Technical article

Developing and testing a $PM_{2.5}$ low-cost sensor in Ethiopia under ambient and indoor air pollution conditions

Johannes Dirk Dingemanse[1,*], **Afework Tademe**[2]

[1]Faculty of Water Supply and Environmental Engineering, Water Technology Institute, Arba Minch University, Ethiopia
[2]Faculty of Electrical and Computer Engineering, Institute of Technology, Arba Minch University, Ethiopia
* Corresponding author: johannesdirk.dingemanse@amu.edu.et

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Abstract

$PM_{2.5}$ low-cost sensors are a promising trend for low-income countries, where the $PM_{2.5}$ associated burden of disease is high and few measurement instruments are available. Commercially available Sensor Systems (SSys) are relatively affordable and easy to use. They are, however, not designed for or evaluated in contexts characterized by much biomass burning, regular power interruptions and/or low internet coverage, typical for low-income countries. Alternatively, local teams can build a sensor system with $PM_{2.5}$ sensors from Original Equipment Manufacturers (OEM). Existing African OEM projects depend on international partners and funding. This puts the affordability for local teams without funding into question. Furthermore, field comparisons of such sensors for ambient concentrations and indoor settings are rarely conducted in low-income contexts. In Arba Minch, Ethiopia, we developed a sensor system (SPSA) with the OEM Sensirion SPS30 and other components, together with an Arduino microprocessor, with LoRaWAN data transmission. We used the hardware and software in multiple configurations. The SPSA was used in 14 contexts typical for Ethiopia. During these tests we encountered problems that were easily solved by maintenance on location. On seven locations we collocated the SPSA with itself, gravimetric instruments and/or SSys. Amongst SPSA we found coefficients of determination (R^2) of at least 0.98 for three ambient and one indoor location. The accuracy in comparison with the gravimetric method was 16% under ambient and 13% under indoor circumstances. This is lower than the internationally required 25%. The R^2 in comparison to two SSys was 0.91-0.98 under ambient and 0.88-1.00 under indoor circumstances. The SPSA is a versatile sensor system that can be used in both ambient and indoor air pollution circumstances. Local development without international partners and funding resulted in local experience gaining, low costs, local ownership, and the possibility of tailoring the system to local needs regarding power and connectivity.

Amharic abstract

ጥቂት የመለኪያ መሰሪያዎች ብቻ ባሉባቸዉና $PM_{2.5}$ ጋር በተያያዘ በሽታ ከምስ። ገበያ ላይ የሚገኙ ሴንሰር ሲስተሞች (SSys) በአንጻራዊነት ሲታዩ ተመጣጣኝ እና ለመጠቀም ቀላል ናቸው። ይሁን እንጂ እነዚህ ሴንሰሮች ብዙ ባዮማስ (ተረፈ ምርት) በሚቃጠልበት፣ መደበኛ የሃይል መቆራረጥ እና/ወይም ዝቅተኛ የኢንተርኔት ሽፋንና ዝቅተኛ ገቢ ያላቸውን አገሮችን ሁኔታ ከግምት ዉስጥ በማስገባት የተነደፉ ወይም የተገመገሙ አይደሉም። ተጠቃሚዎች በአማራጭነት የአገር ዉስጥ ኦሪጂናል የፋብሪካ ዉጤቶችን (OEM) በመጠቀም የ $PM_{2.5}$ ሴንሰሮችን መስራት ይችላሉ። አሁን ላይ ያሉት የአፍሪካ የኦሪጂናል ዕቃ አምራች ፕሮጄክቶች በአለም አቀፍ አጋሮች እና የገንዘብ ድጋፍ ላይ የተመሰረቱ ናቸው። ይህም ያለ የገንዘብ ድጋፍ የሚሰሩትን የሀገር ውስጥ ተመራማሪዎችን አቅም ጥያቄ ውስጥ ይከታል። በተጨማሪም እነዚህን ሴንሰሮች በመጠቀም የቤት ዉስጥና የዉጭ አየር ብክለት መጠን ማነጻጸር በታዳጊ አገሮች ላይ እምብዛም አይካሄዱም። በዚህ ምርምር በአርባ ምንጭ OEM Sensirion SPS30ን እና ሌሎችንም እቃዎች ከአርዱኖ ማይክሮፕሮሴሰርና LoRaWAN ዳታ ማስተላለፊያ ጋር በመጠቀም ተሰርቷል። በዚህም መሰረት የተለያዩ ሃርድዌሮችንና እና ሶፍትዌሮችን በበርካታ ውቅሮች ውስጥ ተጠቅመናል። ለኢትዮጲያ እንዲመች ተደርጎ በ14 የተለያዩ ቦታዎች ላይ ጥቅም ላይ አዉለነዋል። በነዚህ ሙከራዎች ወቅት በቦታው ላይ በተደረገ ጥገና በቀላሉ የሚፈቱ ችግሮች አጋጥመውናል። በሰባት ቦታዎች ላይ SPSAን ከራሱ፣ ከግራቪሜትሪክ መሳሪያዎች እና/ወይም SSys ጋር አቀናጅተን አስቀምጠናል። በዚህም መሰረት SPSAን በመጠቀም በሶስት የዉጪ እና በአንድ የቤት ዉስጥ ሴንሰሮች ላይ የመገናኘት መጠን (R^2) 0.98 አግኝተናል። የትክክለኛነት መጠኑም ከግራቪሜትሪክ ዘዴ ጋር ሲነጻጸር በከባቢ አየር (ከቤት ዉጪ) 16% እና በቤት ውስጥ ሁኔታዎች ውስጥ 13% ነው፡፡ ይህም በአለም አቀፍ ደረጃ ከሚያስፈልገው 25% ያነሰ ነው። R^2 ከሁለት SSys ጋር ሲነጻጸር 0.91-0.98 በቤት ዉጭ እና 0.88-1.00 በቤት ውስጥ ሁኔታዎች ውስጥ ነበር። SPSA ሁለገብ ሴንሰር ስርዓት ሲሆን በሁለቱም የአካባቢ (ከቤት ዉጪ) እና የቤት ውስጥ የአየር ብክለት ሁኔታዎች ውስጥ ጥቅም ላይ ሊውል ይችላል። በዚህም መሰረት የአገር ውስጥ ልማት ያለ ዓለም አቀፍ አጋሮች እና የገንዘብ ድጋፍ የሀገር ውስጥ ልምድን በማስገኘት ፣ ዝቅተኛ ወጪ በማስወጣት ፣ የአካባቢ ባለቤትነት በማስገኘት እና ስርዓቱን ከኃይል እና ተያያዥነት ጋር ለአካባቢያዊ ፍላጎቶች የማበጀት እድል አስገኝቷል።

Keywords

ambient air pollution, indoor air pollution, $PM_{2.5}$, low-cost sensor, Sensirion SPS30, measurement network, Arduino

Introduction

Air pollution is amongst the top risk factors for the global disease burden (Babatola, 2018; Shaddick et al., 2018), placed second for data of 2019 (IHME, 2021). This burden is relatively higher in low-income countries, due to sources like open waste burning and cooking with biomass fuel (World Health Organization, 2021, 2022). Paradoxically, 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 ($PM_{2.5}$) (World Health Organization, 2021). The reference method for monitoring $PM_{2.5}$ is filter-based gravimetry. This method typically assesses concentrations on a 24-hour average level (EPA, 2006; European Commission, 2010), and is associated with high operating costs (Sousan, Regmi and Park, 2021). Various continuous monitors (monitoring concentrations at hour- or even second level) are recognized as equivalent to the reference method, such as the Beta Attenuation Monitor (BAM), the Tapered Element Oscillating Microbalance (TEOM), and Palas Fidas. These are expensive as well, with costs of $11 500 – $30 000 per monitor (Mooney, Willis and Stevenson, 2006), and technically still need calibration to the gravimetric reference method. In high-income countries the application of such monitors is widespread, and measured data is usually openly available. For African countries, however, only few have some coverage (Subramanian and Garland, 2021).

