Hindawi
Journal of Sensors
Volume 2024, Article ID 4895068, 17 pages
https://doi.org/10.1155/2024/4895068

Research Article

Advancements in Mobile-Based Air Pollution Detection: From Literature Review to Practical Implementation

Srdjan Sladojevic, Marko Arsenovic, Danilo Nikolic, Andras Anderla, and Darko Stefanovic

Department of Industrial Engineering and Management, Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovica 6, 21000, Novi Sad, Serbia

Correspondence should be addressed to Marko Arsenovic; arsenovic@uns.ac.rs

Received 22 September 2023; Revised 26 February 2024; Accepted 14 March 2024; Published 28 March 2024

Academic Editor: Ghufran Ahmed

The aim of this paper is to investigate the effectiveness of combining mobile technologies and sensors to detect harmful particles in the air and address the problem of air pollution caused by traffic and exhaust emissions. The paper contains a systematic literature review of information technology research related to pollution detection in order to point out the main obstacles in the field and propose solutions. Furthermore, the paper presents the development of an Android smartphone-based real-time monitoring system that utilizes an external analog sensor board to acquire and evaluate physical measurements. The proposed system is calibrated for CO gas measurements, and it is compared with a commercial gas analyzer instrument. Results imply that the developed system is capable of detecting concentration levels in the air and that the accuracy is within the range of the industrial device's accuracy.

1. Introduction

With an extensive growth in the field of the Internet of Things (IoT), numerous papers have been published regarding IoT device applications [1–4]. One of the applications is regarding air pollution, and in the previous decade, numerous types of research were conducted with the aim of examining air quality and measuring pollution and the presence of certain particles through smart devices and sensors embedded in devices that provide valuable information to the end user through applications.

Reports from the World Health Organization (WHO) indicate an increasing prevalence of issues, year over year, related to the exposure of a significant part of the global population to unhealthy levels of fine particulate matter and nitrogen dioxide, underscoring the widespread problem of air pollution. Particularly, individuals in low and middle-income countries face the greatest risk, with air pollution exceeding the air quality limits set by the WHO. Both outdoor (ambient) and indoor (household) air pollution pose significant environmental risks and are associated with various health conditions. In fact, ambient air pollution alone accounted for an estimated 4.2 million deaths, contributing to conditions such as stroke, heart disease, lung cancer, lower respiratory infections, and chronic obstructive pulmonary disease [5].

The concentration of certain air pollutants has been increasing, possibly due to changes in climate conditions [6]. Consequently, there has been a surge in research focused on pollution measurement using mobile devices. These studies primarily target traffic-heavy areas in cities, aiming to improve the environmental conditions and assess the relative harm caused by different types of motor vehicles [7]. Some researchers have compared various road sections, taking into account geographical factors, weather conditions (such as wind patterns), and the presence of industrial plants in the vicinity [8–11]. Notably, measurements in one study [9] revealed significant levels of harmful particles, even in the absence of heavy traffic, attributing them to nearby industrial facilities. Papers [6, 9, 12] advocate for pollution measurement worldwide, irrespective of the continent, to actively mitigate and reduce pollution levels. Affordable mobile technologies capable of real-time measurements play a vital role in achieving this objective.

While existing smart air quality measuring devices cater primarily to professional use, they are often limited in availability and expensive for the general public. The ultimate aim is to develop devices and simpler systems that are accurate and accessible to everyone, enabling users to monitor the current air pollution levels in real-time within their immediate environment. This approach raises awareness about air pollution and encourages users to adopt preventive and corrective measures to enhance air quality in their respective areas.

This paper presents the results of a systematic literature review of the research on the application of different methodologies and devices that measure air pollution through software and based on the measurement results, evaluate the effectiveness of the device, methodology, or software, all with the aim of providing the user with information in real-time measurement.

This paper conducts a literature review focused on studies published within the past 10 years, following the guidelines outlined in Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The aim of the review is to identify the key challenges in the field of air quality monitoring.

The findings of the systematic literature review emphasize the urgent need for the development of monitoring devices that adhere to quality standards. Addressing these identified gaps, this paper introduces a novel monitoring device that offers an affordable, reliable, and efficient solution for air quality monitoring.

The proposed solution comprises an air quality sensor integrated into a specially designed universal serial bus (USB) sensor board, accompanied by a mobile application and a server-side application. The practical implementation of this system is demonstrated through the measurement of CO gas concentrations in public areas. The results are presented along with a comparison to industrial-grade devices.

This application has the potential to assist practitioners in achieving rapid and effective air quality control. Moreover, the mobile application can be utilized by anyone with a mobile device and an inexpensive sensor board as an early detection solution or for monitoring gas concentrations. Additionally, the sensor board's versatility allows for the measurement of other analog sensor outputs, enabling its use in a wide range of applications beyond gas concentration measurement.

The motivation for this paper lies in the author's previous research regarding analog sensor application in medicine [6], as well as remote sensing for the environmental monitoring presented in papers [6, 7].

The proposed system for analog sensor measurement is the result of a comprehensive analysis of existing solutions discussed in the reviewed literature. By critically examining the limitations of current analog sensor systems, the authors were driven to develop an affordable and straightforward approach that specifically addresses the challenges faced by users, particularly those in developing countries. Leveraging the widespread use of mobile devices, this approach offers an accessible and user-friendly interface for real-time monitoring of sensor data.

Not only is this approach cost-effective, but it is also easy to implement, as the system draws power directly from the mobile device via USB, eliminating the need for an external power supply. Additionally, the proposed system utilizes the human interface devices (HID) protocol, enabling driverless communication with the mobile host, which sets it apart from other available solutions in the market.

In summary, this study presents an innovative and practical approach to analog sensor measurement that fills a significant gap in the market. The proposed system offers a cost-effective and user-friendly solution by capitalizing on the prevalence of mobile devices for real-time monitoring of sensor data. The author's in-depth analysis of existing solutions from the reviewed literature ensures that this approach is tailored to meet the specific needs of users in developing countries, where traditional analog sensor systems can be prohibitively expensive and difficult to access.

The rest of the paper is organized as follows: Section 2 presents the systematic literature review. Section 3 presents the methodology of the conducted review, the inclusion and exclusion criteria, as well as the eligibility of papers for research, which are described in detail. Along with that, Section 3 describes the proposed system that has been developed and tested. In Section 4, the research's conducted study is described in detail, and results are presented and discussed. Finally, Section 5 holds the conclusions.

2. Related Work

In the past 10 years, various studies have been dealing with the assessment of the impact of poor air quality on the population. The replacement of traditional monitoring stations, which are usually placed at a higher altitude and not in the center of cities, with devices and sensors that are easy to install and provide real-time information is being considered. These devices are based on new methodologies and can be placed on cars, bicycles, or hand-held so that the presence of particles and general air pollution can be easily measured in each part.

Ghaffarpasand et al. [8] combined the measurements of the Emissions Detection and Reporting (EDAR) System in the United Kingdom in 2016 and 2017, which were analyzed and included 94,940 vehicles. The levels of CO_2, NO, NO_2, and particular mass (PM) particles in the air produced by motor vehicles were measured, and a distinction was made based on the type of fuel used by motor vehicles. Based on the measurement results, it was observed that a large number of harmful gases were produced for EURO 5 to EURO 6 taxis and heavy goods vehicle types, which greatly increases air pollution.

"AERO-TRAM" is a mobile laboratory created in Germany with the aim of monitoring H_2O, O_3, NO, NOx, CO, and CO_2 in the air, as explained within research [9]. The measurement system contains a global positioning system (GPS) and a camera for measuring slope conditions located at a height of 3.5 m on the tramcars. The work is focused on the analysis of preferred noise criterion (PNC) and NOx measurements in 2010. It was concluded that there is a high concentration of harmful particles in the air, even in rural areas with less traffic. The authors took into account the wind speed that was measured and came to the conclusion that the wind greatly contributes to the distribution of these harmful particles.

In the paper [10], two mobile platforms for measuring pollution at the moment of time are presented, which contain sensors and can establish a connection with a mobile phone. Data storage on the cloud is provided in order to process data and obtain results. When measuring pollution, they placed one device in the car while the other was placed outside the car. It is concluded that both measurements are feasible and that the orientation of the device affects data collection during measurement. This type of device described can greatly help patients with respiratory problems and the development of devices for measuring air pollution.

Study [11] presents mobile monitoring of several pollutants in research and data processing in several ways. The results present a vast amount of knowledge from data processing in the field of air pollution study, which confirms the importance of measurement and data processing in this field.

CLidar (Camera Lidar) is a cheap, simple technique for measuring aerosols in the air. Barnes and Sharma [12] made an overview of the use of this technique under different conditions, noting the benefits and the possibility of really easy implementation and reading of the results.

Research [13] presents the air quality monitoring in Doha using wireless sensor network (WSN) deployment. The measurements are read in real-time and are based on device sensors that send the collected data to the back end, where they are stored. This way of collecting data in real-time is simple and suitable for fast processing.

Another cheap and easy way to collect data on O_3, NO_2, PM10, PM2.5, temperature, relative humidity, and atmospheric pressure is the device presented in the research [14]. The device is in the domain of IoT and functions on the basis of sensors. The authors point out that such a device is of great importance for the further development of devices from this category.

Similar to the solution presented in the paper [13], Tariq et al. [15] introduced measurement using wireless sensors IoT devices in the area of Qatar. During the measurement, geographical factors, such as humidity, temperature, and wind, were also taken into account. Communication between IoT architectural layers is well organized, and in addition, the device can work for up to 2 weeks without charge.

Samad and Vogt [16] introduced a device installed on a bicycle, on the basis of which data on pollution in the territory of Stuttgart is obtained. The amount of PM, ultrafine particle (UFP), black carbon (BC), NO, NO_2, and NO_X was measured, and the device has a GPS based on which the measurement data is allocated. By collecting data and processing it on a laptop, the authors came to the parts of the city with the highest concentration of the particles above in the air. Such a device can increase the control of the number of harmful particles in the air.

Ground-based multiaxis differential optical absorption spectroscopy (MAX-DOAS) measurements monitor the amount of NO_2, SO_2, HCHO, and O_3 in the air. Chong et al. [17] introduced the device based on which results are obtained and they are compared with satellite measurements. The mobile platform of this device is placed on the roof of the vehicle with the telescope directed in the direction of movement of the vehicle. The authors conclude that such devices can be used to validate the results of satellite measurements.

