Pillarisetti, A., Allen, T., Ruiz-Mercado, I., Edwards, R., Chowdhury, Z., Garland, C., Hill, L.D., Johnson, M., Litton, C.D., Lam, N.L., Pennise, D. and Smith, K.R. (2017) 'Small, Smart, Fast, and Cheap: Microchip-Based Sensors to Estimate Air Pollution Exposures in Rural Households', Sensors, 17(8), p. 1879. Available at: https://doi.org/10.3390/s17081879.

Shaddick, G., Thomas, M.L., Amini, H., Broday, D., Cohen, A., Frostad, J., Green, A., Gumy, S., Liu, Y., Martin, R.V., Pruss-Ustun, A., Simpson, D., van Donkelaar, A. and Brauer, M. (2018) 'Data integration for the assessment of population exposure to ambient air pollution for Global Burden of Disease assessment', Environmental Science & Technology, 52(16), pp. 9069–9078. Available at: https://doi.org/10.1021/acs.est.8b02864.

Sousan, S., Regmi, S. and Park, Y.M. (2021) 'Laboratory Evaluation of Low-Cost Optical Particle Counters for Environmental and Occupational Exposures', Sensors, 21(12), p. 4146. Available at: https://doi.org/10.3390/s21124146

World Health Organization (2021) Ambient (outdoor) air pollution, WHO Newsroom. Available at: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (Accessed: 5 September 2022).

World Health Organization (2022) Household air pollution and health, WHO Newsroom. Available at: https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health (Accessed: 5 September 2022).

Zamora, M.L., Rice, J. and Koehler, K. (2020) 'One year evaluation of three low-cost PM2.5 monitors', Atmospheric Environment, 235, p. 117615. Available at: https://doi.org/10.1016/j.atmosenv.2020.117615.