REVIEW ARTICLE

Evaluation Methodologies for Wireless Outdoor Air Monitor Using Low-cost Sensors: Field testing and end-user perspective

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ABSTRACT

With increasing concerns about the impact of outdoor air quality on public health, demand rises for cost-effective, scalable air monitoring solutions. Low-cost sensors offer promise for monitoring outdoor air quality, with potential for widespread deployment. This article presents a comprehensive evaluation methodology for these sensors, focusing on real-world outdoor performance and end-user perspectives. Relevant methodologies for evaluating wireless air monitor with low-cost sensors were sourced from databases. The study outlines rigorous field-testing methodology, addressing sensor accuracy and stability tested in diverse environmental conditions under various climatic and geographical scenarios. This study explores end-user perspectives ensuring data relevance. This research contributes to discourse on low-cost sensor use, emphasizing a comprehensive evaluation framework encompassing technical performance, usability testing, and user perspectives. Insights gained can guide reliable, user-centric air monitoring solutions, enhancing our ability to mitigate health risks from outdoor air pollution.
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INTRODUCTION

Several researchers globally have highlighted the changing paradigm of air pollution monitoring, emphasizing the development of portable, lower-cost air pollution sensors and wireless communication infrastructure [1]. This emphasized the need for increased monitoring density and the reliance on low-cost sensors by public authorities due to budget constraints [2]. Some discussed the impact of air pollution on agriculture, emphasizing the importance of environmental monitoring for economic development [3]. Previous studies underscored the significance of indoor air quality monitoring for managing asthma, a common pediatric chronic disease, highlighting the relevance of air quality monitoring for public health [4].

The importance of sensor calibration and the deployment of air quality monitoring stations aligning with the need for technical performance evaluations and sensor calibration techniques were emphasized to proof the feasibility and reliability of the system [4, 5]. This includes assessing parameters such as sensor accuracy, stability, sensitivity, selectivity, and response time. By conducting rigorous technical performance assessments, researchers and practitioners can verify that the sensors meet quality standards and provide data that can be trusted for decision-making and regulatory compliance [6]. New technology for air monitoring must be developed in tandem with an appropriate and reliable evaluation approach in order to deliver precise and consistent air quality monitoring [7].

Traditional air monitoring methods, while established and reliable, are often associated with several challenges and limitations, highlighting the need for alternative approaches. Traditional air monitoring methods often involve expensive equipment, labor-intensive sample collection, and complex data analysis procedures. The high cost of equipment maintenance, calibration, and operation can limit the scalability of monitoring networks and hinder efforts to increase monitoring coverage in underserved areas [8]. Conventional air monitoring stations are typically stationary and sparsely distributed, resulting in limited spatial coverage and the inability to capture localized variations in air quality. This limitation may lead to underestimation of exposure risks in certain areas, particularly in urban environments with complex pollution sources and dispersion patterns [9]. Traditional air monitoring methods may have limited temporal resolution, with measurements often taken at fixed intervals (e.g., hourly or daily averages). This may not capture short-term fluctuations in pollutant concentrations or provide real-time information needed for timely decision-making and emergency response [10].

Addressing these challenges and limitations requires the development and adoption of alternative approaches to air quality monitoring. Emerging technologies such as low-cost sensors, satellite remote sensing, mobile monitoring platforms, and crowdsourced data collection offer opportunities to overcome some of the limitations of traditional monitoring methods by providing cost-effective, scalable, and real-time monitoring solutions with improved spatial and temporal coverage [11]. By complementing traditional methods with innovative approaches, it is possible to enhance our ability to monitor air quality more effectively, identify pollution hotspots, and implement targeted interventions to protect public health and the environment.