A promising trend is the development of low-cost sensors (LCS). Karagulian et al. (2019) distinguish two types of LCSs: only a sensor as developed by original equipment manufacturers (OEM) and sensor systems (SSys), which combine an OEM with encasing, sampling system, power system, hardware, software, and data acquisition methods. SSys cost between $200 and $500, whereas self-built systems with OEMs for measuring $PM_{2.5}$ can be created for $50. Using SSys does not require skills in programming and electronics, but their internet and power requirements are challenging (Sewor, Obeng and Amegah, 2021). Moreover, SSys are still expensive for African researchers (Subramanian and Garland, 2021), and data ownership of data collected through the network functionality lies with the producer. These issues plea for a focus on OEM. Creating an own system based on an OEM is cheaper, and the users can decide to combine the OEM with alternative energy sources (power bank, solar panel) and network connectivity (LoRaWAN, GSM), according to their context. This makes OEMs more compatible to local climates (Subramanian and Garland, 2021). Working with OEMs requires programming and electronics proficiency. When a local team develops a setup with an OEM, there is local experience gaining, local ownership of instruments and data, and local decision making. Apart from making a system with an OEM locally, it is important to evaluate it under the conditions where it will be used. Parameters such as particle density, particle hygroscopicity, refraction index, and particle composition strongly affect the operational principle of $PM_{2.5}$ LCS (light scattering). All these factors vary from site to site and with seasonality (Karagulian et al., 2019). Open biomass burning, cooking with biomass fuel and older vehicles are air pollution sources typical for a low-income country. The data quality of an OEM should be evaluated under such circumstances.

Three examples of OEM projects in the African continent are https://sensors.africa/air (OEM SDS011), Ngom et al. (2018) (OEM HK-A5) and Airqo.net (Bainomugisha, Ssematimba and Okure, 2023; OEM Plantower PMS 5003). Sensors.Africa and AirQo have international partners and funding. This raises the question whether local development without funding is possible. Furthermore, we only found field tests of data quality in a low-income country context for AirQo. Adong et al. (2022) compared the AirQo to a BAM at two ambient locations in Kampala, Uganda. We did not find any field comparisons under indoor air pollution circumstances for these OEM projects.

Dingemanse (2022) presented the evaluation of three LCS under field conditions in Arba Minch, Ethiopia. One of these LCS was a locally developed system with the OEM Sensirion SPS30 and an Arduino microprocessor. In this article, we present this system and show the field evaluation in more detail. We refer to this system as SPSA, named after the sensor (SPS) and the microprocessor, being Arduino (A). The SPSA has a power back-up and can transmit its data with LoRaWAN technology. This makes the setup compatible with a context that often lacks stable power supply and WiFi. We conducted extensive field comparisons in Ethiopia, at three ambient and four indoor high concentration locations. We collocated the SPSA with itself, with a gravimetric measurement instrument, and with two SSys: IQAir Airvisual Pro (the SSys of Airvisual, which is the largest real-time air quality databank (Wernecke et al., 2021)) and PATS (designed for indoor air pollution measurements). We developed the system and conducted the field comparisons without funding.

The next part of the article includes a description of the system we used and evaluated, followed by an evaluation of its operational reliability and an evaluation of the data quality. This article ends with a discussion and conclusion on the implications of the operational reliability, data quality and field evaluations in general. While we included all parts of a working sensor system with network aspect, our aim is not to present a finished product. Rather, it is a showcase of the potential of Do-It-Yourself development with OEM within Ethiopia. Our unique contributions are the presentation of a sensor system developed locally without international partners or funding, and field tests of this system across both ambient and indoor circumstances in Ethiopia. These are the first field tests of the OEM SPS30 in a low-income country. We hope it inspires the reader to conduct similar projects, including field comparisons, in low-income country contexts. All software and data analysis code and raw data, used in this study, is shared on an OSF repository: https://doi.org/10.17605/OSF.IO/DXEZ8.

Set-up description

Hardware

Components and connections

Core components of the system are a $PM_{2.5}$ sensor, SD card module and Real Time Clock (RTC), connected to a microprocessor. Optional components include a Relative Humidity sensor, LoRaWAN communication shield and LED control light. Table 1 gives an overview of the components.

Table 1: *SPSA components.*

No.	Component	Description
1	Arduino Mega 2560	Microprocessor
2	SPS30 Sensirion	$PM_{2.5}$ sensor
3	DS3231	Real Time Clock
4	Micro SD card reader	Module for SD card, for offline data storage
5	BME280	Relative humidity and temperature sensor
6	Dragino LoRa shield	Module for transmission of data over Long Range (LoRa) network, 868 MHz
7	LED	Green LED for instrument status

The Dragino LoRa Shield is a premade component that fits directly on the pin configuration of the microprocessor. Other components of the system are connected to the main circuit board via shielded connecting wires. The wires are kept short, less than 10 centimeters, to avoid electromagnetic interference and crosstalk. Power supply connections are shared to avoid wiring complexity. Also, the SDA and SCL connection points are shared between the SPS30 and DS3231. Figure 1 shows a sketch of the circuit.

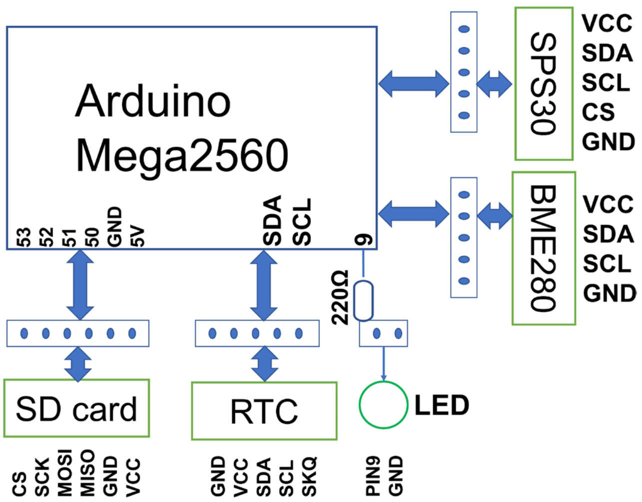

Figure 1: *Sketch of the SPSA circuit. LoRaWAN is not included in the sketch; the Dragino LoRa shield is premade to fit directly on the normal Arduino Uno or Mega pin layout.*

Configurations

The SPSA hardware was combined with a power bank in plastic boxes (lunch boxes or plastic cups). The boxes were chosen based on availability on the local market and the intended use. Three configurations have been used:

- C1: A larger box for stationary sampling, including LoRa and BME280
- C2: A smaller box for stationary sampling, without LoRa and BME280
- C3: A cup-box for personal sampling, without LoRa and BME280.

Figure 2 shows photos of the three configurations.

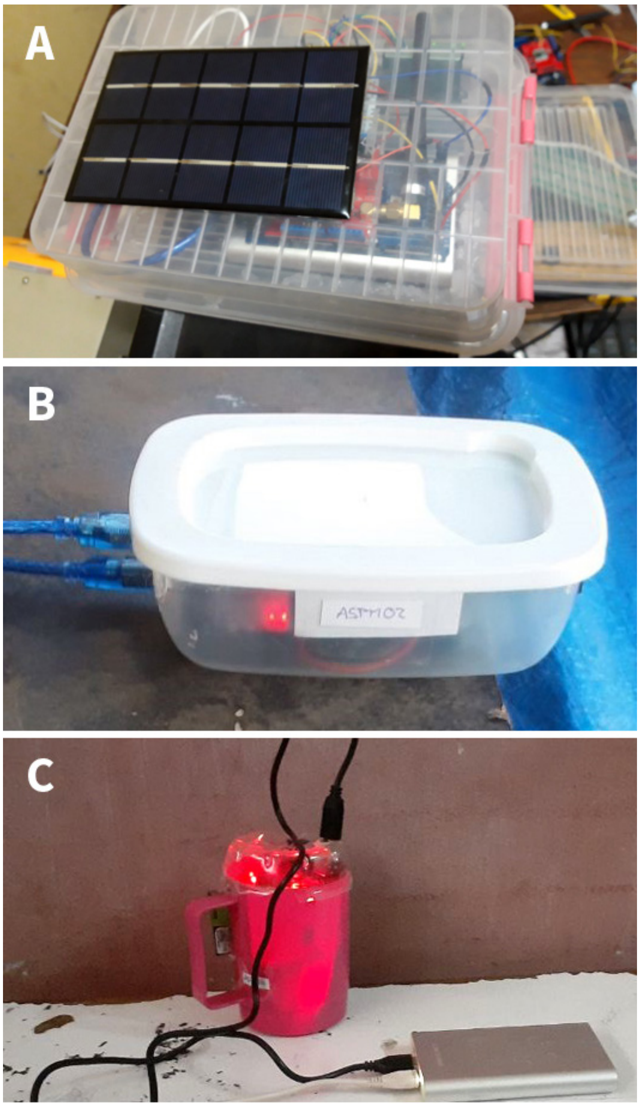

Figure 2: *Configurations of the SPSA. (A) Stationary sampling box with LoRa and BME280. (B) Stationary sampling box without LoRa and BME280. (C) Personal sampling box without LoRa and BME280.*

The air sampling and ventilation openings of the SPS30 are at the frontside of the sensor. In the plastic boxes a hole the size of the SPS30 was cut, and the SPS30 was placed through the hole for approximately 5 millimeters. In this way, the sensor was exposed to the ambient air while keeping most of the sensor safe inside the box. Also, because the hole was exactly sized to the SPS30, movement of the sensor within the SPSA was not possible. All other components were kept at their place with glue. For configuration C1, the BME280 air and humidity sensor was placed outside the box. A hole was cut inside the box for exactly the size of the BME280 wires. Configuration C3's casing was a cup, so that it could be fixed to a belt.