Van Poppel et al. [18] presented a case study to illustrate a method for environmental monitoring. UFP, PM2.5, and BC concentrations were measured in different areas of the city over several days. Data collection was done in several iterations, which were processed and checked. The green zones of the city have a lower concentration of harmful particles than those marked with numbers—zones with less greenery. This method of measuring harmful particles in the air can greatly change the existing method and facilitate the measurement with the aim of improving the living environment.

In their work, Crocchianti et al. [19] focused on the emission of particles in the city of Perugia through a 3-year study. For the measuring stations, they chose two locations of the mini metro, the transport system used in that city, in order to monitor air pollution through a mobile platform. Mini metro was chosen because it has low gas emissions and is far enough away from the main polluters, primarily from traffic. They examined the appearance of particles in relation to transport, time, and previously present particles in the air, and NO, PM, NO_2, and O_3 particles were considered.

Two distinct statistical approaches were applied to the experimental results. Namely, a hierarchical spatiotemporal model was employed to obtain robust information on the spatial and temporal variability of PM. Furthermore, a generalized additive mixed model was used to investigate the influence on PM of covariates such as vehicular traffic, rain, wind, relative humidity, and the stability of the planetary boundary layer [19]. They conclude that reducing the percentage of vehicle use and increasing the use of public transport would contribute to a significant reduction of harmful particles in the air.

Mihăiţă et al. [20] addressed challenges by proposing a comparative and detailed investigation of various air quality monitoring devices (both fixed and mobile), tested through field measurements and citizen sensing in an eco-neighborhood from Lorraine, France, and by proposing a machine learning approach to evaluate the accuracy and potential of such mobile generated data for air quality prediction [13].

Significant knowledge in the paper leads to overcoming the problems of previous devices and methodologies, and the emphasis is placed on the manipulation of data from the devices as well as the use of that data in real-time forecasting in order to raise awareness about air pollution in any location where devices and methodology are used. The measurements were related to NO_2 particles.

Samad and Vogd [21] defined the investigation using a bicycle equipped with different measurement devices to measure air pollutants such as NO, NO_2, O_3, PM, UFP, and BC particles. For this purpose, a platform "MOBAIR" was built and equipped with an aerosol spectrometer working on the principle of light scattering for measuring particles. There were 16 points on the bicycle path where the presence of particles was measured, and they came to the conclusion that particles are much less present in green areas but also that locations, weather conditions and seasons, traffic volumes, etc., significantly influence the measurements. Although the two described measurement methodologies were used, there are deviations and large matches in the measurement results, that is, the presence of particles in relation to identical conditions.

Yang et al. [22] proposed a Gaussian plum model on the basis of the neural network (GPM-NN) to physically characterize the particle dispersion in the air, and then they proposed an adaptive monitoring algorithm to monitor air quality index (AQI) at the selected locations. Experimental results have shown that GPM-NN can achieve higher accuracy than other existing models, so it is very useful for future works, both in 2D and 3D space. The measurements were made in the form of a comparison with other methodologies, and it was based on the fact that AQI is measured in total, and not all particles separately, and presented as such.

As mentioned in previous papers, many researchers use mobile monitoring bicycle-based measurements. Hankey and Marshall [23] developed and examined 1,224 separate land use regression (LUR) models and they compared the models based on the results they produced, and PN, BC, and PM2.5 particles were measured. Since fixed-site monitoring has been used so far, they suggest that LUR modeling for mobile measurement is possible, but a lot needs to be taken into account, such as time-of-day, urban, suburban, or green areas.

A research, presented by Phla et al. [24], developed a system capable of real-time measurement of air-polluted gasses such as CO_2, CO, NO_2, and SO_2. In their system, they have two types of sensors such as electrochemical CO, SO_2, and NO_2 sensors and infrared CO_2 sensors. Sensors communicate with the base stations wirelessly, and the graphical user interface of the system is user-friendly for clients. The performance of the device indicates that the measured values for different gases do not deviate to a large extent from the expected ones, and the occurrence of errors is reduced to a minimum.

The research of Wang and Huang [25] was motivated to mimic human breathing along the city's transportation network by the mobile sensing vehicle of atmospheric quality. To obtain a quantitative perception of air quality, the Environmental Monitoring Vehicle of Wuhan University has been developed to automatically collect data on air pollutants. This device constantly collects data and uses various data mining and analysis techniques to create quality reports. The experimental analysis determined that the device is very efficient and provides an accurate perception of the air. A comparative analysis with meteorological stations also confirms the efficiency of the device. It is important to point out that this type of device can significantly improve air and emergency monitoring of air quality in large and polluted cities.

As in the previous works dealing with air pollution monitoring, Peters et al. [26] emphasized the importance and potential of the mobile measurement method in order to map air pollution in urban areas of the city. Such monitoring can be used both for comparative analyses and for the assessment of absolute levels of certain particles in the air. The paper focused on UFP and PM10 particles. They pointed out that mobile measurements should include spatial and temporal coverage and suggested that portable devices can be included in monitoring by having volunteers or other members of society carry measuring equipment in their daily routine. In this way, even more data are collected and it is possible to draw certain conclusions as well as monitor the daily variations of particles.

Zhang and Smith [27] based their research on the emission of harmful particles, especially ammonia, in real-time at landfills. For this reason, it is important to create a mobile device that will monitor gas emissions and state changes in real-time in relation to all factors. The paper describes in detail the used mobile white cell differential optical absorption spectroscopy system. They conclude that the amount of particles significantly depends on the area being examined, weather conditions, temperature, and other factors. They pointed out that it is of great importance to monitor ammonia at the landfill because its presence is harmful to environmental protection. For such needs, the presented system proved to be an effective tool that tracks ammonia particles in real-time.

As mentioned in papers [14, 20], Hapsari et al. [28] also used a system based on IoT and WSN for real-time indoor air quality monitoring. They tested the device in several locations, i.e., rooms and compared the results obtained in the form of the presence of particles. The device used is described in detail in the paper, and recommendations are given for the use of research in further work, as well as ideas about possible improvements to the system in order to adequately monitor the air quality in closed rooms in real-time.

Similar to the research presented in the paper [28] and a few mentioned as well, the paper [29] proposed a smart solution using IoT. The paper described the methodology as well as the device that monitors indoor air pollution. Sensors collect toxic gasses such as methane, ethanol, toluene, CO_2, CO, alcohol, acetone, LPG, NH_4, benzene, and hexanes. The results show that the proposed system gave a good indicator of indoor air parameters measurements and represents a significant contribution to indoor environmental study.

Research in the paper [30] noted the importance of protocols and standardization of certain sensors as they are increasingly used in research and applied in important air pollution measurements. The first protocol for the line-card-to-swich protocol was developed and compared with reference research instruments used for air pollution assessment, and the sensor was installed on the Google Street car. O_3 and PM2.5 particles in the air were observed.

Paper [31] proposed LoraWAN—a domesticated air pollution monitoring system using IoT to track CO_2 and PM2.5 particles. Methodology and algorithms are described in detail. In order to raise awareness among the government and citizens and to keep everyone informed about air pollution, this system would send real-time notifications and messages to everyone in the event of a high concentration of particles.

As in various papers on this topic, researchers in paper [32] used the LoraWAN system to track air-polluting particles in the air. The authors tested three low-cost sensors, and they proposed a pilot project for air pollution measurement. The authors conclude that a standardization and certification scheme for low-cost sensors must be advanced, allowing the end user to choose a sensor according to the needs of its application and objectives.

Research [33] used mobile technology based on measuring the effect of light absorption depending on the concentration of particles in the air. The area where the measurement was made is one of the biggest cities in Romania, with a large amount of traffic. The period for which the samples were taken was during lockdown during the coronavirus pandemic from March to May 2020. The conclusion drawn by the authors is that the concentration of harmful particles is increased to a certain extent by traffic and by the industrial facilities themselves. Regardless of the reduced traffic in certain parts with the existence of industrial facilities and exhaust gases, the emission of harmful particles remained to a large extent.

Riley et al. [34] introduced a mobile platform for measuring air pollution in the USA, which took into account 10 metrics. In addition, attention was paid to the environment, geographical location, time of day, etc. It was observed that the wind affected the distribution of rock particles in the air to a large extent, as did trucks.

In 2016, Yu et al. [35] presented a new way of mobile measurement and practice of air pollution. Measurements were made simultaneously on different routes, which were compared. In addition, the limitations of measurement were highlighted. Measurements were made on weekdays in the morning hours, and accordingly, there were no measurements on weekends.

As mentioned in previous papers, in many cases, low-cost sensors are used to measure air quality and harmful particles. Qin et al. [36], in their paper, did a comparative analysis between data from nine air monitoring stations with standard PM instruments were used as reference and compared with the data of mobile and fixed PM sensors in Jinan, the capital city of Shandong Province, China. They measured PM2.5 and PM10 particles. They calibrated sensors with different models, and they concluded that the two-step calibration model appeared to be a promising approach to solve the poor performance of low-cost sensors. The two-step calibration of the R2 of fixed sensors increased from 0.89 to 0.98 for PM2.5 and for PM10 from 0.79 to 0.97. This comparison and further research are important for improvement of the model.

In the next two papers, the authors proposed two systems that can be useful in future research. In the paper [37], a three-phase air pollution monitoring system is proposed. This kit can be physically placed in various cities to monitor air pollution. The gas sensors gather data from the air and forward the data to the Arduino IDE (integrated development environment). The kit has been integrated with the mobile application IoT-Mobair and can be helpful to people suffering from respiratory diseases. Further, data logging can be used to predict AQI levels.

Arain et al. [38] proposed a mobile robot solution for autonomous gas detection and gas distribution mapping using remote gas sensing. They deployed a prototype ARMEx in a large indoor environment with eight gas sources. They conclude that the development of such devices can bring significant practical applications in large environments due to the detection of various gasses. By combining previous knowledge and research, significant progress can be made in air and gas quality monitoring.

The identified framework [39] integrates travel-based sensors with bus scheduling efficiently. Proposed multistep optimization for large-scale scenarios optimizes line selection, fleet size, and sensor allocation. Suggested joint optimization of fleet size and detection quality advances coordination. A streamlined approach lays the groundwork for digitalized public transportation, reducing congestion and pollution. Encourages shift to public transportation for significant environmental impact.

