Locating Low-Cost Air Quality Monitoring Devices in Low-Resource Regions Is Not Enough to Acquire Robust Air Quality Data Usable for Policy Decisions

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Brief Report

Locating Low-Cost Air Quality Monitoring Devices in Low-Resource Regions Is Not Enough to Acquire Robust Air Quality Data Usable for Policy Decisions

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Abstract: Air quality monitoring (AQM) is key to maintaining healthy air in cities. This is crucial in low- and middle-income countries due to increasing evidence of poor air quality but lack of monitors to consistently collect, evaluate air quality data and effect policy changes, mainly because of the costs of monitoring devices. In participating in a challenge for the development of low-cost AQM devices in low-resource regions, an Arduino-based device with sensors for particulate matter size, temperature, and humidity data acquisition was developed for deployment in Port Harcourt, a city in Nigeria's Niger Delta region, exposed to poor air quality partly due to gas and oil production activities. During the project, challenges to AQM were encountered, including inadequate awareness of air quality issues, lack of necessary AQM device components, unavailability of trained manpower and partnerships, and lack of funding. However, lack of a means of calibrating the device was a major hindrance, as no reference AQM instrument was available, rendering the data acquired largely qualitative, educational, and useless for regulatory purposes. There is an urgent need for AQM in such cities. However, a robust AQM strategy must be designed and used to address these constraints, especially whilst using low-cost devices, for significant progress in acquiring robust air quality data in such low-resource regions to be made.

Keywords: low-cost air quality sensors; air quality monitoring constraints; calibration; local manufacturing; low-resource regions; air quality policies

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1. Introduction

Air pollution refers to a mixture of contaminants in the air which can damage the environment, plants, animals, and humans. Air quality refers to how much pollution there is in the air [1]. Air pollution is determined by measuring the concentrations of certain gases or emissions in the atmosphere such as particulate matter (PM_1, $PM_{2.5}$, and PM_{10}), carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (such as NO and NO_2), ozone (O_3), polycyclic aromatic hydrocarbons, volatile organic compounds, and so on [2–4].

Air quality monitoring is important because polluted air is unsafe and injurious to human health and biodiversity [3]. In humans, respiratory and cardiovascular diseases, cancers, and even death are associated with polluted air [5]. Concerning other organisms, poor air quality damages vegetation and reduces biodiversity [6,7].

There is a dearth of air pollution data in low-resource regions in the globe such as sub-Saharan Africa. This also leaves a huge gap in public health research in such regions. Even though the governments in those regions recognize the damage caused by poor air quality, limited resources available to the governments mean that air quality monitoring is not usually given as much attention as it requires [8]. Because of these factors, there is a paucity of air quality monitoring devices in these regions. It has been estimated that for every 15.9 million people in sub-Saharan Africa, there is just one ground-level monitor [9], and an average monitor density of 3 per 100 million inhabitants in Africa [10].

The advent of low-cost air quality monitors in the last decade has increasingly enabled the acquisition of air quality data in low-resource regions. Awokola et al. [11] reported that it was feasible and practical to measure ambient $PM_{2.5}$ values in thirteen locations across seven countries in sub-Saharan Africa. The study involved commercially available low-cost air quality sensors, lasting for 30 days with a median data recovery rate of 94% from the devices despite devices located in eleven of the thirteen sites having SD (Secure Digital) memory cards for manual data retrieval rather than having Wi-Fi connections. Three low-cost air quality sensors, developed in a research lab, were deployed successfully at three sites over an eight-month period in Niger [12]. The data obtained indicated that $PM_{2.5}$ and PM_{10} concentration levels were higher during the dry Harmattan season compared to the humid rainy season. This was mainly attributed, using back trajectory analysis, to the influence of the Saharan dust during the Harmattan season, which was similarly observed in a study in Lagos [4]. Interestingly, estimations of the spatial variations of $PM_{2.5}$ and PM_{10} concentration levels in using low-resolution grids from the Copernicus Atmosphere Monitoring Service differed from the values of those obtained from the low-cost sensors deployed during the same period, with the estimated $PM_{2.5}$ values higher and the PM_{10} values significantly lower than the ground level low-cost sensors. Abulude & Abulude [3] presented results from a network of commercial low-cost sensors located at five locations in different geographic areas in Nigeria. Data were continuously available for between 2 to 7 months from the sensors. The PM_1, $PM_{2.5}$, and PM_{10} concentration data indicated that the air quality index at four out of the five locations were unhealthy for sensitive groups of people, and at one of the locations, it was unhealthy for all groups of people during the period of the study. The PM concentration levels were at their highest during the dry Harmattan season (December to February) compared to the rainy season, thus exhibiting seasonal fluctuations observed by other studies [4,12].