Power consumption

Based on their respective data sheets, the power consumption of the SPSA components is as follows:

1. Arduino Mega 2560: 5 V x 50 mA = 250 mW.

2. SPS30: 5 V x 80 mA = 400 mW.
3. DS3231: 5V with a maximum of 0.65 mA = 3.26 mW. A rechargeable battery is included as back-up.
4. Micro SD card with adapter: maximum standby current of 1 mA x 5 V = 5 mW.
5. BME280: 0.0036 mA at 3.6 V = 0.013 mW.
6. LoRaWAN: 5 V x 32 mA = 160mW during transmission, and 5 V x 1 mA = 5 mW during sleep mode. This transmission is used once every five minutes. We assume a transmission time of maximum 20 seconds. This results in per hour 20 * 12 = 240 seconds of transmission mode, and remaining time sleep mode.
7. LED: 40 mA x 5 V = 200 mW when in use. A blink time of 0.2 seconds is used per minute, leading to a usage time of 0.2 * 60 = 12 seconds per hour.

Table 2 gives an overview of the SPSA hourly power consumption.

Table 2: *Power consumption calculation for the SPSA.*

No.	Component	Consumption (mW)	Operation time %	Average hourly consumption mW
1	Arduino Mega 2560	250	100	250
2	SPS30 Sensirion	400	100	400
3	DS3231	3.25	100	3.25
4	Micro SD card reader	5	100	5
5	BME280	0.013	100	0.013
6	Dragino LoRa shield	Transfer mode: 160 Sleep mode: 5	7 93	10.7 47
7	LED	ON mode 200 OFF mode 0	0.3	0.7
	Total			674

Most commercial power banks have a capacity of 6-10 Ah at 5 V. In case of connection to an irregular power grid, a 6 Ah power bank can provide back-up power during power interruptions for 6 Ah / (0.674 W / 5 V) = 44 hours. In combination with a 1.5 W solar panel, the power bank can be charged during daytime and used during nighttime. The battery capacity for 12 hours, including a maximum depth of discharge of 20%, should then be (0.674 W * 12 h) * 1.2 / 5 V = 1.94 Ah.

Introduction of a sleep mode for the SPS30 can decrease power consumption. Under certain conditions, it is possible to achieve the same monitoring quality through point measurements taken every 15 minutes. This would reduce the power consumption of the SPS30 sensor with at least 90%. As a result, the total system consumption would drop to 314 mW from its current level of 674 mW.

Software

Figure 3 shows a flowchart of the SPSA operation process.

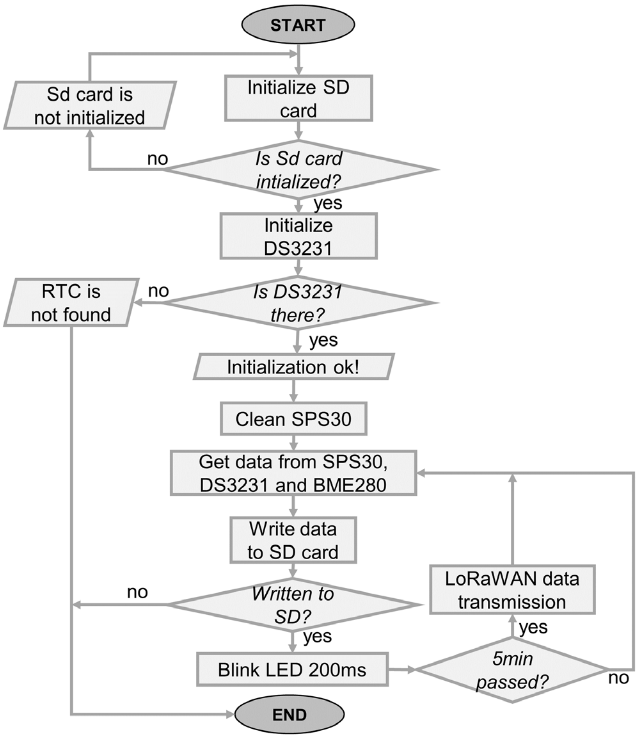

Figure 3: *Flowchart of software on the SPSA.*

SPSA software

Three versions of software have been used:

- For C1, 1-minute average
- For C2, 1-minute average (C2_1)
- For C2 and C3, 10-second point measurement (C2_2 and C3).

All three software scripts are included in the supplementary materials and available at the OSF repository (https://doi.org/10.17605/OSF.IO/DXEZ8).

LoRa network software

With LoRa functionality, data is sent to a gateway. The gateway is registered at The Things Network (TTN; https://www.thethingsnetwork.org/). If the receiving gateway is connected to the internet, the data is stored on the TTN server for seven days. Within those seven days, data can be retrieved from the server. For proof of concept, we created Python code for the following tasks:

- Retrieving data from TTN
- Creating a graph of the data
- Uploading a graph to a website.

Example code is uploaded to the OSF repository (https://doi.org/10.17605/OSF.IO/DXEZ8). If this code runs on an online server, data sent over LoRa can be turned into online visualizations. This creates a real-time measurement network. This data transmission method can also be used to check the SPSA, such as the general operation, the real-time clock, and the measured values.

Operational reliability evaluation

This section discusses to what extent the SPSA, our setup, is operationally reliable in the context of Arba Minch and Addis Ababa. The evaluation methodology section describes how the SPSA is used under different circumstances. The operational reliability section describes the findings on operational reliability based on this use.

Evaluation methodology

The SPSA is used under various circumstances: indoor and outdoor, stationary, and mobile and in high concentration and low concentration environments. For stationary measurements, the instruments were placed between 1.5–2.5 meters above the ground. Mobile measurements have been taken by placing the instrument in the frontside of a public transport tricycle, or by letting students walk around with the instrument on a belt (personal sampling). Most measurements have taken place in Arba Minch, but two set-ups have been installed in Addis Ababa. A full overview of measurement circumstances is given in Table 3.

Measurements at locations A1-A3 and K1-K4 were conducted for an evaluation of the SPSA data quality. These locations are selected for their distinct ambient and indoor concentration levels. Regarding these locations, more information is given under the measurement locations section of the data quality evaluation. Other measurements were part of student measurement projects. Locations and durations were chosen by the students.

In situations 4, 8, 9 and 14, the instruments were used with a power bank that was charged before each use. In all other situations a continuous power supply was maintained by connecting the instruments to the grid via the power bank.

In situations 1, 2, 10 and 11 the SPSA was deployed with LoRa functionality. Two gateways were installed in Arba Minch. A full network structure including database was not yet built. Instead, the focus was on ‘proof of concept’: for a certain time having the gateways up and testing the reception at different distances.

Operational reliability

This section describes the experiences related to the operational reliability of the SPSA which were gained while conducting the measurements as described in the evaluation methodology section.

Instrument

Single SPSAs functioned well in all measurement locations, except for the following three issues:

- In the first period of field measurements (No. 1, 2), one type of SD cards (brand FFFAS, 16 GB) malfunctioned. After it happened in multiple SPSAs, other brands of SD cards were used.
- In some cases (No. 1, 2, 3 7, 8, 14), the battery of the Real Time Clock died, resulting in a reset of the time. In most cases, data could be restored by comparing the (wrong) time on the instrument with the actual time, and changing the time based on that difference. Validation of this was done based on comparison with collocated sensors and occurrence of daily concentration peaks.
- In two cases (No. 1 and 2), an SPS30 sensor was giving extremely high values without an air pollution source nearby. The sensors in question were replaced.