Variability among low-cost sensors due to manufacturing methods and sensor history impacts measurement accuracy. Calibration methods and models are crucial for converting raw sensor responses into concentrations. Temperature and relative humidity can influence sensor performance, requiring frequent testing and recalibration. Access to various sensors of different quality and cost complicates integration, but mobile applications streamline data integration. Continuous testing and calibration are essential for overcoming sensor challenges [40].

The Environmental Protection Administration in Taiwan deployed [41] low-cost air quality microsensors near industrial zones for local air quality monitoring. However, issues like missing sensor data could hinder prompt responses to pollution incidents. A study proposed a hybrid deep learning model (AE-CNN-BP) integrating autoencoder (AE), convolutional neural network (CNN), and backpropagation neural network (BPNN) to forecast PM2.5 concentration 4 hr ahead with high spatiotemporal resolution. The model was trained and tested in three industrial zones in Kaohsiung, Taiwan, addressing challenges in air quality monitoring.

Study [42] demonstrated the feasibility of high-resolution spatial and temporal analysis of particle concentrations in urban areas using mobile setups. Results comparable to fixed station network values, offering insights into PNC and particle concentration variability. Reveals emission patterns aiding efficient urban traffic planning and reducing fine particle pollution.

Study [43] aims to develop a prototype model for monitoring vital signs and ambient conditions for asthmatic patients. The integrated system utilizes Arduino Uno, ESP8266-NodeMCU, and sensors, transmitting data to platforms like ThingSpeak and Blynk for analysis. Rigorous validation techniques ensure the reliability of sensor data. IoT-based health monitoring system has the potential to transform asthma care, providing real-time data to healthcare professionals and caregivers, thus reducing hospitalizations and improving patient outcomes.

The paper [44] proposes calibrating low-cost air quality sensors using statistical algorithms and offset values from official measurement stations to enhance reliability. It investigates methods for addressing sensor challenges like low accuracy and short lifespans, focusing on peak detection and correlation with temperature and humidity variations.

The study evaluates the common air quality index against data from public monitoring stations, highlighting the potential for improving urban air monitoring using cost-effective sensor solutions.

Verde et al. [45] utilized IoT and sensor technology to monitor methane emissions from cattle, proposing a measurement system integrated into milking machines to ensure periodic monitoring while considering animal welfare and addressing the lack of instrumentation on farms to quantify emissions. This is crucial given that agriculture accounts for 8%–10.8% of global greenhouse gas emissions, with estimates suggesting animal contributions to be as high as 18%, as indicated by lifecycle analyses.

The study [46] utilized a mobile air monitoring unit equipped with modules including the DustTrak II Aerosol Monitor 8530 and a GPS antenna for real-time data transmission. This unit, loaned from the Krakow Smog Alert Association, offers valuable insights not achievable by fixed monitoring stations, aiding in detecting suspicious activities and estimating pollution loads. While mobile systems increase public awareness and complement fixed monitoring networks, they depend heavily on stationary measurements for accurate analysis and should be used accordingly.

Vajs et al. [47] examined COVID-19 lockdown effects on air pollution in Serbia, deploying low-cost sensors alongside a reference station in Belgrade over three periods. Results show a decrease in NO_2 but steady or increased levels of pollutants from domestic heating during lockdown, indicating the influence of predominant pollution sources. The IoT-based ekoNET AQ10x system used for monitoring integrates low-cost sensors with cloud storage, data analytics, visualization tools, and a web application, enhancing air quality monitoring capabilities in urban areas.

Research [48] compared the performance of random forest (RF) and linear regression models for predicting air quality parameters, favoring linear regression for its accuracy and simplicity. Parametric models like MLR offer straightforward adjustments over time and are less computationally demanding, making them suitable for nonexperts. Despite sensor variability, linear models effectively monitored air quality in AirLine LC stations equipped with metal oxide sensors, highlighting their effectiveness despite requiring careful parameter adjustments.

An air quality monitoring system [49] continuously assesses pollutants with strategically placed sensors, transmitting real-time data via communication protocols like Wi-Fi or cellular networks. Cloud-based infrastructure enables the storage, processing, and analysis of data for informed decision-making by policymakers and environmental agencies. Arduino boards provide flexibility for customization to meet specific requirements and objectives.

Paper [50] introduced a low-cost pollution measurement station capable of monitoring multiple environmental parameters, transmitting data in real-time over Wi-Fi, or storing it locally. Priced at USD 628.12, the system integrates various measurement sources without compromising accuracy, validated with an average error of approximately 2.67%. Key features include noise intensity and direction measurement, CO_2 assessment, and humidity and temperature evaluation. The system offers easy assembly, multiple power supply options, and interoperability, enabling customization and correlation analysis between pollution variables.

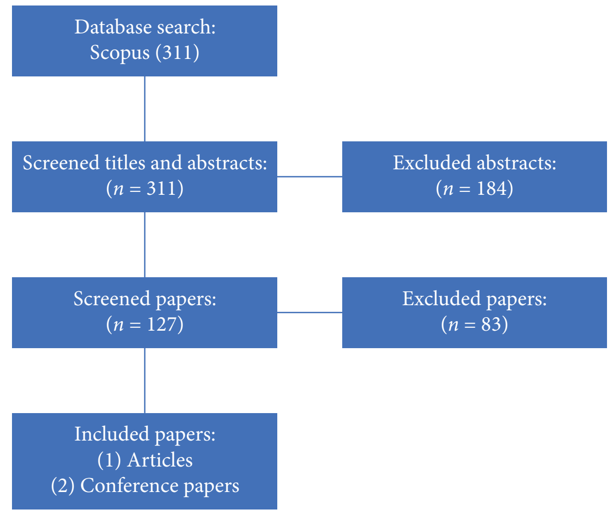


Figure 1: PRISMA diagram for systematic literature review.

The proposed solution [51] utilizes calibration propagation through a network of low-cost devices, demonstrating significant improvements in the Pearson correlation coefficient and reductions in NO_2 and PM10 levels. This approach offers efficient and cost-effective hybrid sensor air quality monitoring deployments. By combining public monitoring stations with multiple low-cost devices, periodic sensor recalibration is simplified without physical retrieval. Machine learning algorithms, particularly RF, play a key role in predicting data without overfitting. Ensuring a sufficiently dense grid of sensors allows adjacent devices to calibrate each other, enhancing data accuracy and reliability in urban air quality monitoring.

Air pollution is a complex issue requiring comprehensive understanding and collective action. Effective policies, clean technologies, and sustainable practices are crucial for mitigation. Collaboration and continuous efforts globally are necessary to safeguard present and future generations. Analytical techniques such as in situ measurements and satellite observations help in understanding and addressing air pollution. Accurate measurement and monitoring are essential for identifying pollution sources and evaluating mitigation strategies, employing various analytical techniques and instruments, including ambient air monitoring and air quality modeling [52].

3. Methodology

3.1. PRISMA. A systematic literature review was carried out in several parts, shown in the PRISMA diagram in Figure 1. A review protocol was created, describing the article search strategy, inclusion and exclusion criteria. The search for papers was carried out in the SCOPUS online database of scientific papers by searching for keywords in the field of measuring harmful particles in the air using mobile applications that have

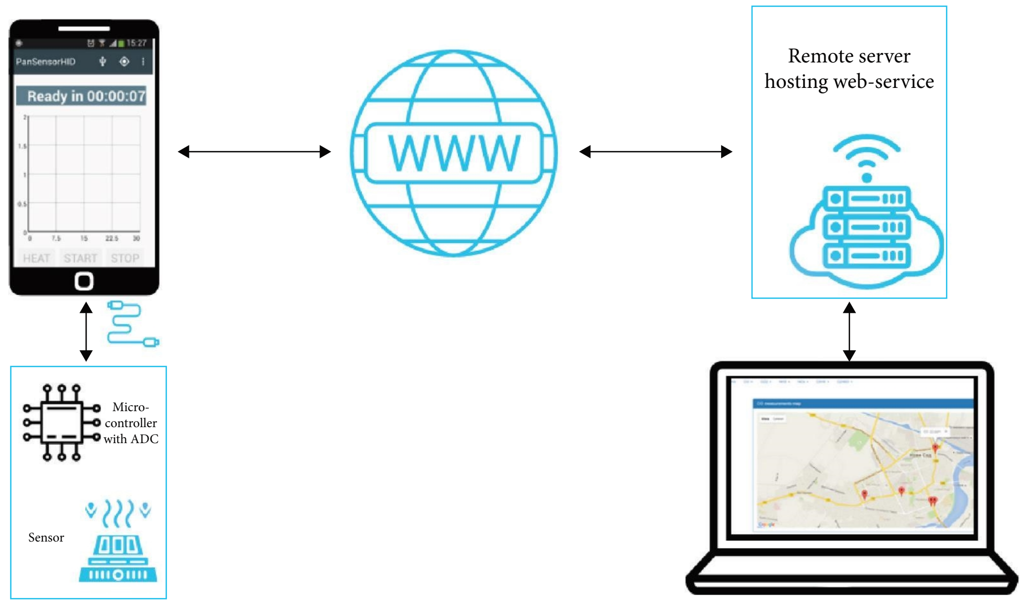


FIGURE 2: Block diagram of the smart mobile-based monitoring system.

a sensor. From the information retrieved, the search strings used are given:

(i) Search string 1: (air AND quality AND tracking, AND mobile, AND gas AND measurements).
(ii) Search String 2: (air AND monitoring, AND mobile, AND measurement).
(iii) Search String 3: (air AND monitoring, AND mobile, AND measurement, AND low cost).

The criteria for inclusion in the selection of works are based on the very topic of the work in the field of mobile technologies and measurements at the moment of observation. The criteria for inclusion of work are as follows:

(i) A detailed description of the algorithm that measures harmful particles in the air.
(ii) The existence of suitable sensors that enable the measurement of harmful particles in the air.
(iii) Performed and described measurements with a discussion of the given results.

On the other hand, the criteria for the exclusion of papers are also defined. The criteria for excluding papers are as follows:

(i) Works that are older than 2012.
(ii) They do not describe a device in the form of a sensor that measures harmful particles in the air.