Air quality studies using low-cost sensors in low-resource regions are characterized by discontinuities; they are usually short-term studies, lasting for weeks, months, or rarely more than a year [4], funded by international organizations using commercial devices. Air quality data collection usually ends at the end of the projects, as the local partners cannot fund the continual use of the commercial low-cost sensors. Thus, there are inconsistent data collections with gaps over periods of time in which collection campaigns are not running. One way of getting around this is to use data from satellite-based sensors where ground-based measurements are not available. However, it has been suggested that such $PM_{2.5}$ concentration estimates from satellite-based observation systems should be assigned a higher uncertainty [9,13]. Another approach would be to use locally manufactured air quality sensors for local air quality monitoring campaigns, thus reducing the costs of the devices, and increasing the longevity of the measurement campaigns. Current campaigns towards this later approach employ citizen science projects. In this vein, the Societal Value of Quality Low-Cost Urban Air Monitoring in Low Resource Environments (SQUARE) program at the University of Manchester, UK [4,14,15], in 2023, organized a challenge to develop a low-cost (<£100) air quality monitoring device that can be used in a low-resource region. The authors participated in this challenge.

There have been persistent air quality issues in Port Harcourt in recent years [16] and the authors were motivated by the realization that there were no known air quality monitoring schemes in the area. Thus, they embarked on the design and construction of a low-cost AQM device and used it to monitor both indoor and outdoor air quality on the main campus of Rivers State University, in Port Harcourt. In this brief report, we describe the constraints encountered during the process.

2. Materials and Methods

2.1. Study Location

The study was carried out in Port Harcourt which is a major city in the Niger Delta in southern Nigeria. With an estimated population of 3,636,547 in 2024 [17], it is also the fifth largest city in Nigeria. It is host to several international and indigenous petroleum production and allied companies and is prone to air, water, and land pollution from gas flares from oil production activities typical of this region [18,19]. Pipeline vandalism has also contributed greatly to the pollution of the biosphere of this city, leading to losses in wildlife and fisheries [20]. The soot pollution, which was very prominent in 2016 [21], is still an issue of health concern. In addition to the activities of petroleum and allied industries, the use of petroleum-powered electricity generators and the growing population among other factors also impact the city's air quality [22]. The air quality monitoring was mostly conducted at the main campus of the Rivers State University (4.79 N, 6.98 E) in Port Harcourt.

2.2. Air Quality Monitoring Device

We designed, assembled, and tested an Arduino-based air quality monitoring device to measure air quality data, ambient temperature, and humidity levels. We used a Plantower PMS5003 particulate matter sensor with the capacity to detect $PM_{1.0}$, $PM_{2.5}$, and PM_{10} particles. It works on the principle of laser light scattering, with a fan sucking the air through the sensor past the laser light in the AQM enclosure; this sensor is popular with low-cost sensor AQM and has been widely reviewed by several scholars [23]. A DHT11 Humidity and Temperature sensor was used to measure the ambient temperature and humidity values. The data obtained by these sensors are then read through an OLED display. All the data obtained from the sensors are recorded and displayed every two seconds. An image of the assembled AQM is presented in Figure 1. An example of the data obtained from the device is presented in Figure 2. The inability to robustly calibrate the AQM sensors in the local environment, however, rendered the data acquired educational. This led to the examination of the constraints that were encountered in deploying and using low-cost AQM devices in such a low-resource region, and these are presented in the following sections.

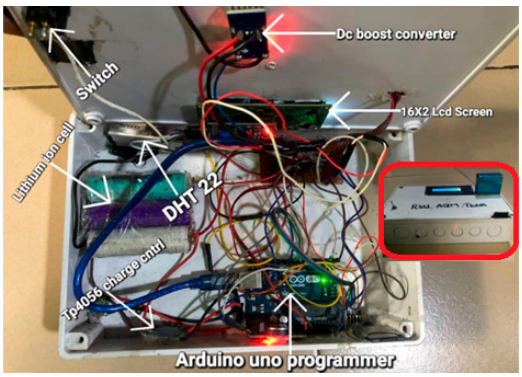


Figure 1. Air quality monitoring device with low-cost sensor. Main picture: inside of the device with labelled components. Insert: assembled device with lid covered.