This situation highlighted the role of participatory sensing in addressing air pollution, aligning with the consideration of end-user perspectives and community engagement in air quality monitoring to be able to produce vast and accurate data to the public [12, 13]. The consideration of end user perspectives is also aligning with the usability testing component of sensor evaluation [14]. By assessing usability through user testing and feedback, developers can identify usability issues, improve system design, and enhance user acceptance and adoption [15]. Involving end-users in the evaluation process ensures that the monitoring system is designed and implemented with their needs, preferences, and contexts in mind. End-user perspectives provide valuable insights into usability requirements, use cases, data interpretation needs, and integration with existing workflows or decision-making processes. By considering end-user perspectives, developers can design more user-centric monitoring systems that are more likely to be accepted, adopted, and effectively utilized in real-world settings [16].

In summary, the evaluation of low-cost sensor-based wireless outdoor air monitors requires a comprehensive approach that integrates technical performance assessments, usability testing, and consideration of end-user perspectives. By conducting rigorous technical performance assessments, researchers and practitioners can verify that the sensors meet quality standards and provide data that can be trusted for decision-making and regulatory compliance [6]. This approach contributes to the development of more robust, scalable, and user-centric air monitoring solutions, and advances our collective ability to combat the health risks associated with outdoor air pollution. In summary, this paper emphasized the strategy of enhancing our ability to combat the health concerns connected with outdoor air pollution and added to the overview of evaluation methodologies for low-cost air monitors, which include field testing and end-user perspectives.

MATERIALS AND METHODS

This article provides a thorough evaluation technique for these sensors, including usability testing, end-user feedback, and how well they operate in outdoor environments. It covers a few evaluation-related topics, such as sensor stability and accuracy. Several databases, including PubMed, Springer Online, BioMed Central, and several university databases, were examined to analyse the availability of the most appropriate evaluation procedures, which included field testing and involved the end user in usability testing. The keywords include “field test”, “usability testing”, “collocation” and “air monitors”, and “sensors”. The research, which was carried out between 2000 and 2018, has used a wide spectrum to ensure that all prospective routes for research in this industry have been investigated.

APPROACHES ON EVALUATION TECHNIQUES

Field Testing - Assessment of the Wireless Outdoor Exposure System

Low-cost sensor technologies offer a more affordable alternative to traditional monitoring methods, making it feasible to establish dense monitoring networks even in resource-constrained settings [1]. Many low-cost sensor systems provide real-time data monitoring capabilities, allowing for immediate feedback on air quality conditions. This real-time data access enables timely decision-making for pollution mitigation efforts, public health interventions, and emergency response actions [17]. However, there are controversial; opinions on the data produced by these sensors. They may not provide accurate measurements of air pollutant concentrations, leading to potentially misleading assessments of public health risks. Such inaccurate data could underestimate the severity of air pollution, resulting in inadequate protective measures and increased exposure to harmful pollutants especially among the public [18]. While low-cost sensors offer a more affordable alternative, their reliability and accuracy must be carefully evaluated to ensure effective resource allocation and optimal public health outcomes [1]. To mitigate these environmental and health implications, it is crucial to complement low-cost sensor data with data from traditional monitoring methods and reference instruments. Integrating multiple monitoring approaches can provide a more comprehensive understanding of air quality, improve data reliability, and enhance decision-making processes aimed at protecting human health and the environment.

For monitors that is utilizing wireless system and low-cost sensors, it is essential to evaluate its effectiveness and sensitivity in collecting all the parameter desired for determining the surrounding air quality. Testing should be conducted in a well-controlled environment (not necessarily a laboratory), where accurate measurements are possible. The researcher decides where the experiment will take place, at what time, with which participants, in what circumstances and using a standardized procedure. For in-field experimentations, they are done in every day (i.e., real-life) environment of the participants and compared with the data gathered from conventional air monitoring, commonly referred to as the collocation method. The experimenter still manipulates the independent variable but in a real-life setting [19]. To evaluate the wireless air monitoring system and demonstrate its functionality and feasibility, it is essential to consider the integration of wireless sensor networks (WSN) and the monitoring of air quality parameters. The use of WSN in air quality monitoring has been widely recognized as an effective approach [20]. These systems are designed to provide real-time monitoring of air quality parameters such as PM2.5 concentration, temperature, humidity, and gas concentrations [21].