In the first iteration of collecting papers, a total of 311 papers were obtained based on defined keywords. By reviewing the appendices and abstracts of the papers, 184 papers were excluded in the second iteration. After that, the remaining 127 papers were read in their entirety. Based on the defined inclusion criteria, a total of 44 papers were included in the further process of systematic literature review.

Researches covered using this methodology were described in the previous section. Along with that, a detailed paper's analysis that further describes the paths of the conducted research in this area will be presented in Section 4.1.

3.2. System Design. The system consists of the following parts: hardware, a USB sensor board, and software. The USB sensor board contains a microcontroller and an analog sensor for measuring physical quantities. The software includes two independent applications: a native mobile application for displaying real-time measurements on a mobile device and a web application for persisting the measurement data on a server and enabling application programing interface for the required data. The microcontroller communicates with the mobile device via the USB interface, and the mobile application sends the measurements to the server for storage and analysis. The system is designed to provide a compact and easy-to-use solution for acquiring and analyzing analog sensor data on mobile devices. The diagram of the entire system is shown in Figure 2. All mentioned parts of the system are elaborated in further subsections.

3.3. Mobile Application. The mobile application is designed to enable easy acquisition and representation of measured values from the sensor board. By simply connecting the sensor board to the user's mobile device, the user can use the hardware to measure with various types of sensors. The application allows the user to configure the frequency of measurements and the displayed interval. If necessary, the user can also set the heating mode for the sensors that require preheating.

The application has both manual and automatic heating modes. In the automatic mode, when the USB device is connected, heating starts automatically by sending the heat command to the firmware's ProcessHIDReport. After the heating duration has elapsed, the user can start the sensor

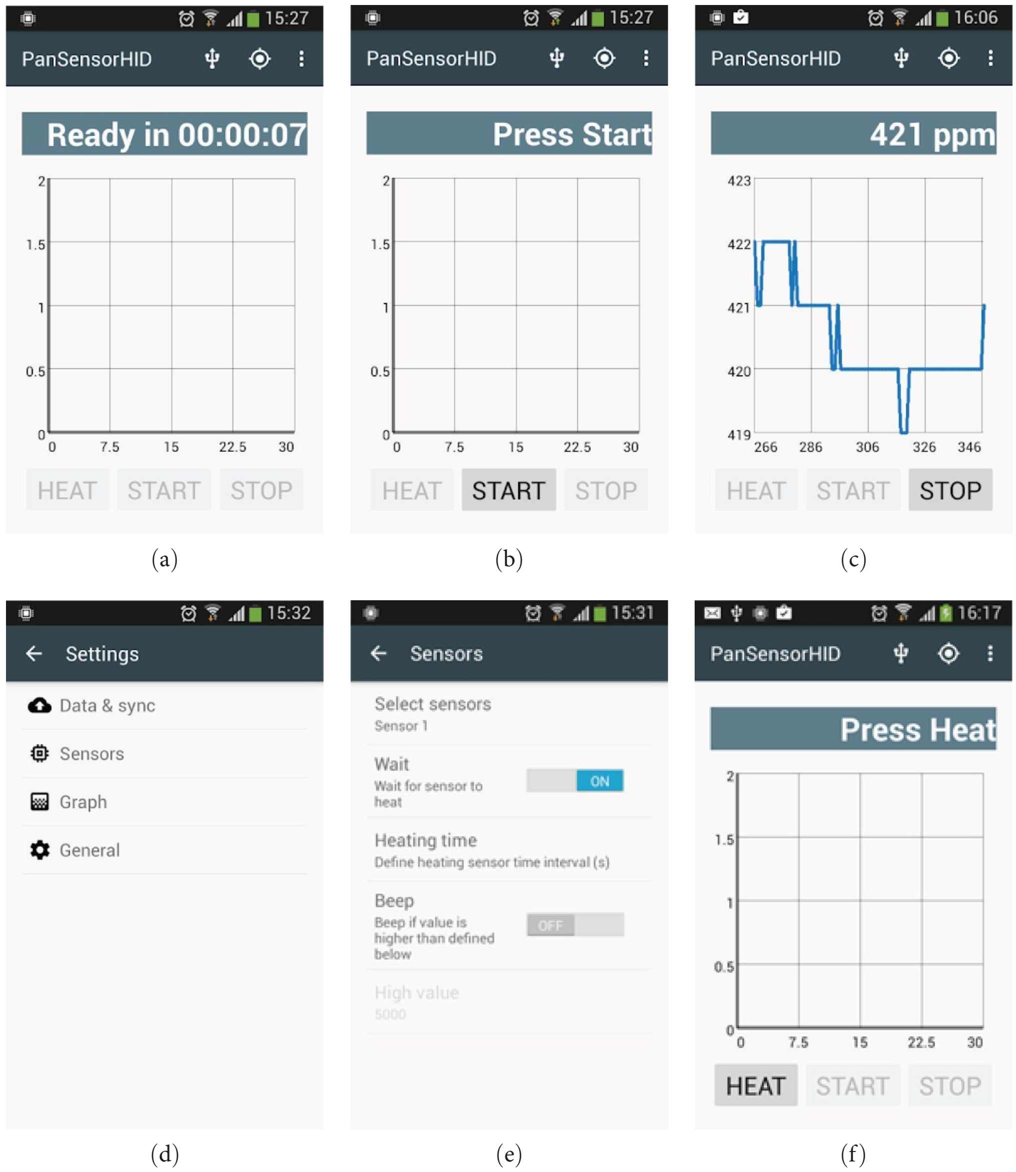
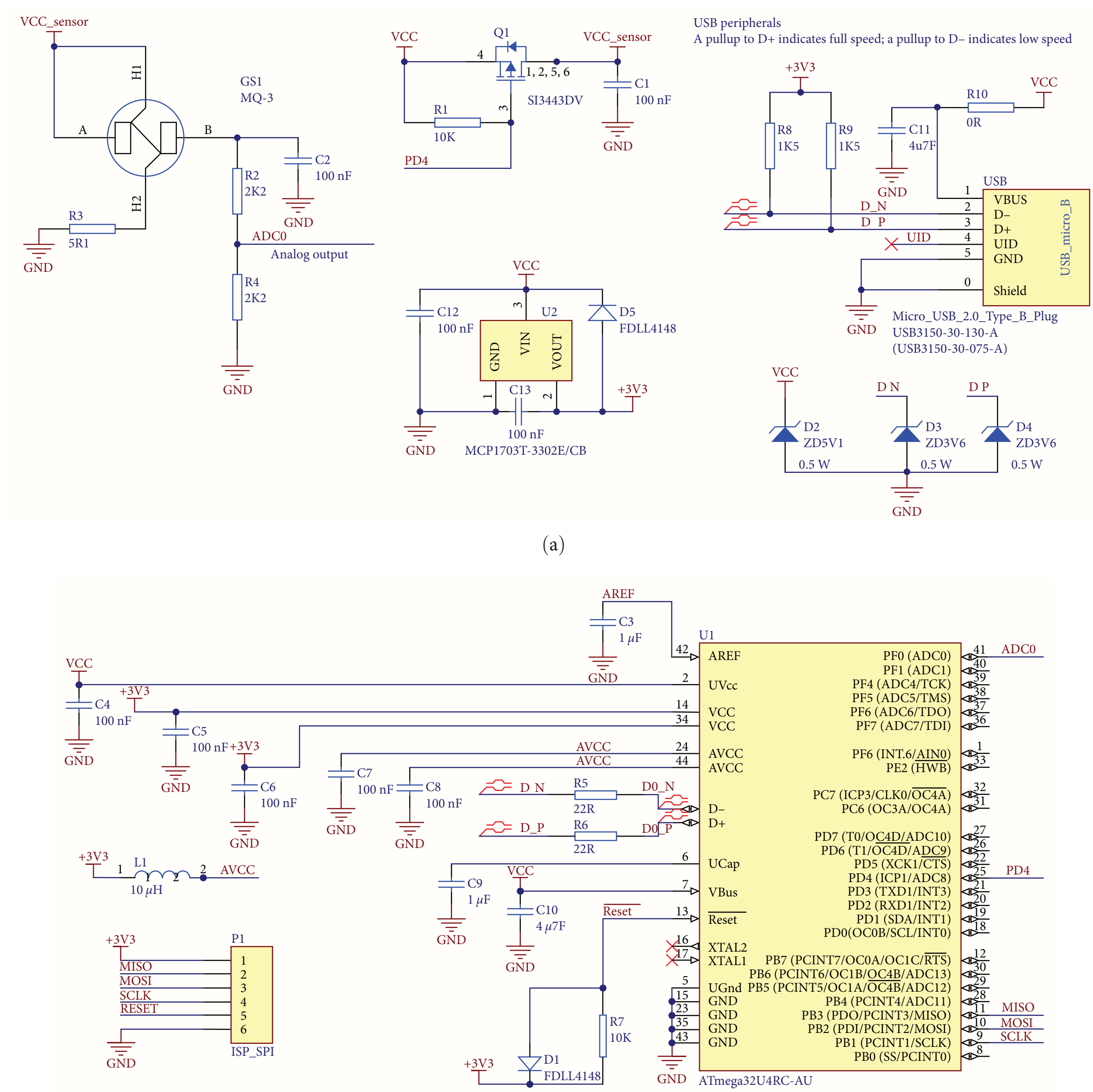


Figure 3: Mobile application for analog sensor measurement system: (a) automatic mode: heating, (b) automatic mode: start measuring, after heating is done, (c) automatic mode: measurements display, (d) configuration menu, (e) configuration of automatic/manual heating, and (f) manual mode: heating.

measurement, which is displayed both graphically and numerically. In the manual mode, the user can start and stop the heating by clicking the heating button. Once the heating is complete, the user can take measurements and view the results. Screenshots of the developed mobile application are displayed in Figure 3.

3.4. Web Application. The server-side application of the system consists of a database, a web service, and a single-page web application. The main purpose of the server side is to store the sensor measurements and metadata (such as geolocation and sensor type) sent from the user's mobile application. The stored records can be accessed and displayed in the web application, making the data publicly available. This creates a powerful information system that allows users to track and monitor various measured values in real-time and across different locations. The database can also be exported in comma-separated files, allowing users to use the data for further research or analysis.