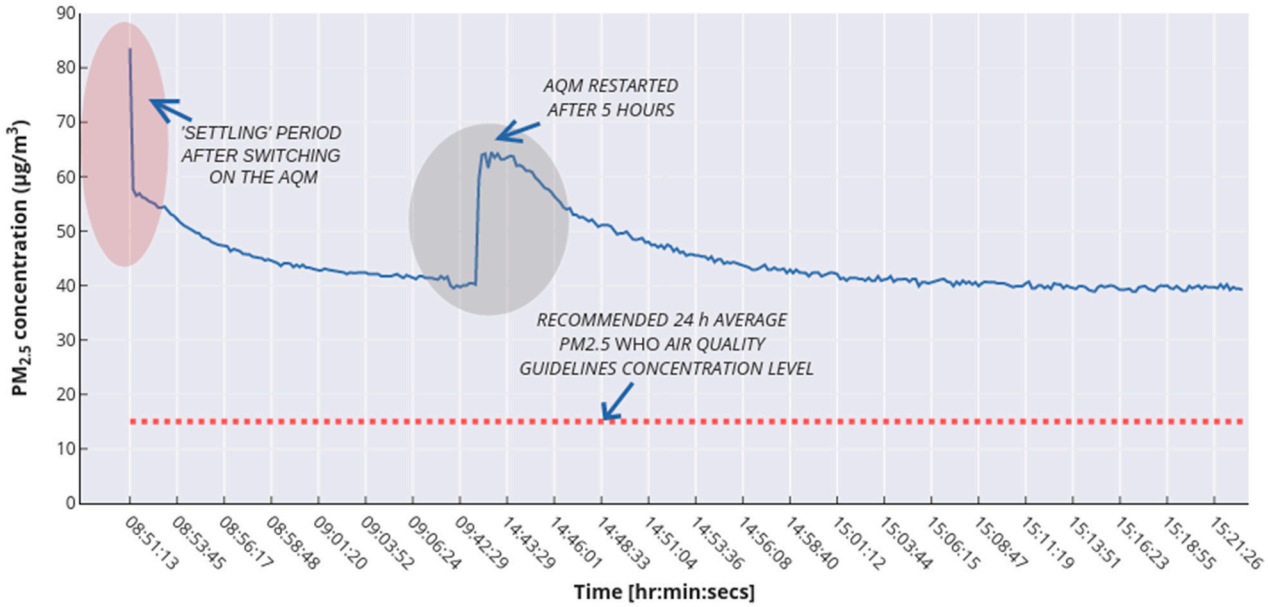


Figure 2. Example of the (unvalidated) $PM_{2.5}$ concentration measurements acquired with the low-cost AQM over a short period inside an unoccupied office at the Rivers State University, Port Harcourt, on 8 June 2023. The office was fitted with tables and chairs with the door and windows open but not exposed to any obvious pollution emission sources. The data suggest a mean $PM_{2.5}$ concentration value of ≈45 µg/m^3 during the recording period, which is three times the recommended WHO daily exposure. Maximum/minimum ambient temperature recorded: 30.3/28.0 °C. Maximum/minimum relative humidity recorded: 85.0/75.8%.

3. Results

3.1. Constraints to Air Quality Monitoring in Port Harcourt, Nigeria

In this section, the constraints that were encountered whilst carrying out the SQUARE challenge to design, assemble, and deploy an AQM for a low-resource region are presented.

3.1.1. Lack of Awareness of the Possibility of Air Quality Monitoring

In the last decade, worrying levels of soot pollution [16,21] have drawn the attention of the residents and authorities in Port Harcourt to the air quality issues, as opposed to polluted waters and land areas for which there have always been public awareness [20]. This awareness is reflected by a study that examined the perception of this soot pollution [22], which showed that 81.5% of the interviewees were aware of the problem and 87.8% believed it was caused by artisanal refinery of petroleum products. From our interactions during the study, many residents recognize 'black soot' as a form of air pollution, like the outcomes from the work of Whyte et al. [22], but not other sources, such as natural (such as dust storms, wildfire, and volcanic activity) and anthropogenic (such as agricultural activities and waste dumps).

On the health impacts of air pollution, there is some knowledge of irritation of the nose and eyes, perhaps because people were affected during the peak soot pollution episode [22]. Other health impacts (including cardiovascular diseases, cancers, dysfunction of the reproductive and central nervous system, as well as cutaneous diseases, diabetes, and obesity, etc.) are poorly understood.

Generally, there was inadequate knowledge of air pollution and its impacts on human and environmental health. From our interactions, several people were not conscious of actions that could contribute to improving air quality. Few individuals recognized the need for ambient air quality monitoring. There was also poor knowledge of air quality indices and their interpretation.