Table 3: *Details on measurement locations of the SPSA, including per location the SPSA type, number of SPSAs (#) and the amount of data collected at that location (data quantity)*

No.	Measurements		Measurement location		SPSA		Data quantity
	Type	Method	ID	Description	Type	#	
1	Ambient	Stationary	A1	Arba Minch, quiet neighborhood	C1	3	9889 hours
2	Ambient	Stationary	A2	Arba Minch, center	C1	2	3874 hours
3	Ambient	Stationary	A3	Addis Ababa, Tikur Anbessa area	C2_2	2	12 642 hours
4	Ambient	Stationary	A4	Quiet road, entrance to university	C2_1	1	321 hours
5	Ambient	Stationary	A5	Arba Minch, busy traffic square	C2_1	1	643 hours
6	Ambient	Stationary	A6	Arba Minch, busy traffic square	C2_1	1	687 hours
7	Ambient	Stationary	A7	Arba Minch bus-station	C2_1	1	258 hours
8	Ambient	Mobile	A8	Arba Minch public transport tricycle	C2_2	1	265 hours
9	Ambient	Mobile	A9	Arba Minch public transport tricycle	C2_2	1	259 hours
10	Indoor	Stationary	K1	Next to wood cooking kitchen, in same room charcoal burning	C1	1	993 hours
11	Indoor	Stationary	K2	In kitchen, above wood cooking location	C1	1	96 hours
12	Indoor	Stationary	K3	Wide kitchen, various wood cooking places	C2_2	2	457 hours
13	Indoor	Stationary	K4	Wide kitchen, various wood cooking places	C2_2	2	377 hours
14	Ambient & indoor	Mobile	P1	Student personal sampling	C3	3	647 hours

Despite the above-mentioned problems, many hours of data have been collected. This shows that the SPSA is operationally reliable. The setup was able to collect data under ambient (1-7), on-road mobile (8,9), indoor (10-13) and personal (14) circumstances. It could be used by staff (No. 1-3, 10-13) and students (No. 4-9, 14). Regular check-up is advisable, considering the above-mentioned problems. However, we found that also without check-up some systems could operate without errors for a long period. In Addis Ababa (No. 3) the instruments were installed in July 2022. For logistical reasons there was no check-up from the end of July 2022 until May 2023.

Network

The network potential of a group of SPSAs works well with LoRa. The transmission over LoRa is largely dependent on the proper placement of the gateway. Messages have been received over an 8 km distance. This reception is greatly influenced by obstruction of line-of-sight. One gateway received significantly less messages from the direction where a large building was obstructing line of sight to the SPSA. For about two weeks a full 'network' was running: SPSAs with LoRa functionality were deployed, gateways were up and running, and the Python scripts, as listed in the LoRa network software section, ran on an hourly interval at a Virtual Private Server. During those weeks, an hourly updated real-time graph showed live $PM_{2.5}$ concentrations on various locations in Arba Minch.

Data quality evaluation

This section discusses the field testing we conducted with the SPSA for the purpose of data quality evaluation. The evaluation methodology section discusses the methodology we use for evaluating data quality. The concentration patterns section displays what concentrations were measured (to validate that measurements were taken under various conditions). The remaining sections show the data quality metrics for the three comparison types we used: within, gravimetric and SSys.

Evaluation methodology

Measurement locations

Table 3 listed 14 locations where the SPSA has been used. For data quality evaluation, three ambient locations (A1-A3) and four indoor locations (K1-K4) were selected. Only at these locations, the SPSA was collocated with itself and/or other instruments. For the three ambient locations, sources of $PM_{2.5}$ are traffic and neighborhood biomass burning. The three ambient locations represented three distinct concentration levels. Two locations were in Arba Minch, and one location in Addis Ababa, sub-city Lideta. According to latest projections, population of Arba Minch town, Addis Ababa, and its sub-city Lideta are 210 255, 3 945 000 and 290 466, respectively (Ethiopian Statistics Service, 2023). The population in Addis Ababa is higher than in Arba Minch, and the number of vehicles per person is also higher. As per 2020, Addis Ababa had registered 630 440 vehicles, while the region SNNP (of which Arba Minch is a part), with a population estimation of 13 044 044, had registered 118 424 vehicles (Abiye, 2020). Location **A1** was in front of a house in a quiet neighborhood in Arba Minch (latitude 6.01589 N, longitude 37.55480 E). At the compound of this house, cooking only is done with electric stoves. The nearest road to this location is approximately 120 meters, and this road is only used by local traffic. Location **A2** was at the entrance of a hotel compound in the center of Arba Minch (latitude 6.03311 N, longitude 37.55783 E). The instrument was approximately 15 meters from the nearest road. This road is the main road through Arba Minch. It is used by traffic driving through Arba Minch, and by stopping and starting traffic visiting businesses. Location **A3** was in Addis Ababa, sub-city Lideta, at the city monitoring station of the Ethiopian Meteorology Institute (latitude 9.01888 N, longitude 38.74728 E). This location is approximately 10 meters from the nearest road.

The four indoor locations were selected for their use of biomass fuel, to represent (extremely) high and variable concentrations. All four locations were in Arba Minch. Location **K1** was in a small local restaurant, in a room connected to the kitchen. In that room, charcoal fire was used for coffee preparation. In the kitchen, food was prepared with biomass fuel. Location **K2** was in the kitchen of a student restaurant. In this kitchen, food was prepared with biomass fuel. Locations **K3** and **K4** were in a large kitchen with more than six biomass fuel cooking locations. These two locations were on opposite sides of the kitchen, and cooking fires closest to the respective locations were used at different times. For this reason, these locations are considered separate.

Measurement comparison types

We evaluate data quality by comparing measurement results of an SPSA with instruments that are collocated. Three types of measurements have been conducted for data quality evaluation. The **first** type compares measurement results of SPSAs amongst each other (*within* comparison). We placed multiple SPSAs in the same location.

The **second** type compares SPSA with a gravimetry instrument (*gravimetric* comparison). Reference measurement methods for $PM_{2.5}$ are based on gravimetry. As gravimetric instrument, we used the Ultrasonic Personal Aerosol Sampler (UPAS), as this instrument was the only available gravimetric instrument in Arba Minch, Ethiopia. The UPAS is designed for measuring medium to high concentrations. Over ranges of 20–1000 µg/m^3, Volckens et al. (2017) found strong correlations with the EPA federal reference method. Afshar-Mohajer et al. (2021, p. 131) found that 'the UPAS may be a suitable alternative for [Respiratory Dust] mass sampling' for ranges of 100–500 µg/m^3 in occupational settings. We conducted gravimetric analysis of the filters with a Mettler AE240 Dual Range balance. This balance has a readability of 10 µg and a reproducibility of ±20 µg (IET, no date).

For Addis Ababa (3), there were no gravimetric measurements taken by us. At another location (Jacros area, Addis Ababa, distance to location A3 8 km, latitude 9.01163 N, longitude 38.82151 E), the US Embassy operates a BAM. A BAM is

Table 4: *Overview of measurements used for the data evaluation of the SPSA. Individual SPSAs are labeled Spx, where x refers to the setup ID number. IQAV and PATS are coded Iqx and Pax, respectively.*

Location	SPSA	Gravimetry	SSys	Period[1]
A1	Sp1, Sp2		Iq2	April 2021 – April 2022
A2	Sp3, Sp5	UPAS (3 samples)	Iq1	June 2021 – October 2021
A3	Sp11, Sp12	Indicative: BAM, gravimetry	Iq7, Iq10	July 2022 – April 2023
K1	Sp2, Iq5		Iq5	June 2021 – August 2021
K2	Sp4, Iq3	UPAS (3 samples)	Iq3	1–5 October 2021
K3	Sp6, Sp7	UPAS (2 instruments, both 4 samples)	Pa1, Pa3, Pa4	7–18 June 2022
K4	Sp8, Sp9	UPAS (4 samples)	Pa2, Pa5, Pa6	7–18 June 2022

[1] Not all instruments were available during the whole period. Therefore, the relationship between the number of data pairs in evaluations and the period duration is not linear.