The deployment of WSN for air quality monitoring is crucial in both indoor and outdoor environments, as it enables the collection of data from various positions, leading to faster and more accurate detection of air quality conditions [20]. Furthermore, the implementation of WSN for air quality monitoring requires the consideration of adaptability and the use of advanced technologies such as wireless communication and embedded systems [22]. The adaptability of the system is crucial for its successful operation in diverse environmental conditions. Additionally, the use of low power wireless communication technologies, such as ZigBee, is essential for the efficient operation of the monitoring system [23]. These technologies enable the unified management and networking of air quality data, providing a basis for the evaluation and improvement of environmental air quality [23].

Moreover, the feasibility of the wireless air monitoring system is supported by the potential for cost-effective deployment in various environments, including industrial settings. Industrial wireless sensor networks have been identified to optimize the management of industrial systems, leading to significant savings and reduced air-pollutant emissions [24]. Additionally, the use of WSN for environmental monitoring extends beyond air quality, with applications in marine-coastal environment monitoring using unmanned aerial vehicles [25]. The assessment of the wireless air monitoring system involves the integration of WSN, adaptability, low power wireless communication technologies, and the potential for cost-effective deployment in various environments. These factors collectively contribute to the functionality and feasibility of the system, enabling real-time monitoring and data management for the evaluation and improvement of air quality. This information is critical for optimizing sensor networks and making informed decisions to address air quality concerns.

The lack of standardized guidelines or procedures for assessing new technological sensors, including low-cost sensors, presents a significant challenge in the field of air quality monitoring. Without established protocols for evaluating sensor performance, reliability, and accuracy, there is a risk of inconsistent data quality and reliability across different monitoring systems. Researchers and regulatory agencies emphasize the importance of developing standardized protocols for evaluating the performance of new sensor technologies. These protocols should encompass various aspects such as sensor calibration, validation against reference instruments, data quality assurance, and uncertainty analysis [1]. Intercomparison studies involving multiple sensor technologies and reference instruments provide valuable insights into the strengths and limitations of different monitoring approaches. Findings from these studies help identify common challenges, establish best practices, and inform the development of standardized testing procedures [17].

International collaborative efforts, such as the European Union's Joint Research Centre (JRC) and the World Meteorological Organization's (WMO) Global Atmosphere Watch (GAW), play a crucial role in harmonizing air quality monitoring standards and protocols worldwide. These initiatives facilitate knowledge exchange, capacity building, and the development of consensus-based guidelines for sensor evaluation [6]. Engaging stakeholders, including researchers, manufacturers, regulatory agencies, and end-users, is essential for developing effective guidelines and standards for sensor evaluation. By soliciting input from diverse perspectives, it is possible to address the specific needs and requirements of different stakeholders while ensuring the integrity and credibility of the evaluation process [7]. By addressing the lack of standardized guidelines and procedures for assessing new technological sensors, the air quality monitoring community can enhance the reliability, accuracy, and credibility of sensor-based environmental data.

Usability Testing

A usability score of the prototype from the user end the feedback to indicate its usability for its end user which utilizes a usability testing is crucial. Usability testing is described as any methodology used to assess a product or system [26]. It is a procedure that utilizes individuals who are representative of the target audience as test subjects to determine the extent to which a product meets specific usability requirements [27,28]. Usability requires the accuracy and ease with which the website can be manipulated and navigated by the user, clarity of interaction, ease of reading, information arrangement, speed, and style. Usability enhances user interface design by assessing the interface's organization, presentation, and interactivity [29]. Usability testing may be conducted officially, for observation in a usability lab with video cameras, or informally, with a paper mock-up of an application or website. Based on the results of the usability tests, several improvements are made to the application or site. If the test is formal or unofficial, participants of the usability test are encouraged to think aloud and share their every decision [30, 31,32].