3.5. Hardware. The designed hardware consists of several key components. It is designed to be a general-purpose system for acquiring and evaluating analog sensor measurements, and the first version of the hardware includes a dedicated socket for a specific gas sensor. In the case study experiment, an MQ-135 analog air-quality sensor is used. This is a hazardous semiconductor gas sensor that is commonly used for air quality control and is suitable for detecting a range of harmful gases such as ammonia, sulfide, and benzene. The sensor has a simple drive circuit and offers a number of benefits, including long life, low cost, and good sensitivity to harmful gases over a wide range. It is suitable for a variety



(a)

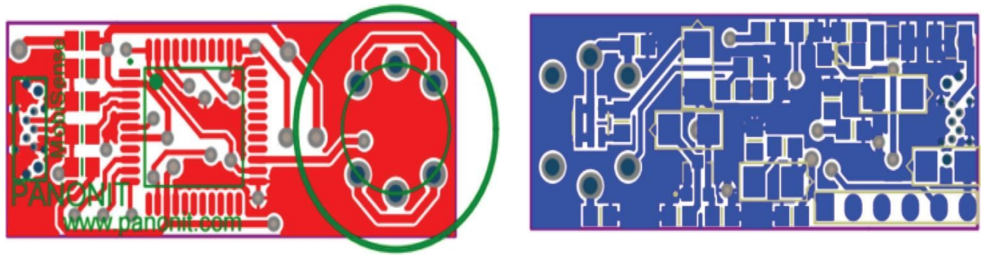
(b)

Figure 4: Electrical schematic of the designed board: (a) analog sensor, USB, and power supply; (b) microcontroller part.

of applications and can be used as a portable domestic or industrial air pollution detector.

The MQ-135 sensor has six pins, four of which are used to fetch signals, and the other two are used to provide a heating current. It operates on a voltage of AC (alternating current) or DC (direct current) $5\text{V} \pm 0.1$ and has a heating consumption of less than 800 mW. The electrical schematic of the designed board is shown in Figure 4. It utilizes an 8-bit Atmel ATmega32U4 microcontroller with 16/32 kB of in-system programing flash and a USB connection. It is USB-powered and has an internal analog/digital (A/D) converter and an internal reference voltage. The sensor board is supplied with 5 V of power via the USB connection, and a voltage regulator is used to maintain a constant voltage and supply the microcontroller with 3.3 V.

The sensor board's design ensures minimal power draw from the smartphone's USB connection, optimizing power efficiency to minimize the impact on the smartphone's battery life. Preliminary testing indicates that, with continuous use for air quality measurements and data transmission to



(a) (b)

Figure 5: PCB layout of the sensor board—top layer and bottom layer: (a) top layer and (b) bottom layer.

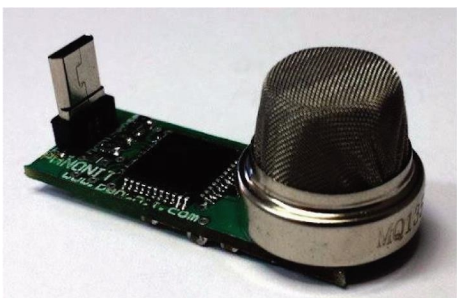


Figure 6: Prototype of the developed system.

the web, the smartphone's battery life is expected to decrease by a marginal percentage, ensuring several hours of uninterrupted usage on a single charge.

The printed circuit board (PCB) layout of the prototype is displayed in Figure 5, showing the top and the bottom layers.

The prototype of the developed system is presented in Figure 6.

3.6. Firmware. The firmware for the sensor board is developed as a generic HID with configured A/D conversion. The firmware reads data from the A/D converter and forwards it to the mobile application, where it is interpreted and displayed to the user.

Before taking a measurement, it is necessary to heat the sensor to ensure accurate data. This is done by applying a current to the sensor through a field-effect transistor, which is controlled by a general-purpose input–output pin (as shown in Figure 4 (a)). The real data from the sensor is in analog form, so it must be converted to a digital signal using the ADC before it can be processed by the MCU (microcontroller) and sent to the host.

The ATmega32U4 microcontroller has a 10-bit successive approximation ADC, which is connected to a 12-channel analog multiplexer that provides six single-ended voltage inputs. In this system, only one analog channel is used by the MQ-135 sensor, leaving 11 available channels for other potential measurements. The ADC has a Sample and Hold circuit that maintains a constant level of input voltage during the conversion process. The microcontroller also has internal reference voltages of nominally 2.56 V or AVCC that can be used for the conversion.

In terms of firmware design, there are two callback functions: ProcessHIDReport for processing reports received from the host and CreateHIDReport for sending data to the host. ProcessHIDReport accepts the following commands from the host:

(i) Command 1: start heating the sensor (if necessary).
(ii) Command 2: stop heating the sensor (if necessary).
(iii) Command 3: start measurements.
(iv) Command 4: stop measurements.

CreateHIDReport performs the A/D conversion to read the sensor probe measurement and sends the data back to the host. This simple communication protocol is designed to be easy to use and understand.

3.7. USB Interface. All USB devices provide information about themselves in a data structure called USB descriptors. These descriptors are hierarchical and contain information about the device, its configuration, endpoints, and interfaces. The host obtains the descriptors from the device by sending standard control requests to the default endpoint. In response, the device sends the descriptors with the required information.

USB devices can operate in two different modes: as a host or as a device. The sensor board is designed to operate as a USB device. It is developed according to the generic HID device application, where the USB subclass is undefined. This approach allows the sensor board to use the basic USB HID drivers included in most modern operating systems without requiring any special drivers. The sensor board has one interface with two endpoints for input and output. It does not need a separate power connection because it draws all necessary power from the smartphone's USB interface.

By default, the sensor board can accept and send up to 8-byte reports to and from the USB host. The bytes sent from the host are interpreted as commands, while the bytes sent from the device to the host are interpreted as answers or data packets. When the system is started, the sensor board automatically enumerates and functions as a vendor HID device. When controlled by a custom HID class application, reports can be sent and received using the standard data endpoint and control request methods defined in the HID specification.

The USB descriptor for the sensor board is developed according to the USB speeds supported by the microcontroller

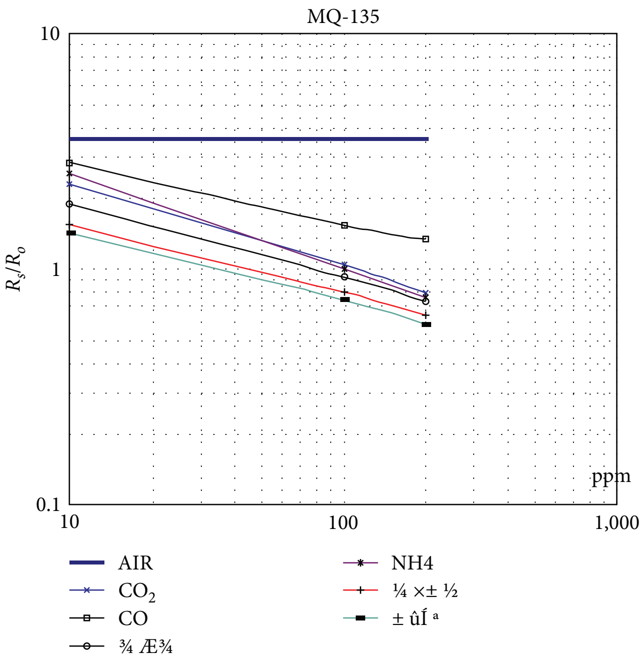


Figure 7: Sensitivity characteristics of MQ-135.

(low-speed mode and full-speed mode). It is designed to operate in full-speed mode. The descriptor is also developed according to the relevant standards: USBIF HID specification [53] and USBIF HID usage tables [54]. This ensures that the sensor board is compliant with the relevant standards and can be used with a variety of host devices.

If a figure consists of multiple panels, they should be ordered logically and labeled with lowercase Roman letters (i.e., a, b, c, etc.). If it is necessary to mark individual features within a panel (e.g., in Figure 3 (a)), this may be done with lowercase Roman numerals, i, ii, iii, iv, etc. All labels should be explained in the caption. Panels should not be contained within boxes unless strictly necessary.

3.8. Calibration. Many sensors on the market are suitable for noncritical applications without any additional calibration. However, to achieve the best possible accuracy, it is important to calibrate the sensor for the specific purpose it will be used for. The main characteristics of a good sensor are precision and resolution. Accuracy is a combination of these characteristics with proper calibration. By calibrating the sensor, it is possible to improve its precision and resolution, which can result in more accurate measurements. Calibration is especially important for applications where the accuracy of the measurements is critical, such as in scientific research or industrial processes.

MQ-135 sensor has been used for measuring purposes in the system described in this paper. Its sensitivity characteristics are displayed in Figure 7.

The graphics in Figure 7 represent the power function (Equation (1)), which indicates ppm (parts per million) measurement (Equation (2)):

$$y = kx^n, \quad (1)$$

$$\text{ppm} = k\left(\frac{R_s}{R_o}\right)^n. \quad (2)$$

The scaling factor (k) and exponent (n) can be obtained for the required measured gases by applying power regression. From Equation (2), R_o can be calculated as Equation (3):

$$R_o = R_s e^{\frac{\ln\left(\frac{a}{\text{ppm}}\right)}{b}}. \quad (3)$$

Due to calibrate the sensor, information on the amount of a certain gas in the system is needed. The sensor resistance output value R_s can be read. Accounting all that, calibrated R_o can be calculated with Equation (3). The calibration process should be repeated for each type of gas.

The calibration of low-cost MQ-135 sensors involves both laboratory and field procedures to enhance precision and reliability. Initially, sensors are calibrated in a controlled laboratory environment with known concentrations of CO gas to establish a baseline response curve. Subsequently, field calibration adjusts this curve based on real-world environmental conditions, alongside a reference-grade instrument, to account for variables such as temperature and humidity.

Addressing the inherent limitations of such sensors, detailed calibration processes and statistical data analysis significantly improve their accuracy. Environmental compensation techniques are employed, adjusting readings based on ambient temperature and humidity to ensure reliable measurements across varied conditions.

Comparison with the EXTECH CO10 meter, which serves as a reasonable accuracy benchmark, acknowledges the limitations of both the low-cost sensor and the reference instrument. Through rigorous calibration and adjustments for environmental factors, a cost-effective, reasonably accurate solution for air quality monitoring in noncritical applications is achieved.