Table 5: *Data quality metrics.*

Metric	Source	Requirement	Scope[1]	Calculation method
Slope (S) and coefficient of determination (R^2)	Often used	R^2>0.75 (R^2>0.9 'very good')	All	Calculation resulting from Ordinary Least Squares (OLS) regression without intercept.
Coefficient of Variation (CV)	EPA, NIOSH	<10%	Within	$CV = \frac{1}{n}\sum\frac{\sigma_i}{\mu_i}$, where σi is the standard deviation and μi is the mean of measurements of identical LCS during time period i, and n is the number of time periods.
Between-sampler uncertainty (u_{bs})	DEM	<2.5 μg/m³	Within, ambient, daily	$u_{bs} = \sqrt{\frac{\sum(y_{i,1}-y_{i,2})^2}{2n}}$, where $y_{i,1}$ and $y_{i,2}$ are the results of parallel measurements for time period i, and n is the number of time periods.
Pearson correlation coefficient (r)	EPA	>0.97	Gravimetric	
Bias (B)	NIOSH	Correction if >10%	Gravimetric	$B = \frac{1}{n}\sum(\frac{x_i}{y_i} - 1)$, where x_i is the concentration of the LCS and y_i the concentration of the reference instrument for time period i, and n is the number of time periods. Corrected data xnew based on the old data x_{old} was calculated with $x_{new} = \frac{x_{old}}{B+1}$
Accuracy (Ac)	NIOSH	<25%	Gravimetric	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. We used the names $Ac_{\_BC}$ and $Ac_{\_AC}$ to distinguish between accuracy before and after bias correction, respectively.

[1] Not all metrics apply in all situations. Where applicable, the table lists the scope of application with respect to type of comparison (within, gravimetric, SSys), time-averaging period (10-minute, hourly, daily, filter-duration or monthly) and/or context (ambient, indoor).

Table 6: *Data quality evaluation summary.*

Evaluation	Time periods[1]	Metric	Locations
Within (SPSA versus SPSA)	1,2,3 1,2,3 3	S & R^2 CV u_{bs}	A1-A3, K3, K4 A1-A3, K3, K4 A1-A3
Gravimetric (SPSA versus gravimetric method) *Indicative* comparison	4 4 4 4 3, 5	r S R^2 B & Ac S & R^2	A2, K2- K4 A2, K2-K4 A2, K2-K4 A2, K2-K4 A3
SSys (SPSA versus IQAV or PATS)	2,3	IS & R^2	A1-A3, K1-K4

[1] We conducted data quality evaluations at time periods 10-minute (1), hour (2), day (3), filter-duration (4) and month (5).

recognized as equivalent to the gravimetric reference method. Data of this BAM is available online (AirNow Department of State, 2023). We used measurements of this BAM for *indicative* comparison: indicative because the BAM and SPSA are not at the same location. Location A3 is within the city ring roads, while the location with the BAM is closer to the outskirts of Addis Ababa. A second source of indicative comparison is a gravimetry measurement project at the same location as our measurements (A3). During November 2015 – November 2016, Tefera et al. (2020) collected 69 $PM_{2.5}$ samples. Their measurement method is the official $PM_{2.5}$ reference method (gravimetry), and their measurements are at the same location, but their measurements are not during the same time period. We used these measurement results as indicative comparison with respect to the long-term concentration level.

The **third** type compares measurements of the SPSA with two SSys (*SSys* comparison): Airvisual Pro (IQAV) and UCB-PATS+ (PATS). Like the SPS30 in our system, both IQAV and PATS estimate the $PM_{2.5}$ concentration based on scattering of infrared light (Pillarisetti et al., 2017; Zamora, Rice and Koehler, 2020; Sousan, Regmi and Park, 2021). 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. We used the IQAV both in ambient and indoor situations. The IQAV is not meant for very high concentrations (>5000 µg/m³), because the highest reported value of the IQAV is set to 4488 µg/m³.

Table 4 shows an overview of all measurements used for data quality evaluation.

Data corrections

In their guidelines for Demonstrating Equivalence of Ambient Air Monitoring Methods (DEM) the European Commission (2010) allows for removal of up to 2.5% percent of outliers based on Grubb's outlier test at 99% level. We removed outliers with this method for Sp3 and Sp5 at location A2, and for Sp11, Sp12, Iq7 and Iq10 at location A3.

The Sp11 and Sp12 comparison is only done from October 2022, because up to that time there was a real time clock (RTC) issue for Sp11. In contrast, the Sp12 / IQAV comparison could only be done with measurements until October 2022, because after October 2022 both Iq7 and Iq10 malfunctioned.

At locations K3 and K4, there was data loss during the gravimetric measurements. We did not use LCS results with more than 15% data loss during measurements with the gravimetric method in the gravimetric comparison.

Data analysis

Metrics for expressing equivalence of instruments that are reported most often, are Slope (S) and a coefficient of determination (R^2) originating from Ordinary Least Squares (OLS) regression. Official guidelines for testing the equivalence of $PM_{2.5}$ measurement methods have been made by the Environmental Protection Agency of the United States of America (EPA) (EPA, 2006), the National Institute for Occupational Safety and health (NIOSH) (NIOSH, 2012), and by the European Commission in the Guide to the Demonstration of Equivalence of Ambient Air Monitoring Methods (DEM) (European Commission, 2010). Evaluation metrics are taken from these sources and summarized in Table 5.

The DEM also prescribes expanded uncertainty (WCM) for ambient reference comparison. That metric applies to reference comparison at 24-hour level. With the gravimetric method available in our study (the UPAS) it was not possible to conduct 24-hour comparison measurements under ambient circumstances. Although Dingemanse (2022) reported this metric, we did not include it in our study.

For data-analysis, we used five time-averaging periods: 10-minute, hour, day, filter-duration, and month. Hour-averages are most used in monitoring networks, while daily averages represent the short-term WHO $PM_{2.5}$ guideline value. Filter-duration is used in the gravimetric comparison, where the duration varied according to the time needed to get sufficient filter load. We only used monthly averages for the indicative comparison. For the SPSA inter-comparison, we also present 10-minute averages. Table 6 shows a summary of the data quality evaluation.

Concentration patterns

Figure 4 shows the average and 95-percentile concentrations per 10-minute period on a day, for locations A1, A2 and A3. This is not meant to compare locations, since they are not from the same time. It is merely to show the order of magnitude of measured concentrations.

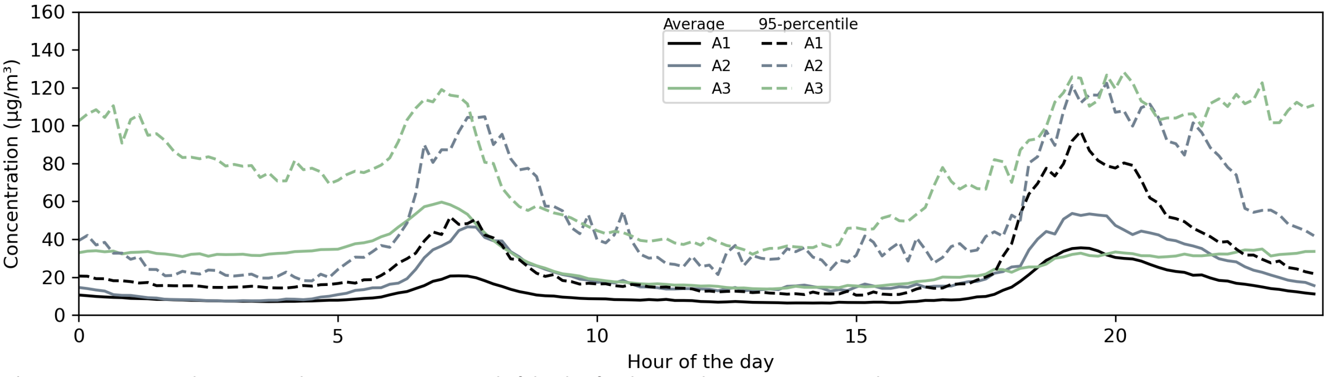

Figure 4: *Average and 95-percentile per 10-minute period of the day for three ambient measurement locations.*

***Table 7:** Number of data pairs (N) and data quality metrics for two collocated SPSAs. The results are ordered according to location and time averaging period.*

Averaging period	Parameter	Location A1		Location A2	Location A3	Location K3	Location K4
		Sp1/Sp2	Sp1/Sp4	Sp3/Sp5	Sp11/Sp12	Sp6/Sp7	Sp8/Sp9
Daily	N Slope (R^2) CV[1] [%] u_{bs} [µg/m³]	5 0.94 (1.00) 5.1 0.63	66 1.04 (1.00) 0.34	84 1.05 (1.00) 3.3 0.73	205 1.10 (1.00) 7.0 1.65	11 1.08 (1.00) 5.3	11 1.13 (1.00) 6.6
Hourly	N Slope (R^2) CV[1] [%]	101 0.94 (0.99) 4.8	1539 1.03 (1.00)	1600 1.05 (1.00) 3.6	4909 1.09 (0.99) 8.7	218 1.07 (1.00) 6.2	140 1.14 (0.78) 6.6
10-min	N Slope (R^2) CV[1] [%]	599 0.93(0.98) 5.4	9211 1.02 (0.99)	9436 1.05 (1.00) 4.0	29 365 1.09 (0.99) 9.1	1294 1.07 (1.00) 6.3	788 1.10 (0.87) 5.7

[1] CV is calculated for any number of collocated instruments, instead of a single pair.