Usability testing of wireless outdoor air monitors using low-cost sensors is essential to ensure that the monitoring systems are user-friendly and meet the needs of various stakeholders, including community members and environmental agencies. Usability testing should be conducted iteratively and involve representative users to ensure that the wireless outdoor air monitoring system is not only technically accurate but also user-friendly and accessible. Usability testing uses questionnaires as a tool to achieve its objective and the standard questionnaires available include, but are not limited to [33]:
1) The Computer System Usability Questionnaire (CSUQ), created by IBM's James Lewis [33], is well-respected and publicly accessible.
2) Software Usability Measurement Inventory (SUMI) is "an intensively tested and proven method of measuring the quality of software from the point of view of the end-user." According to Usability Net, SUMI is "a mature questionnaire regularly updated with the standardization base and manual." It applies to a variety of application types from desktop applications to wide domain-complex applications [34].
3) After Scenario Questionnaire (ASQ), developed by IBM, is available in the public domain [35].
4) The IBM-developed Post-Study Device Usability Questionnaire (PSSUQ) is available to the public [33, 35].

The PSSUQ questionnaire is designed to calculate the utility of the system, the quality of information and the quality of the user interface and has been used for usability studies on website and smartphone application [36]. The PSSUQ is a standardised 16-item questionnaire and is widely used to assess how satisfied people are with a website, programme, system, or product at the end of a research [37]. In 1988, PSSUQ evolved out of an internal IBM initiative called SUMS (System Usability Metrics). PSSUQ Version 3, which is now in use widely and was used in this study, is the product of several rounds of improvements [36]. PSSUQ follows a 7-point Likert Scale where the overall result is calculated by averaging the scores from the 7 points of the scale. In PSSUQ, it has 3 sub-scales, namely system usefulness, information quality, and interface quality [29]. The scores of the PSSUQ are categorised as such [36];
▪ Overall: the average scores of questions 1 to 16
▪ System Usefulness (SYSUSE): the average scores of questions 1 to 6
▪ Information Quality (INFOQUAL): the average scores of questions 7 to 12
▪ Interface Quality (INTERQUAL): the average scores of questions 13 to 15

The sub-scales give a more in-depth look at the various aspects that influence the website, software, system, or product [36,37]. The PSSUQ score ranges from 1 (strongly agree) to 7 (strongly disagree). The better the performance and satisfaction, the lower the score. Since the PSSUQ could be broken down into four sections: overall, SYSUSE, INFOQUAL, and INTERQUAL, a careful review of the scores for each of the 16 questions is required [30]. For example, for question 7, "The system gave me error messages that clearly advised me how to fix problems," most systems tend to perform worse. This suggests that more effort should be invested into creating an effective error message [37]. As an outcome, the true problem can be quickly identified and corrected.

Sample size determination in usability testing depends on various factors, including the complexity of the technology, the diversity of the user population, the number of tasks to be evaluated, and the desired level of statistical power. While there is no universally accepted formula for determining sample size in usability testing, researchers often aim for a balance between statistical rigor and practical considerations [38]. One commonly used approach is to recruit a minimum of 5-8 participants for each user group or persona represented in the target user population. This ensures that most usability issues can be identified with a reasonable level of confidence, while also allowing for efficient use of resources and time [39].

Standardized usability questionnaires often focus on specific aspects of usability, such as ease of use, learnability, efficiency, and satisfaction. While these dimensions are important, they may not capture the full range of user experiences or the context in which the technology is used. Users may have different priorities, preferences, and needs that are not adequately addressed by standardized measures [40]. Standardized usability questionnaires typically assess usability at a single time point, often after users have completed a specific task or interaction with the technology. This approach may overlook changes in usability over time, such as learning effects, adaptation to the technology, or evolving user needs and preferences [41].

Such limitations, however, can be encountered by embarking several approaches including supplementing standardized questionnaires with a variety of evaluation methods, including user interviews, think-aloud protocols, task analysis, user observations, and usability testing. Triangulating data from different sources can provide a more comprehensive understanding of usability issues and mitigate the limitations of any single method [40]. Also, by providing training to evaluators administering the PSSUQ, consistency in data collection and interpretation can be ensured. Familiarize evaluators with best practices in usability evaluation, questionnaire administration, and data analysis techniques to enhance the reliability and validity of the evaluation process [41].