4. Results and Discussion

4.1. Result Analysis. This section is about the previous experiences and results related to the selected papers through a systematic literature review. These conclusions are significant for further work and what has been done in the last decade in the progress of measuring air quality in the world. Figure 8 presents included papers and the publication year of the papers. At least one paper has been published on a given topic in the previous 12 years, excepted 2022 due to the inclusion and exclusion criteria of this research, which implies that the trend and awareness of air pollution are increasing, as well as potential ideas in solving that problem when it comes to air measurement. Citizens' awareness is raised if they have daily insight into which particles in the air are most present so that information reaches them in real-time. Between 2012 and 2019, an average of two papers per year were published in the field of papers considered in this research. In 2020, the number of articles published increased rapidly and reached ten, representing a milestone since the publication of the first paper on this topic. The expansion of papers in 2020 can be

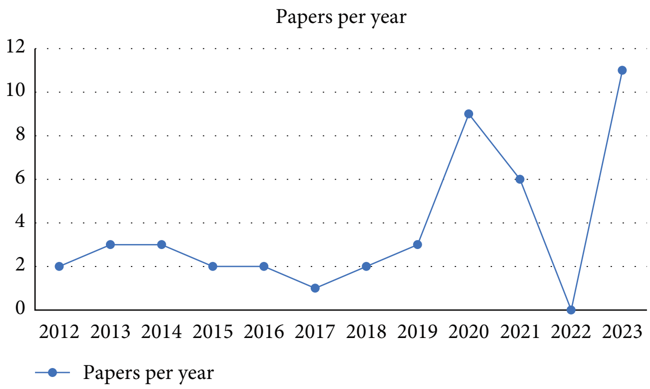


FIGURE 8: Published papers per year.

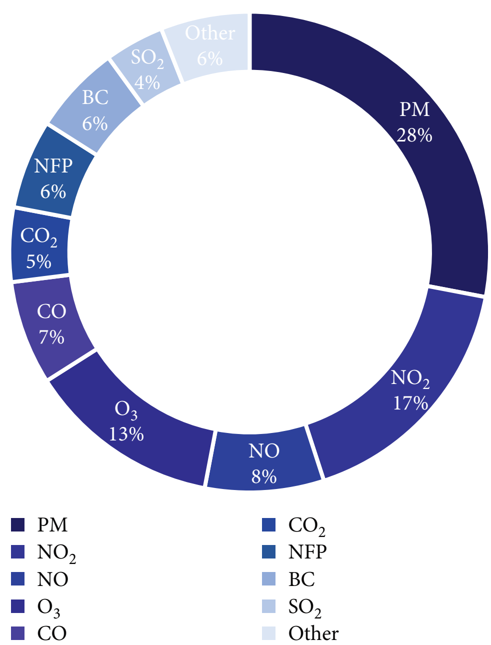


FIGURE 9: Particles included in measurements in selected papers.

linked to the coronavirus pandemic, because at that time, air pollution, due to the shutdown of many industrial plants and the limited movement of the population, led to pollution in cities being much lower than average. The researchers, guided by this, could use that time to lay the foundations for their future work. The papers from the year 2023 are being predominantly included in the research, 11 of 44, indicating a growing emphasis on this field and its increasing relevance year by year.

Figure 9 presents the particles that were measured in the selected research. The largest percentage of described devices and sensors refers to the measurement of PM particles. PM particles are divided into PM2.5 and PM10, and this refers to the diameter of the particle itself expressed in micrometers. Chemical compounds are also specified in the papers, so 12 papers explicitly deal with the measurement of NO_2 particles, followed by NO with six and O_3 particles with nine papers. All these compounds, when they exceed a certain defined limit, have a negative effect on air quality and are important in research for the health of the environment and people, especially in larger populated areas. The increase in these particles results in the use of industrial plants, transportation, and general exhaust gases.

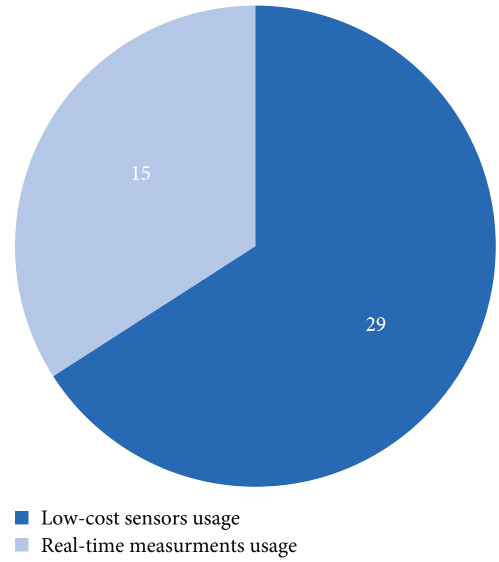


FIGURE 10: Count of papers that provide low-cost sensors and real-time measurements.

It is important to point out that devices and sensors are designed differently in relation to the type of particles they measure in order to be effective. Due to the size of the particles themselves and their properties, it is necessary to implement devices and sensors in a different way in order to qualitatively measure the percentage of the presence of particles in the air.

Figure 10 shows the count of papers that use low-cost sensors as well as those that support real-time measurement. A total of 29 papers describe a low-cost device with associated sensors for measuring harmful particles in the air. On the other hand, in 15 papers, the measurement was performed in real-time. These data confirm the increasing use of cheap devices from the field of mobile technologies that read measurements in real-time. The papers [10, 22] highlight the problem of high prices of individual parts of the device, but also of the device as a whole for measuring particles in the air. The problem of high prices can greatly affect the very course of research and solving the problem of air pollution. “Air monitoring instrumentation continues to advance toward greater portability, higher time resolution, greater capacity for operating autonomously, and lower costs; it is likely that these types of studies will become even more ubiquitous,” as noted in the paper [11]. On the other hand, the popularization of low-cost devices is emphasized as a form of the future in this field, as described in the paper [13]. Additionally to this is a research from 2020 [14] that is based on real-time measurement of harmful particles using mobile technologies as an efficient, effective, and low-cost way of measuring harmful particles in the air.

Table 1: Measured values in the case study CO (ppm).

CO measured values (ppm) with the developed device	CO measured values (ppm) with Extech CO10	The difference (%)	Location	
			Latitude	Longitude
5	5	0	45.2426875	19.8405901
15	16	6.25	45.2426875	19.8405901
4	4	0	45.2426875	19.8405901
11	12	8.34	45.2427164	19.8428234
10	11	9.1	45.2427164	19.8428234
14	14	0	45.2427164	19.8428234
3	3	0	45.247278	19.820828
30	32	6.25	45.247278	19.820828
43	44	2.28	45.247278	19.820828
1	1	0	45.2676214	19.843332
62	63	1.59	45.2676214	19.843332
22	21	4.55	45.2676214	19.843332
11	12	8.34	45.2458253	19.7960826
6	6	0	45.2458253	19.7960826
28	30	6.67	45.2458253	19.7960826

In addition to the results of a systematic literature review, in order to provide an adequate solution, the authors included research in the field of smartphone-based embedded measuring instruments [55–58], as well as smartphone-based measuring instrument interfaces. This results in the development of a solution in the form of a device that is presented in the case study [59–63]. Including other databases might result with a broader selection of studies, but it is left for future work.

A number of papers show interest in the development of low-cost sensors for measuring harmful particles in the air. The results of the existing measuring devices show the influence of various factors, such as the environment, traffic, and altitude on the results, which show a high concentration of harmful particles. The trend of sensor development in this area is to increase, as shown by the review of the literature, guided by the motivation of protecting the environment and human health. Future trends in this specific domain may be the use of artificial intelligence for the detection and recognition of particle concentration, as well as examples of image processing through segmentation at the level of satellite images.

4.2. Case Study. A case study related to air quality measurement is presented in this section, along with further discussion. The case study was conducted using the system described in this paper.

Although different types of gas concentration measurements could be performed by the developed system as specified in the previous sections, CO concentration is assessed in the city of Novi Sad, Serbia. The measurements were taken at car workshops and public garages, taking into account that these places have higher concentrations of CO in the air. Multiple measurements were taken and validated against the commercial gas analyzer instrument, EXTECH CO10: Carbon Monoxide Meter. It displays CO levels from 0 to 1,000 ppm, with 1 ppm resolution with ±5% or ±10 ppm basic accuracy. Some of the measurements were taken in empty spaces to achieve lower ppm values, and some were taken close to the cars with running engines in order to acquire higher concentration measurements. All measurement values, along with the GPS location of the places where the measurements were taken, are displayed in Table 1. The majority of values measured with the proposed system match the corresponding values obtained with the commercial gas analyzer. There are a few instances where the measured values deviate slightly and some measurements have a perfect match. Overall, the measured values align closely, suggesting reliable measurements and a relatively accurate monitoring system.

The CO measurement values presented in the web application are displayed in Figure 11.

The developed system allows the usage of a smartphone or a tablet device with a larger screen and attached sensor board in order to measure values from the installed analog sensors. Moreover, it enables the analog sensor's continuous monitoring in a real-time manner. Acquired values can be sent to the remote server, stored in the database, and then used for further analysis and possible dissemination of the data.

Data recorded on the remote server provide a substantial contribution to spatial analysis because users can track the locations of all the measured values displayed by the type of measurement. For instance, if a large number of devices in a region measure similar types of measurements (i.e., CO), it is possible to track this movement. The more users in the system, the larger area is covered. This possibility might be used for spatial analysis or studies regarding the forecast.