Average concentrations at locations A1, A2 and A3 are 12.6, 20.6 and 27.8 µg/m³, respectively. 10-minute average concentrations ranged up to 120 µg/m³, in Addis Ababa (A3) this happened both in the morning and in the evening.

Figure 5 shows box plots of 10-minute, hourly and daily averaged concentrations in the four indoor locations K1-K4.

Averages in the four indoor locations ranged from 300 to 2 000 µg/m³, with the highest 10-minute concentrations well over 10 000 µg/m³.

Collocated SPSA (*within* comparison)

Figure 6 shows data pairs for all collocated SPSA measurements, on different time averaging periods. Table 7 shows the data quality metrics.

Both Figure 6 and Table 7 show that multiple SPSA under the same circumstances show an extremely similar signal across all concentration ranges. At location K4, for the hourly and 10-minute averages the R^2 is 0.78–0.87. In all other cases the R^2 is at least 0.98. The CV is lower than the required 10%, and the ubs is lower than the required 2.5 µg/m³.

Gravimetric comparison

SPSA vs UPAS

Figure 7 shows the UPAS gravimetry and SPSA measurement results. Table 8 shows the data quality metrics.

Accuracy is sufficient in all cases (<25%). For ambient circumstances, the Pearson correlation is too low (<0.9). This most probably has to do with the fact that there have only been limited gravimetric measurements in ambient conditions (n=6). Both slope and bias show that under ambient conditions a calibration of a factor 2 is required. For indoor / high exposure conditions this is not required (|B| < 10%). This observation implies that the SPS30 sensor responds differently to aerosols primarily originating from biomass burning compared to those originating from a variety of ambient sources.

***Table 8:** Number of data pairs (N) and data quality metrics for SPSA compared to UPAS gravimetric measurements.*

Location	SPSA	N	r	S, R^2	A_{c_BC}	Bias	A_{c_AC}
A2	Sp3,5	6	0.70	1.93, 0.99	53	-0.47	16
K2-4	Sp6-9	21	0.99	0.95, 0.98	15	-0.08	13

Addis Ababa indicative comparison

Figure 8 shows daily and monthly averaged concentrations for Sp12 in comparison with a BAM at another location in Addis Ababa. Despite these not being on the same location, the correlation is good (R^2>0.9). This indicates that the SPSA follows the city-wide concentration trend.

On the same location, between November 2015 and November 2016 the average concentration for measurements with the gravimetric reference methods was 53.8 µg/m³ (Tefera et al., 2020). The average for 10 months of measurements with the Sp12 was 28.7 µg/m³. This indicates a factor two difference with the gravimetric method. This is similar to the calibration factor found between SPSA and gravimetry under ambient circumstances in Arba Minch (see the SPSA vs UPAS section).

Comparison with SSys

Table 9 shows the slope and R^2 for SPSA versus the two SSys, IQAV and PATS. It is shown for all hourly and daily averaged data pairs. For some locations there are multiple SPSA. At those locations, the SPSA which has the most data pairs with the collocated SSys is selected.

Correlations are high to both IQAV in ambient (R^2 0.91–0.98) and PATS in indoor (R^2 0.88–1.00) circumstances. For the IQAV we see similar slopes under similar circumstances. For the PATS there is a rather large variability in witnessed slopes. The IQAV under indoor circumstances gives estimations that are too low because all concentrations higher than 4488 µg/m³ are reported as 4,488 µg/m³. Table 10 shows correlation results between SPSA and IQAV for only <4489 µg/m³ data. For that data, slopes are substantially closer to 1, and R^2s are on average higher.

Table 9: *Data pairs comparison between the SPSA and SSys.*

Location	X	Y	Hourly		Daily	
			N	S (R^2)	N	S (R^2)
A1	Sp1	Iq2	7164	1.08 (0.93)	316	1.12 (0.96)
A2	Sp5	Iq1	1015	1.19 (0.91)	85	1.15 (0.97)
A3	Sp12	Iq7 Iq10	1516 1507	0.74 (0.96) 0.71 (0.95)	67 67	0.79 (0.98) 0.73 (0.96)
K1	Sp2	Iq5	942	0.10 (0.53)	48	0.16 (0.71)
K2	Sp4	Iq3	94	0.17 (0.93)	5	0.19 (0.98)
K3	Sp6	Iq3 Iq4 Iq5 Pa1 Pa3 Pa4	239 239 239 92 92 92	0.36 (0.91) 0.41 (0.92) 0.46 (0.92) 0.59 (0.98) 1.25 (0.88) 0.53 (0.99)	11 11 11 6 6 6	0.46 (0.96) 0.50 (0.97) 0.56 (0.96) 0.59 (0.99) 0.94 (0.97) 0.52 (1.00)
K4	Sp8	Iq6 Iq7 Iq8 Pa2 Pa5 Pa6	132 133 139 90 90 90	0.49 (0.74) 0.62 (0.83) 0.52 (0.90) 0.66 (0.93) 0.57 (0.93) 0.67 (0.90)	11 11 11 6 6 6	0.52 (0.99) 0.65 (1.00) 0.58 (0.99) 0.67 (1.00) 0.56 (1.00) 0.70 (0.98)

Table 10: *Data pairs comparison between the SPSA (only <4489 μg/m³) and IQAV.*

Location	X	Y	Hourly		Daily	
			N	S (R^2)	N	S (R^2)
K1	Sp2	Iq5	942	0.92 (0.90)	48	0.95 (0.99)
K2	Sp4	Iq3	94	0.42 (0.95)	5	0.46 (0.99)
K3	Sp6	Iq3 Iq4 Iq5	239 239 239	0.50 (0.94) 0.58 (0.95) 0.64 (0.92)	11 11 11	0.58 (0.99) 0.63 (0.99) 0.70 (0.99)
K4	Sp8	Iq6 Iq7 Iq8	132 133 139	0.58 (0.75) 0.74 (0.83) 0.62 (0.89)	11 11 11	0.60 (1.00) 0.75 (0.99) 0.66 (1.00)

Discussion

The implications of our showcase involve two areas: the operational reliability and the data quality in contexts as encountered in Ethiopia. In the operational reliability and data quality sections, we discuss these two areas subsequently. We discuss field testing in general in the field testing section.

Operational reliability

Regarding operational reliability it was found that not all systems were without errors. However, the problems were solved by replacing materials such as a sensor or a real time clock battery. A malfunctioning SSys requires shipment to the producer for repair. Our system simply needs replacement of the broken part, which can be done on location. However, to get reliable repair services, knowledge of both air quality and electronics, or a close collaboration with electronics staff is necessary.

The LoRa network functionality worked well if the sensors were placed outside. A network of LoRa will more likely become operational if additional setups, measuring other environmental data like soil and water quality, are used in the study area. As an alternative to LoRa, in bigger cities with stable internet connection, WiFi is an option. Most SSys use this to turn their systems into a network. Alternatively, GSM communication can be used. More generally, with an OEM-based self-built system the data transmission method can be chosen according to the local context. A SSys with WiFi instead forces the user to provide good internet connections or face data loss.