Advantages of the Incorporating both Evaluation Methods

Conducting both field testing and usability testing for wireless outdoor air monitors using low-cost sensors prototypes offers a comprehensive evaluation that is essential for proving their successfulness. These two testing approaches provide a range of benefits that ensure the functionality, effectiveness, and user-friendliness of the monitoring system. The key advantages are the real-world validation: where a field testing allows the prototype to be tested in actual outdoor environments where it will be deployed. This ensures that the system's performance is validated under real conditions, including variations in weather, air quality, and environmental factors [19]. Field testing helps determine the accuracy of the low-cost sensors. By comparing their measurements to reference instruments, it verifies the reliability of the data collected, which is crucial for making informed decisions and taking effective actions [42]. This field testing over an extended period also proving the stability and long-term performance of the sensors. It reveals if the sensors maintain their accuracy and reliability over time and in different conditions. This allows for the collection of real data, which can be used to validate the sensors' measurements against established air quality standards, ensuring the data's credibility. Any issues or shortcomings identified during field testing can be addressed and optimized, resulting in a more robust and dependable monitoring system [34].

Usability testing focuses on the user's experience, ensuring that the monitoring system is designed with the user's needs and preferences in mind. It fosters a user-centred approach to system development. This testing helps uncover any usability issues or pain points that users may encounter while setting up, interacting with, or interpreting data from the monitoring system. These issues can be addressed to enhance user satisfaction. Also, from the testing, designers and developers are allowed to understand user expectations and preferences, which can inform design changes and feature enhancements [41]. A user-friendly monitoring system is more likely to be adopted and used effectively by the target audience. Usability testing ensures that the system's interface and interaction processes are intuitive and easy to navigate. By identifying and addressing potential sources of user error during usability testing, the system can be designed to minimize mistakes and misinterpretations, leading to more reliable data collection. Most importantly, a monitoring system that is easy to use and meets user needs results in higher user satisfaction, fostering positive perceptions of the technology and its value [40,43].

In summary, conducting both field testing and usability testing for wireless outdoor air monitors using low-cost sensors prototypes provides a well-rounded evaluation approach. Field testing ensures that the sensors' data is accurate, stable, and reliable in real-world conditions, while usability testing ensures that the system is user-friendly and meets the expectations of the intended users. These tests collectively contribute to the overall success and effectiveness of the monitoring system, facilitating its adoption and impact on public health and environmental management.

CONCLUSION

This article overviews the elements in the evaluation methodology of the wireless outdoor air monitors using low-cost sensors research done by the previous scholar. The present study discusses the importance of conducting both field evaluation and usability testing to prove the effectiveness of the wireless air monitoring system. From these evaluations, the reliability of the data will be proven. Additionally, the incorporation of usability testing illuminated the vital importance of ensuring that these air monitors are accessible and user-friendly. Usability testing allows us to consider the practicality of these systems from setup to data interpretation. The success of air quality monitoring is inherently intertwined with the ease of access and understanding of the data by a diverse range of users.

In conclusion, our research underscores the necessity of a holistic evaluation framework that combines technical assessment, usability testing, and end-user perspectives. This multifaceted approach ensures that low-cost sensor-based wireless outdoor air monitors are not only technically accurate but also practical and relevant to those who rely on the data. We passionately believe that such an approach is instrumental in advancing the field of air quality monitoring, providing more effective deployment strategies, ensuring data quality, and enhancing sensor calibration techniques. Furthermore, this research reinforces the idea that, beyond technical assessments, the democratization of air quality monitoring is a powerful means to empower communities to take an active role in addressing local air quality concerns. As we move forward, we must continue to bridge the gap between technological innovation and user expectations, ensuring that air quality data is accessible, understandable, and actionable for the betterment of public health and the environment. By working in harmony with users, we can collectively make strides toward mitigating the health risks associated with outdoor air pollution and creating a cleaner, healthier world for all.

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