3.1.2. Unavailability of Trained Manpower and Partnerships

Several efforts were made at contacting institutes and organizations involved in environmental monitoring (environmental protection authorities, academic research institutions, ministries in charge of the environment) for partnerships in air quality monitoring, but the impression received was that they were not actively involved in air quality monitoring. They were more interested in other aspects of environmental concerns such as oil pollution in the waters and soil, with no trained personnel available for air quality monitoring.

Generally, there was apathy towards creating partnerships, especially with information sharing that could lead to training and education.

3.1.3. Lack of Funding

Access to adequate funding is a huge challenge because of the cost implications of acquiring the components for the device, intellectual proprietary rights, and mass production of the device to create adequate air quality monitoring campaigns for communities or areas of interest. While some of the components were readily available from local markets, a few (such as the PMS5003 particulate matter sensor) were purchased abroad from online stores; thus, the cost of producing the devices depended partly on the local currency exchange rates to the currency of the country of import of the components in question. Whereas in high-resource regions, AQM devices that cost less than £100 might be regarded as low-cost; as of the time of this study (August 2023), this was about twice the official minimum monthly salary for Nigeria, and thus, such devices are hardly low-cost for individuals and institutions for citizen science and educational campaigns in low-resource regions.

To adequately run air quality campaigns in communities across low-resource regions of interest would entail either local mass production, assembly of the devices, importation of them by the local authorities, or environmental protection agencies that, however, suffer from inadequate funding for their core services.

3.1.4. Legal and Regulatory Frameworks

There are environmental laws and regulations in place in Nigeria, such as the National Oil Spill Detection and Response Agency (NOSDRA) act [24], the Environmental Guidelines and Standards for the Petroleum Industry in Nigeria (EGASPIN) act [25], and the National Environment Standards and Regulations Enforcement Agency (NESREA) act [26]. However, they are ineffective due to overlapping functions, poor enforcement, and financial constraints. With regards to the study presented in this paper, there is no stand-alone AQM protocol in Nigeria; thus, there is no way of monitoring and demonstrating compliance with air quality standards in the NESREA act or of ensuring consistency and comparability of data across different locations and studies.

3.1.5. Lack of Reference AQM Equipment/Stations for the Calibration of AQM Devices

AQM using low-cost sensors has richly added to the spatial and temporal air quality data acquisition in low-resource regions where AQM is either sparse or non-existent. However, if these sensors are not calibrated, then the acquired air quality data cannot be relied upon for human health and environmental risk assessments [27].

As mentioned in Section 2.2, we were able to design, assemble, and test an AQM device using low-cost sensors for the SQUARE challenge, but we were then exposed to the difficulty of finding air quality monitoring reference equipment/devices in Port Harcourt, Nigeria, when the need to co-locate and calibrate the device arose. Enquiries were made at institutes in two universities in Rivers State, and at the State Ministry of Environment, all without success. There were referrals to private individuals/companies, all of which yielded nothing, except for one in a remote part of the State, where individuals who owned

an Aerocet 531 AQM were met, and this was used for co-locating our device. However, the data obtained from this device seemed implausible, and this was not pursued further.

Thus, due to the lack of equipment for calibration, data obtained from the AQM device produced during this study could not be validated; therefore, they are unusable for anything except for educational purposes. This lack of reference instruments and calibration devices is a major constraint in such regions.

4. Discussion

Poor air quality is a concern in low-resource regions such as Nigeria. The Air Quality Life Index [28] reported Nigeria to be one of the pollution hotspots in Central and West Africa and 'the sixth most polluted country in the world'. This report elucidated that air pollution impacted life expectancy more than 'HIV/AIDS, malaria, and water and sanitation concerns.' However, another ranking placed Nigeria as the 18th most polluted country in the world with average particulate matter concentration of 34.0 $\mu g/m^3$ [29].

A report from the United Nations Children's Fund (UNICEF) in November 2021, showed that 'in Nigeria, 78 per cent of air pollution-related pneumonia deaths are among children under-five' [30]. This illustrates the burden of air pollution in the country. Nwachukwu et al. [31] stated that diseases including pneumonia, upper respiratory tract infections, acute bronchitis, etc., were resultant from the pollution of the ambient air in Rivers State, Nigeria. The soot pollution of Port Harcourt which commenced in 2016 [21] is still a matter of environmental and health concern in the city. In their publication, Kalagbor et al. [32] reported high risks of cancer in Port Harcourt inhabitants due to black soot pollution.

Air quality monitoring is critical to solving the challenge of air pollution and improving the quality of life [33]. Monitoring outdoor and indoor air quality is routinely performed in developed countries [34], but it can be a challenge in developing nations. However, air quality monitoring using low-cost sensors can provide an affordable means of personal exposure monitoring as well as community involvement in decision-making processes on air quality [35].