For upscaling the SPSA to a whole network of SPSAs, a higher level of organization is needed. Production, installation, maintenance, data collection and data distribution of many more systems are not likely run by a single initiative taker, such as was the case in this showcase. There are some examples of organized LCS application in the African continent. Awokola et al. (2020) describe the use of the SSys PurpleAir at 13 different sites across 7 African countries. Afriqair.org (Giordano and Jaramillo, 2021) is another African initiative that uses existing SSys (PurpleAir and MetOne). Working with a SSys, however, results in dependency on foreign funding, foreign expertise, specifications that are not necessarily designed for the local context, and it raises questions on data ownership. Local development with OEM sensors, instead keeps the costs lower, gives local staff the opportunity to gain expertise, gives the possibility for systems tailor-made for the local context and gives clear local ownership. We found three African initiatives that create their own sensor system with OEMs: https://sensors.africa/air (OEM SDS011), Airqo.net (Bainomugisha, Ssematimba and Okure, 2023; OEM Plantower PMS 5003), and Ngom et al. (2018) (OEM HK-A5). Sensors.Africa is based on the German initiative Luftdaten, which instead of a SSys has made their system build with OEM completely public and therefore useable by others. They are currently providing measurements in 11 cities across 7 African countries. AirQo.net is modelled after the SSys PurpleAir, since like the PurpleAir they use two Plantower PMS 5003 sensors in their system. They provide their sensor as African-made SSys, and have sensors installed in eight African countries. Both sensors.Africa and AirQo use WiFi to turn their systems into a network of data collection. Ngom et al. (2018) presented separate work of a sensor system used in Senegalese cities, with LoRa data transmission.

Data quality

Regarding the data quality, this case shows high concentration correlations between collocated instruments. This is especially the case for Arba Minch, where abundant measurements were conducted. Less evidence is gathered for Addis Ababa. The strong correlations between SPSAs show high instrument reliability. This implies calibration can happen in retrospect or with other studies. For ambient conditions, the results suggest a strong equivalence with the gravimetric method if calibration is conducted, but more evidence is required. For indoor circumstances, the strong correlation with the gravimetric reference method, in combination with the low bias, shows that the SPSA can be used without calibration. The strong correlations between measured concentrations of collocated

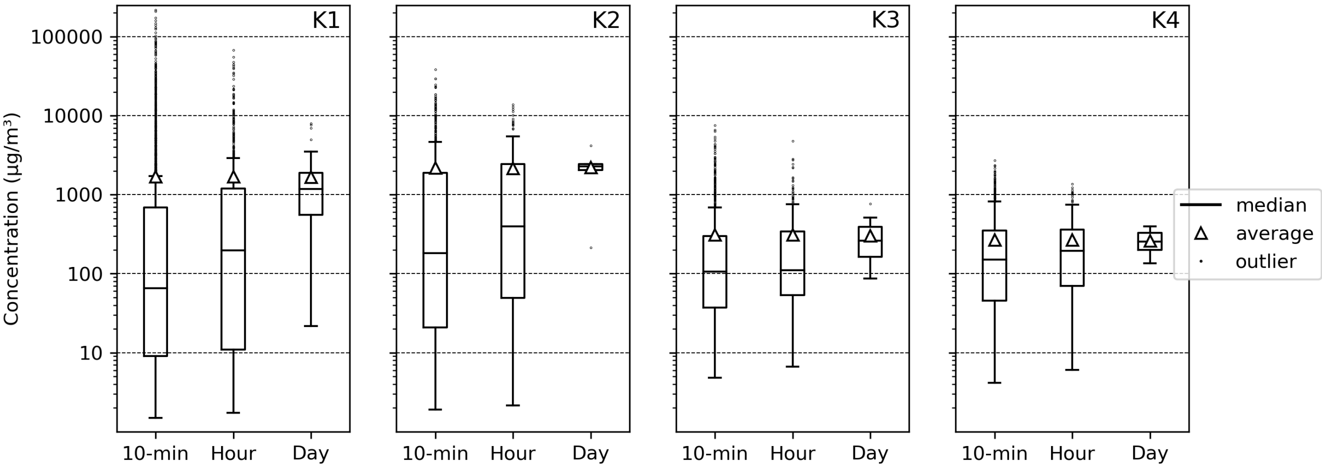

Figure 5: *Box plots of time averaged data for four kitchen locations (K1-K4). The boxes extend from the first quartile (Q1) to the third quartile (Q3) of the data. The whiskers extend from the boxes by 1.5 times the inter-quartile range (Q3-Q1).*

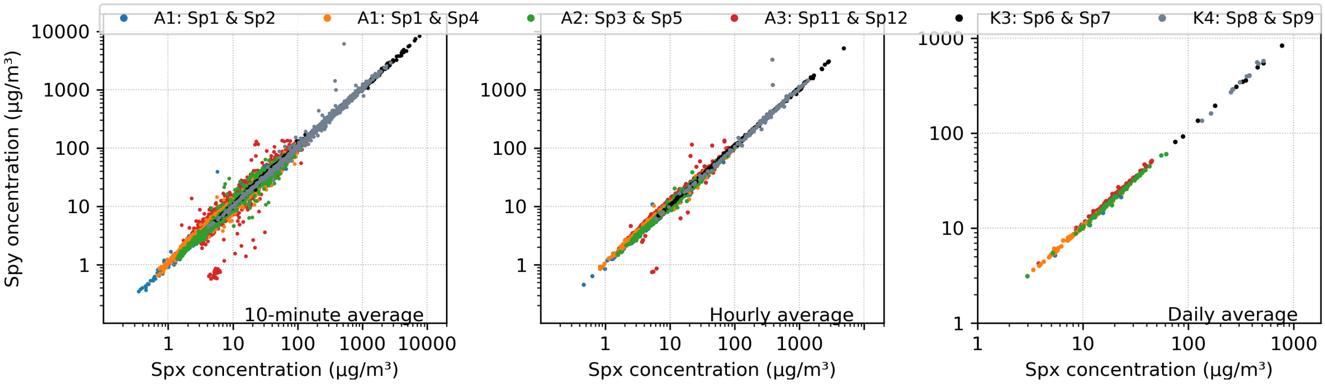

Figure 6: *Scatter plots for all data pairs of collocated SPSA, (A) 10-minute averages, (B) hourly averages and (C) daily averages.*

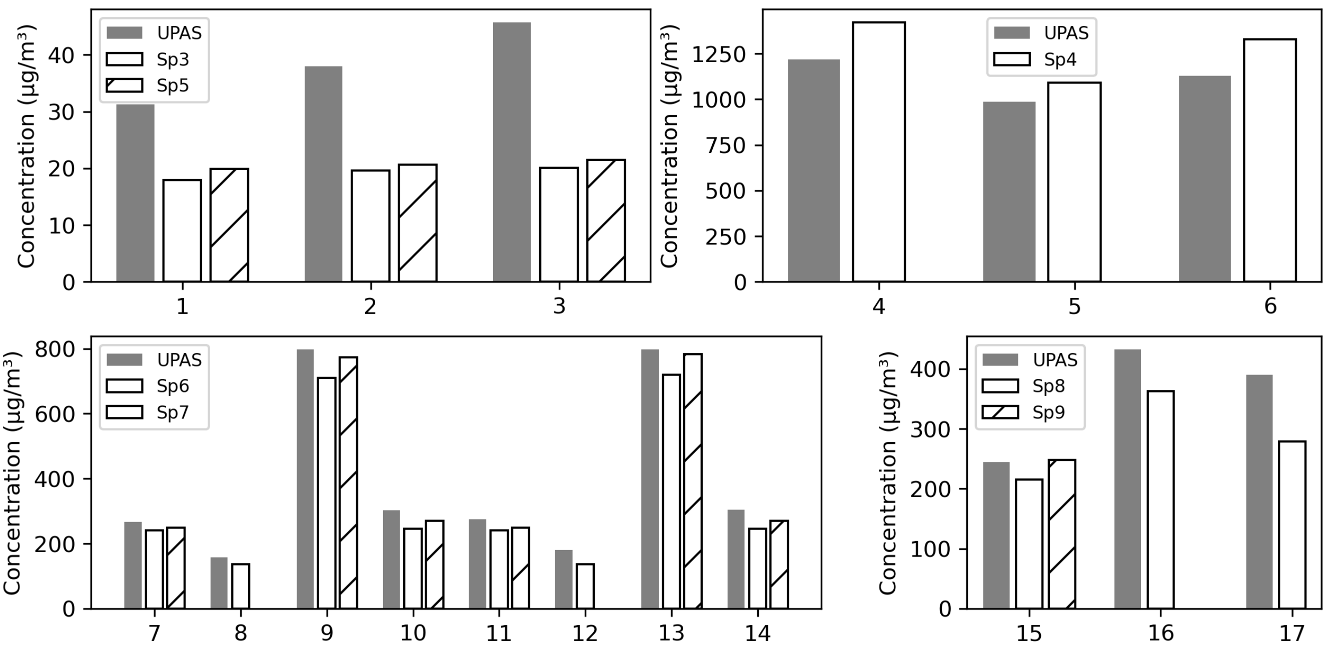

Figure 7: *UPAS and SPSA measurement results for 17 samples across locations A2 (A), K2 (B), K3 (C) and K4 (D).*