The designed hardware component can support various types of analog sensors for different measurements such as air humidity, temperature, solar and ultraviolet radiation, etc. In this paper, a prototype of the system that measures only one sensor output at a time has been presented. It is possible to measure more values simultaneously, but that requires additional sockets in the board supported by available ADC channels. One of the future research directions is to include additional logic on the board, which would enable the software to acquire more measurable physical values. The

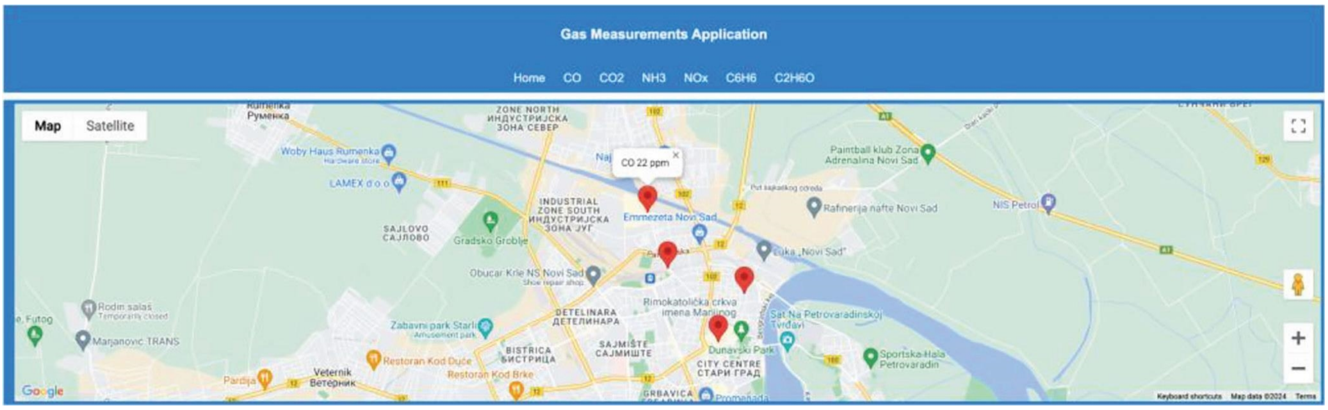


FIGURE 11: Web application—measured data displayed on the map by gas type.

proposed system can already process more sensor outputs and send the data over USB to the host by changing the report size from 8 to more bytes.

In comparison to other similar devices, the proposed device has an advantage in terms of size, accessibility, and price (under \$10), which is very important in developing countries that cannot afford expensive systems with similar capabilities. In addition, an important feature is that the board containing the sensor is powered by the mobile device USB port, which leads to immediate measurement of the analog values whenever the mobile device battery is charged. Moreover, there is no need for additional cables since the sensor board is directly attached to the mobile device, making an easy-to-use, mobile monitoring system of desired analog sensor outputs.

As a confirmation of the presented work, a case study verified that the developed system is capable of detecting concentration levels in the air. Moreover, previously defined values can be used to trigger an alarm that notifies the user about the values that exceed normal conditions. Differences between industrial measurements and those done by the developed device are within the range of the industrial device's accuracy. Thus, measurements done by the developed device can be accepted.

As previously noted, the air quality sensor used in the case study can deal with other gas concentrations, not just CO measurements. In order to acquire other supported gas concentrations, the proposed system should be just recalibrated. When it comes to air quality, continuous monitoring can be used for the prevention of chronic respiratory diseases, giving users the possibility to track air quality by using simple and inexpensive measuring equipment that could easily fold into the user's daily activities.

5. Conclusions

The development of the proposed low-cost and easy-to-use monitoring system for analog sensor measurements was the result of a detailed analysis of current solutions from reviewed papers. The results shown in Section 4 proved the usefulness of the proposed device for real-time monitoring of gas concentrations, providing high spatial and temporal resolution measurements through a hardware device attached to a mobile device. There was no significant difference between the measurements taken with the industrial device and the proposed system. Thanks to its small dimensions and ease of use, it represents a cost-effective and accessible monitoring solution for various environmental applications.

While the system does have certain limitations, its potential for improvement lies in the development of end-user applications for different operating systems and the expansion of supported sensors, which could enhance its usability and functionality. By systematically reviewing the literature presented in this paper, we underscore the significance of affordable and accessible monitoring systems in advancing environmental research and protection. This study highlights the essential role of low-cost and user-friendly monitoring systems in environmental research and protection, showcasing the prevalent use of analog sensors in the creation of economical mobile systems that significantly improve the accessibility and affordability of monitoring solutions.

Overall, the proposed system and the literature review demonstrate the importance of affordable and accessible monitoring systems in advancing environmental research and protection. The newly developed system holds immense potential for monitoring gas concentrations across various environments, and with further advancements, it could emerge as a valuable tool for researchers, engineers, and professionals engaged in environmental monitoring.

Data Availability

Data will be available upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

References

[1] G. Kambourakis, C. Kolias, D. Geneiatakis, G. Karopoulos, G. M. Makrakis, and I. Kounelis, "A state-of-the-art review on the security of mainstream IoT wireless PAN protocol stacks," *Symmetry*, vol. 12, no. 4, Article ID 579, 2020.

[2] J. H. Park, "Advances in future internet and the industrial internet of things," *Symmetry*, vol. 11, no. 2, Article ID 244, 2019.

[3] R. Hassan, F. Qamar, M. K. Hasan, A. H. M. Aman, and A. S. Ahmed, "Internet of things and its applications: a comprehensive survey," *Symmetry*, vol. 12, no. 10, Article ID 1674, 2020.
[4] T. Martin, D. Geneiatakis, I. Kounelis, S. Kerckhof, and I. N. Fovino, "Towards aformal IoT security model," *Symmetry*, vol. 12, no. 8, Article ID 1305, 2020.
[5] S. Sladojevic, M. Dulic, P. Jelovac, I. Edelinski, and D. Stefanovic, "One solution of web application for data acquisition from remote sensing devices," in *Proceedings of 14th International Symposium Infoteh-Jahorina*, Institute of Electrical and Electronics Engineers (IEEE), East Sarajevo, 2015.
[6] S. Sladojevic, M. Arsenovic, T. Loncar-Turukalo, M. Sladojevic, and D. Culibrk, "Personalized USB biosensor module for effective ECG monitoring," in *In pHealth 2016—Proceedings of the 13th International Conference on Wearable Micro and Nano Technologies for Personalised Health, Studies in Health Technology and Informatics*, vol. 224, pp. 201–206, 2016.
[7] T.-H. Kim, V. S. Solanki, H. J. Baraiya, A. Mitra, H. Shah, and S. Roy, "A smart, sensible agriculture system using the exponential moving average model," *Symmetry*, vol. 12, no. 3, Article ID 457, 2020.
[8] O. Ghaffarpasand, D. C. S. Beddows, K. Ropkins, and F. D. Pope, "Real-world assessment of vehicle air pollutant emissions subset by vehicle type, fuel and EURO class: new findings from the recent UK EDAR field campaigns, and implications for emissions restricted zones," *Science of the Total Environment*, vol. 734, Article ID 139416, 2020.
[9] R. Hagemann, U. Corsmeier, C. Kottmeier, R. Rinke, A. Wieser, and B. Vogel, "Spatial variability of particle number concentrations and NOx in the Karlsruhe (Germany) area obtained with the mobile laboratory 'AERO-TRAM'," *Atmospheric Environment*, vol. 94, pp. 341–352, 2014.
[10] S. Devarakonda, P. Sevusu, H. Liu, R. Liu, L. Iftode, and B. Nath, "Real-time air quality monitoring through mobile sensing in metropolitan areas," in *Proceedings of the 2nd ACM SIGKDD International Workshop on Urban Computing*, pp. 1–8, ACM, Chicago Illinois, 2013.
[11] H. L. Brantley, G. S. W. Hagler, E. S. Kimbrough, R. W. Williams, S. Mukerjee, and L. M. Neas, "Mobile air monitoring data-processing strategies and effects on spatial air pollution trends," *Atmospheric Measurement Techniques*, vol. 7, no. 7, pp. 2169–2183, 2014.
[12] J. E. Barnes and N. C. P. Sharma, "An inexpensive active optical remote sensing instrument for assessing aerosol distributions," *Journal of the Air & Waste Management Association*, vol. 62, no. 2, pp. 198–203, 2012.
[13] E. Yaacoub, A. Kadri, M. Mushtaha, and A. Abu-Dayya, "Air quality monitoring and analysis in Qatar using a wireless sensor network deployment," in *2013 9th International Wireless Communications and Mobile Computing Conference (IWCMC)*, pp. 596–601, IEEE, Sardinia, Italy, 2013.
[14] Y. Ben-Aboud, M. Ghogho, and A. Kobbane, "A research-oriented low-cost air pollution monitoring IoT platform," in *2020 International Wireless Communications and Mobile Computing (IWCMC)*, pp. 1324–1329, IEEE, Limassol, Cyprus, 2020.
[15] H. Tariq, A. Abdaoui, F. Touati, M. A. E. Al-Hitmi, D. Crescini, and A. B. Mnaouer, "An autonomous multi-variable outdoor air quality mapping wireless sensors IoT node for Qatar," in *2020 International Wireless Communications and Mobile Computing (IWCMC)*, pp. 2164–2169, IEEE, Limassol, Cyprus, 2020.
[16] A. Samad and U. Vogt, "Mobile air quality measurements using bicycle to obtain spatial distribution and high temporal resolution in and around the city center of Stuttgart," *Atmospheric Environment*, vol. 244, Article ID 117915, 2021.
[17] J. Chong, Y. J. Kim, M. Gu, T. Wagner, and C. H. Song, "Mobile MAX-DOAS observation of NO_2 and comparison with OMI satellite data in the western coastal areas of the Korean peninsula," *Chemosphere*, vol. 143, pp. 10–16, 2016.
[18] M. Van Poppel, J. Peters, and N. Bleux, "Methodology for setup and data processing of mobile air quality measurements to assess the spatial variability of concentrations in urban environments," *Environmental Pollution*, vol. 183, pp. 224–233, 2013.
[19] S. Crocchianti, S. Del Sarto, M. G. Ranalli et al., "Spatiotemporal correlation of urban pollutants by long-term measurements on a mobile observation platform," *Environmental Pollution*, vol. 268, Article ID 115645, 2021.
[20] A. S. Mihăiţă, L. Dupont, O. Chery, M. Camargo, and C. Cai, "Evaluating air quality by combining stationary, smart mobile pollution monitoring and data-driven modelling," *Journal of Cleaner Production*, vol. 221, pp. 398–418, 2019.
[21] A. Samad and U. Vogt, "Investigation of urban air quality by performing mobile measurements using a bicycle (MOBAIR)," *Urban Climate*, vol. 33, Article ID 100650, 2020.
[22] Y. Yang, Z. Zheng, K. Bian, L. Song, and Z. Han, "Real-time profiling of fine-grained air quality index distribution using UAV sensing," *IEEE Internet of Things Journal*, vol. 5, no. 1, pp. 186–198, 2018.
[23] S. Hankey and J. D. Marshall, "Land use regression models of on-road particulate air pollution (particle number, black carbon, $PM_{2.5}$, particle size) using mobile monitoring," *Environmental Science & Technology*, vol. 49, no. 15, pp. 9194–9202, 2015.
[24] K. S. E. Phala, A. Kumar, and G. P. Hancke, "Air quality monitoring system based on ISO/IEC/IEEE 21451 standards," *IEEE Sensors Journal*, vol. 16, no. 12, pp. 5037–5045, 2016.
[25] L. Wang and Y. Huang, "Mobile atmospheric sensing," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, vol. XLII-3/W2, no. W2, pp. 217–221, 2017.
[26] J. Peters, J. Theunis, M. V. Poppel, and P. Berghmans, "Monitoring PM10 and ultrafine particles in urban environments using mobile measurements," *Aerosol and Air Quality Research*, vol. 13, no. 2, pp. 509–522, 2013.
[27] X. Yi, Z. Zhang, and P. Smith, "Real-time measurements of landfill atmospheric ammonia using mobile white cell differential optical absorption spectroscopy system and engineering applications," *Journal of the Air & Waste Management Association*, vol. 71, no. 1, pp. 34–45, 2021.
[28] A. A. Hapsari, A. I. Hajamydeen, D. J. Vresdian, M. Manfaluthy, L. Prameswono, and E. Yusuf, "Real time indoor air quality monitoring system based on IoT using MQTT and wireless sensor network," in *2019 IEEE 6th International Conference on Engineering Technologies and Applied Sciences (ICETAS)*, pp. 1–7, IEEE, Kuala Lumpur, Malaysia, 2019.
[29] R. S. AbdulWahhab, "Air quality monitoring system: towards iot based system for air pollutant concentration prediction," in *2020 10th International Conference on Advanced Computer Information Technologies (ACIT)*, pp. 311–316, IEEE, Deggendorf, Germany, 2020.
[30] W. Mui, B. Der Boghossian, A. Collier-Oxandale et al., "Development of a performance evaluation protocol for air