However, experience from this study has shown that the use of AQMs with low-cost sensors on their own cannot solve the low air quality monitoring coverage in low-resource regions. Inadequate awareness of the possibility of AQM, trained personnel, lack of funding, ineffective regulatory bodies, and lack of reference equipment for data validation and calibration were found to be the major constraints on air quality monitoring. Abulude et al. [36] also reported that in Nigeria, air quality monitoring is hampered by the lack of necessary equipment, high cost of purchase of equipment and chemicals, lack of research funds and lack of cooperation from industries, among others.

There is a lack of awareness of the possibility of AQM and the extent to which poor air quality can affect human health. Similarly, Whyte et al. [22] identified that residents of Port Harcourt were aware of the black soot pandemic that enveloped the city, especially in 2016. Although these authors reported that the residents interviewed recognized that the soot was a form of air pollution, they did not fully appreciate the details of the concept of air pollution, neither were they aware of the need to constantly monitor the quality of ambient air. Some others are aware of respiratory diseases as consequences of air pollution, but not of cutaneous diseases [2] or others such as diabetes and obesity [37], etc. Most did not consider indoor air pollution as hazardous as outdoor air pollution. However, studies indicate that women in low- and middle-income economies are most at risk from indoor air pollution from the use of wood fires for cooking [2]. In the same vein, such women, older age groups [38], commuters, and traffic wardens [37] have been reported to be the groups most at risk.

Consequent to this lack of awareness is the unavailability of trained personnel in AQM, and this also affects the capacity of the regulatory bodies to regulate effectively. Even though this study demonstrated that AQM with low-cost sensors can be built and tested, the lack of calibration devices, which are essential for such sensors [5,9], rendered the acquired data academic. Adequate funding, which many of the local authorities lack for AQM, would be required to address these constraints.

Other approaches are possible for providing estimates to guide poor air quality awareness in data-scarce regions. For instance, air quality dispersion modeling could be used. They potentially could be less costly than deploying and maintaining AQM sensors and could provide large spatial coverage compared to sparsely deployed monitors. However, lack of local air quality data for validation, lack of up-to-date or incomplete emission inventories, atmospheric chemistry data, and assumptions used could render the data obtained from them unreliable [39,40]. The use of satellite sensors to obtain air quality data in data-scarce regions is feasible but the uncertainty of the data acquired could be high if they are not paired with ground-based measurements [9,13]. Machine learning techniques are now available, but they require ground-based data for training [15]. Hybrid approaches such as those using satellite data and ground measurements [41], and a network of low-cost sensors and urban-scale air quality models [42] can reduce the uncertainty in the AQM data acquired but training of staff and investment in the sensor networks are still needed [9].

5. Conclusions

An AQM device using a low-cost sensor for the acquisition of $PM_{1.0}$, $PM_{2.5}$, and PM_{10} data in Port Harcourt Nigeria was designed, built, and tested. This was part of a challenge to develop an air quality monitoring device that can be used in a low-resource region. In the past decade, Port Harcourt has been plagued with poor air quality issues, particularly soot pollution. The data acquired from the device, however, could not be used for human health and environmental risk evaluations, as there was no means of calibrating the instrument and co-locating it with a reference device in the field, as no such instruments or devices were known to exist in Port Harcourt at the time of the study. Some of such advanced reference instruments can be found in high-resource regions and can be costly to maintain.

AQM devices using low-cost sensors have become very popular for increasing the density of the spatio-temporal understanding of air pollution levels, for citizen science engagements and for acquiring air pollution data in low-resource regions where these are unavailable due to lack of advanced AQM instruments.

However, this work has shown that deploying AQM devices with low-cost sensors in low-resource regions will not, on their own, be enough to acquire robust air quality data that are usable for policy decisions. Instead, an AQM strategy or plan should be drawn up which should include awareness campaigns, training of relevant personnel, strengthening the ability of regulatory authorities to carry out robust AQM and enforce the regulations, and having sustained campaigns of AQM lasting for years in the defined areas of interest. Robust AQM campaigns include robust calibration of the low-cost sensors, maintenance and replacement of the sensors, and awareness of their technical limitations. Thus, an AQM strategy will require funding beyond those that are currently being spent on the acquisition of AQM devices with low-cost sensors that are deployed in low-resource regions.

Such an approach would help to reduce the constraints to AQM in low-resource regions using low-cost sensors and allow for the data acquired to be used for appropriate policy interventions.

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