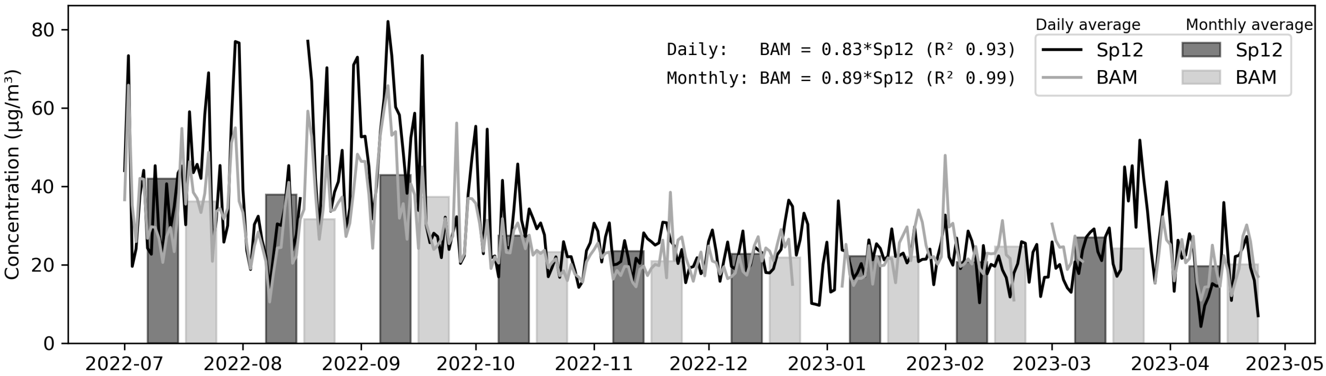

***Figure 8:** Daily and monthly averaged concentration for one SPSA and a BAM, at distinct locations in Addis Ababa.*

SPSA and SSys imply that SSys can be used as unofficial calibration instruments in local and remote contexts that have no resources for calibration with a gravimetric method. The large difference in required calibration between ambient and indoor circumstances is most likely due to particle differences (Karagulian et al., 2019). For the SPS30, Sousan et al. (2021) found under laboratory conditions highly linear results (r = 0.99) with a reference instrument for three aerosol types. The slopes for each of the aerosol types, however, were different, ranging from 0.75 to 2.0. This underlines the importance of testing an LCS at the location of intended use. We further discuss this under the field testing section.

Of all OEMs created, we have only used the SPS30 in our setup. Other studies find that of the different OEMs, SPS30 performs well. In their laboratory study, Sousan et al. (2021) compared the SPS30 along with other LCS to a reference instrument. They conclude that the 'SPS30 and OPC-N3 (…) demonstrated the best performance, with high correlation and lowest bias values, for all aerosol types and PM metrics in environmental and occupational settings. (…) In contrast, AirBeam2 and PMS A003 exhibited low accuracy for all aerosol types and PM metrics in both settings.' (Sousan, Regmi and Park, 2021, pp. 23–24). The AirBeam2 uses instruments and calibration like the PurpleAir. The PMS A003 is a Plantower instrument, used both in the PurpleAir and AirQo. A common problem for a $PM_{2.5}$ LCS is influence by relative humidity (RH). However, compared to OEMs Plantower and Honeywell, SPS30 has the lowest reaction to RH (Hassani et al., 2023). According to Budde et al. (2018), the SDS011 (used in sensors.Africa) has a significant variance amongst similar sensors and is strongly influenced by relative humidity. Like Sousan et al. (2021), we observed a robust performance of the SPS30 across different concentration ranges. The sensor showed a small variance amongst collocated identical sensors. The sensor is versatile for both indoor and ambient situations, across all concentration ranges. This was less the case for the two SSys used as comparison in our study (IQAV and PATS). A low influence of RH also follows from the fact that over a period of 10 months the SPSA followed the city-wide concentration trend in Addis Ababa, across both dry and wet seasons.

Field testing

It is important to evaluate LCSs in the same context as where they will be used to monitor air quality. For both SSys and OEMs, field validation in low-income country contexts is limited. Karagulian et al. (2019) conducted a review of 112 different LCS (64 independent studies, 31 OEMs and 81 SSys). From all 64 studies, only one concerned a $PM_{2.5}$ sensor which is evaluated in a low-income country: the SSys PATS inside kitchens in Guatamala (Pillarisetti et al., 2017). Most projects using SSys and OEMs in Africa do not mention field tests at the location of the study. Awokola et al. (2020) present the data of measurements with a PurpleAir 'as is' and refer for field tests to studies conducted at regulatory sites in the USA (Malings et al., 2020). AfricaAir, using the SSys PurpleAir and Met-One, likewise refer to these studies. For OEMs, Adong et al. (2022) compared the AirQo (OEM Plantower) to a BAM at two ambient locations in Kampala city in Uganda, with average concentrations of 37.5 and 45.1 µg/m³. Wernecke et al. (2021) announced tests of LCS and reference-grade instruments collocated at one ambient location, for half a year in 2021. We were not able to find any published results of this yet. For indoor contexts, we did not find any field validation of OEMs in a low-income country. Also, none of the sparse ambient field validations make mention of comparison with the gravimetric method. In other words, thus far the field validation of LCS in African contexts has been poor, both for indoor and ambient studies circumstances. Our study is the first to compare the SPS30 under indoor field circumstances to a gravimetric method. Our ambient field testing is also a first of its kind in this size (multiple ambient locations across multiple cities). Still also in our study the ambient testing is limited. We have only used the gravimetric method three times at one ambient location. Currently, data collection for the SPSA is ongoing at ambient locations in Addis Ababa and Adama, with 20 collocated gravimetric samples planned. We used the UPAS for both ambient and indoor measurements for comparison, but the UPAS is designed for indoor concentrations. Using a gravimetric instrument made for ambient monitoring (such as a Low Volume Sampler) would make the reliability of the data quality testing stronger. At this moment, such an instrument is not available in Ethiopia.

In any case, a large advantage of using OEMs instead of SSys is that, when a better sensor enters the market, one can decide to self-assemble the newer sensor in the system. For example, sensors.Africa at this moment uses the SDS011. They are likely to have the infrastructure to switch to an OEM with lower variance and less reaction to RH, like the SPS30 seems to have.

Conclusion

Low-cost sensors are a promising direction for $PM_{2.5}$ monitoring in Ethiopia, and self-developing the sensor system with an OEM even more so. While low-cost sensor projects have started in the African continent, most are externally funded and field validation at the location of deployment is still very poor. Our results from Arba Minch and Addis Ababa show the potential for a cheap, flexible, and reliable $PM_{2.5}$ measurement instrument, across both ambient and indoor pollution circumstances, based on the OEM Sensirion SPS30. To use it in larger quantities (such as a network), or for others to use it, either a more official approach is required (with the danger of losing ownership), or good cooperation between experts of different professions. Challenges of working with an OEM are the required expertise and lower ease of use compared to a SSys. These challenges should be seen as opportunities for increasing local skill, local ownership, instruments tailormade for local use, and for achieving the highest data quality for the lowest costs.

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Author contributions

Johannes Dirk Dingemanse: conceptualisation; methodology; data collection; sample analysis; data analysis; validation; data curation; writing – the initial draft; writing – revisions; student supervision; project leadership; project management. Afework Tademe: methodology; data collection; validation; writing – the initial draft.

Data availability

The data generated and/or analysed for the current study (measurement data and Python scripts) is available in the OSF repository https://doi.org/10.17605/OSF.IO/DXEZ8. For locations A1, A2 and K1-K4, data quality evaluations were first shown in Dingemanse (2022). Processed data files for those locations are taken from that study. Preprocessing and raw data for those locations are in the OSF repository https://doi.org/10.17605/OSF.IO/YTV79.

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