sensors deployed on a google street view car," *Environmental Science & Technology*, vol. 55, no. 3, pp. 1477–1486, 2021.

[31] E. Twahirwa, K. Mtonga, D. Ngabo, and S. Kumaran, "A LoRa enabled IoT-based air quality monitoring system for smart city," in *2021 IEEE World AI IoT Congress (AIIoT)*, pp. 0379–0385, IEEE, Seattle, WA, USA, 2021.

[32] A. Candia, S. N. Represa, D. Giuliani, M. A. Luengo, A. A. Porta, and L. A. Marrone, "Solutions for SmartCities: proposal of a monitoring system of air quality based on a LoRaWAN network with low-cost sensors," in *2018 Congreso Argentino de Ciencias de la Informática y Desarrollos de Investigación (CACIDI)*, pp. 1–6, IEEE, Buenos Aires, 2018.

[33] A. Ro u, D.-E. Constantin, M. Voiculescu et al., "Assessment of NO_2 pollution level during the COVID-19 lockdown in a Romanian City," *International Journal of Environmental Research and Public Health*, vol. 18, no. 2, Article ID 544, 2021.

[34] E. A. Riley, L. Banks, J. Fintzi et al., "Multi-pollutant mobile platform measurements of air pollutants adjacent to a major roadway," *Atmospheric Environment*, vol. 98, pp. 492–499, 2014.

[35] C. H. Yu, Z. Fan, P. J. Lioy, A. Baptista, M. Greenberg, and R. J. Laumbach, "A novel mobile monitoring approach to characterize spatial and temporal variation in traffic-related air pollutants in an urban community," *Atmospheric Environment*, vol. 141, pp. 161–173, 2016.

[36] X. Qin, L. Hou, J. Gao, and S. Si, "The evaluation and optimization of calibration methods for low-cost particulate matter sensors: inter-comparison between fixed and mobile methods," *Science of The Total Environment*, vol. 715, Article ID 136791, 2020.

[37] S. Dhingra, R. B. Madda, A. H. Gandomi, R. Patan, and M. Daneshmand, "Internet of things mobile-air pollution monitoring system (IoT-Mobair)," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 5577–5584, 2019.

[38] M. A. Arain, V. H. Bennetts, E. Schaffernicht, and A. J. Lilienthal, "Sniffing out fugitive methane emissions: autonomous remote gas inspection with a mobile robot," *The International Journal of Robotics Research*, vol. 40, no. 4-5, pp. 782–814, 2021.

[39] W. Ji, K. Han, and T. Liu, "Trip-based mobile sensor deployment for drive-by sensing with bus fleets," *Transportation Research Part C: Emerging Technologies*, vol. 157, Article ID 104404, 2023.

[40] L. B. Frederickson, H. S. Russell, D. Fessa et al., "Hyperlocal air pollution in an urban environment-measured with low-cost sensors," *Urban Climate*, vol. 52, Article ID 101684, 2023.

[41] K.-Y. Wu, I.-W. Hsia, P.-Y. Kow, L.-C. Chang, and F.-J. Chang, "High-spatiotemporal-resolution PM2.5 forecasting by hybrid deep learning models with ensembled massive heterogeneous monitoring data," *Journal of Cleaner Production*, vol. 433, Article ID 139825, 2023.

[42] Y.-L. Chiang, J.-C. Wang, C.-H. Sun, T.-H. Wen, J.-Y. Juang, and J.-A. Jiang, "Mobile measurement of particulate matter concentrations on urban streets: system development and field verification," *IEEE Access*, vol. 8, pp. 197617–197629, 2020.

[43] A. Chakraborty, R. D. Gupta, M. Z. Kabir, and S. Dhar, "Development of an IoT-enabled cost-effective asthma patient monitoring system: integrating health and indoor environment data with statistical analysis and data visualization," *Internet of Things*, vol. 24, Article ID 100942, 2023.

[44] D. D. Drajic and N. R. Gligoric, "Reliable low-cost air quality monitoring using off-the-shelf sensors and statistical calibration," *Elektronika ir Elektrotechnika*, vol. 26, no. 2, pp. 32–41, 2020.

[45] M. T. Verde, P. Guerriero, F. Bonavolonta et al., "A measurement system for enteric CH4 emissions monitoring from ruminants in livestock farming," *Acta IMEKO*, vol. 12, no. 4, pp. 1–6, 2023.

[46] M. Maslouski, E. Jarosz-Krzemińska, P. Jagoda, and E. Adamiec, "A mobile car monitoring system as a supplementary tool for air quality monitoring in urban and rural environments: the case study from Poland, Sci," *Scientific Reports*, vol. 13, no. 1, Article ID 15856, 2023.

[47] I. Vajs, D. Drajic, and Z. Cica, "COVID-19 lockdown in Belgrade: impact on air pollution and evaluation of a neural network model for the correction of low-cost sensors' measurements," *Applied Sciences*, vol. 11, no. 22, Article ID 10563, 2021.

[48] A. Cavaliere, F. Carotenuto, F. Di Gennaro et al., "Development of low-cost air quality stations for next generation monitoring networks: calibration and validation of PM2.5 and PM10 sensors," *Sensors*, vol. 18, no. 9, Article ID 2843, 2018.

[49] P. Gopal Krishna, Y. Subbarayudu, G. S. Keerthana et al., "IoT sensor based sustainable air quality monitoring system for humans and ecosystems in the world empowerment," *E3S Web of Conferences*, vol. 430, Article ID 01080, 2023.

[50] J. S. Botero-Valencia, C. Barrantes-Toro, D. Marquez-Viloria, and J. M. Pearce, "Low-cost air, noise, and light pollution measuring station with wireless communication and tinyML," *HardwareX*, vol. 16, Article ID e00477, 2023.

[51] I. Vajs, D. Drajic, and Z. Cica, "Data-driven machine learning calibration propagation in a hybrid sensor network for air quality monitoring," *Sensors*, vol. 23, no. 5, Article ID 2815, 2023.

[52] G. Mekuria, "Air pollution: a review of its impacts on health and ecosystems, and analytical techniques for their measurement and modeling," *Journal of Environmental Informatics Letters*, vol. 10, pp. 115–131, 2023.

[53] USB Implementers' Forum, "Device class definition for human interface devices (HID) firmware specification," 2022.

[54] USB Implementers' Forum, "HID usage tables for universal serial bus (USB)," 2023.

[55] S. Abbate, M. Avvenuti, F. Bonatesta, G. Cola, P. Corsini, and A. Vecchio, "A smartphone-based fall detection system," *Pervasive and Mobile Computing*, vol. 8, no. 6, pp. 883–899, 2012.

[56] N. Ravi, N. Dandekar, P. Mysore, and M. Littman, "Activity recognition from accelerometer data," *American Association for Artificial Intelligence*, pp. 1541–1546, 2005.

[57] P. Pelegris, K. Banitsas, T. Orbach, and K. Marias, "A novel method to detect heart beat rate using a mobile phone," in *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology*, pp. 5488–5491, IEEE, Buenos Aires, Argentina, 2010.

[58] D. A. Johnson and M. M. Trivedi, "Driving style recognition using a smartphone as a sensor platform," in *2011 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, vol. 2011, pp. 1609–1615, IEEE, Washington, DC, USA, 2011.

[59] S. Aram, A. Troiano, and E. Pasero, "Environment sensing using smartphone," in *2012 IEEE Sensors Applications Symposium Proceedings*, pp. 1–4, IEEE, Brescia, Italy, 2012.

[60] P. Zappi, E. Bales, J. Park, W. Griswold, and T. Rosing, "The citisense air quality monitoring mobile sensor node," Proc. IPSN12 Workshop Mob. Sens, 2012.

[61] D. Oletic and V. Bilas, “Empowering smartphone users with sensor node for air quality measurement,” *Journal of Physics: Conference Series*, vol. 450, Article ID 012028, 2013.

[62] D. Hasenfratz, O. Saukh, S. Sturzenegger, and L. Thiele, “Participatory air pollution monitoring using smartphones,” in *Proceedings of the 2nd International Workshop on Mobile Sensing*, Academic Press, Beijing, China, 2012.

[63] T. Fahrni, M. Kuhn, P. Sommer, R. Wattenhofer, and S. Welten, “Sundroid: solar radiation awareness with smartphones,” *Associations for Computing Machinery*, pp. 365–374, 2011.