ORIGINAL ARTICLE

Emerging Trend in Low – Cost Indoor Air Quality Sensing Technologies: A Global Bibliometric Analysis

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ABSTRACT

Introduction: There has been growing interest in low-cost indoor air quality (IAQ) sensors, in recent years, primarily due to their affordability and potential as practical alternatives to conventional monitoring systems. These devices are now widely implemented in environments such as households, offices, vehicles, and schools to provide real-time insights into pollutants like $PM_{2.5}$, CO_2, and volatile organic compounds (VOCs). However, a comprehensive synthesis of existing research in this area remains limited. **Methods:** This study conducts a bibliometric analysis to explore global trends in low-cost IAQ sensing technologies, examine recent advancements in sensor development, and evaluate their emerging role within vehicle environments. **Results:** Based on a review of 82 publications indexed in the Scopus database between 2006 and 2025, the study utilizes VOSviewer for visualization and analysis. Results from this study indicate a clear picture of the integration of low-cost indoor air quality sensors within vehicle environments. **Conclusion:** The deployment of these sensors allows for a proactive approach to managing air quality by providing timely alerts regarding elevated levels of pollutants like particulate matter. This guide policymakers toward targeted measures and enable industry to implement practical controls to reduce in-cabin pollution.
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Keywords: Low-Cost Sensors, Portable Sensors, Indoor Air Quality (IAQ), Air Quality Monitoring, Indoor Air Pollution

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INTRODUCTION

The growing recognition of the health harms of indoor air pollution has spurred rapid development and deployment of low-cost IAQ monitoring devices (1). Traditional methods of indoor air quality monitoring have often been constrained by the high costs, large size, and operational complexity of the equipment, rendering high-resolution spatial and temporal monitoring impractical (2). Low-cost sensor technology presents a paradigm shift, enabling the deployment of dense networks of air quality monitors at a fraction of the cost of conventional methods (3). This affordability facilitates widespread adoption in homes, offices, schools, and public spaces, empowering individuals and communities to make informed decisions regarding their indoor environments (4). This technology also enables community-driven science and citizen science initiatives (1). The accessibility of these sensors allows for real-time data collection and analysis, which can then be used to determine patterns of exposure and inform immediate action (5).

Thus, this bibliometrics analysis study aims to map global trajectories in low-cost IAQ sensing, synthesize recent sensor innovations, and evaluate their emerging utility within in-vehicle settings in vehicle settings.

Furthermore, these low-cost sensors can act as support and extensions of current technology that is available (6). Low-cost sensors have emerged as promising tools for ubiquitous monitoring due to their compact size, affordability, and ease of operation (7). The current understanding of low-cost IAQ sensing technologies remains limited, encourage this study to systematically evaluate advances that enable high-resolution spatiotemporal characterization of pollutants, thereby informing evidence-based air-quality management and quantitative health-risk assessment (8). It is important to note, however, that the field still faces many challenges regarding sensor performance and reliability (1).

The recent research on low-cost IAQ sensors has accelerated across environmental health and IoT, yet findings remain fragmented, terminology inconsistent, and validation practices heterogeneous, limiting cumulative inference and comparability. Accordingly, we perform a bibliometric analysis to map global trajectories, synthesize sensor innovations, and appraise emerging applications in vehicular microenvironments. This study will serve as a basis for researchers, policymakers, and individuals to understand the growing research trends in low cost sensor, specifically in the vehicle setting, and discover the potential and possibilities for further research and collaborations.

METHODS

Bibliometric analysis is a quantitative and statistical method used to describe publication patterns in a specific area based on academic literature databases (9). This paper chose the Scopus database as the academic literature database. Scopus database was selected as it is the world's largest peer-reviewed abstract and citation database, with cutting-edge tracking, analysing, and visualising research tools (10) that integrate seamlessly with VOSviewer, supporting reproducible workflows. A single-database reliance can limit completeness and incorporating another database can broaden retrieval and reduce database bias. To mitigate this limitation, transparency of all documents search strings and inclusion criteria is provided and sensitivity analyses that replicate the workflow across multiple databases to assess the robustness of the findings is recommended.

Data Source

The search was conducted in the first week of July 2025 by using the following query string: TITLE-ABS-KEY (("low-cost sensor" OR "low cost sensor" OR "affordable sensor" OR "low-cost monitor" OR "low cost monitor" OR "low-cost device" OR "affordable device") AND ("indoor air quality" OR "indoor pollution" OR "indoor environmental quality" OR "indoor air monitoring") AND ("trend" OR "development" OR "innovation" OR "emerging technology" OR "application" OR "performance" OR "vehicle" OR "automobile" OR "car cabin" OR "transport")).

Documents were searched based on the title, abstract, and keywords. The Scopus database resulted in 163 articles published between 2006-2025. The journal articles, review articles and conference proceedings were referred to as articles. Only 82 articles were found aligns to the research scope, which focuses on innovation of indoor air quality sensors over 2006-2025, using low cost technology to address its emerging role within vehicle environments. **(Fig. 1).** The exclusion criteria includes book chapter, conference review and data paper. This is to ensure consistent peer-review standards, complete citation and affiliation metadata, as well as cross-record comparability required for robust VOSviewer network analyses.

Bibliometric Maps

VOSviewer software (version 1.6.19) was used for constructing and visualising bibliometric maps. Bibliographical information and author keywords for the 82 articles were exported to VOSviewer where the information such as countries and author keywords were analysed to create co-authorship and co-occurrence maps. The relationship between two items, e.g., two keywords, were visualised with a link, and the strength

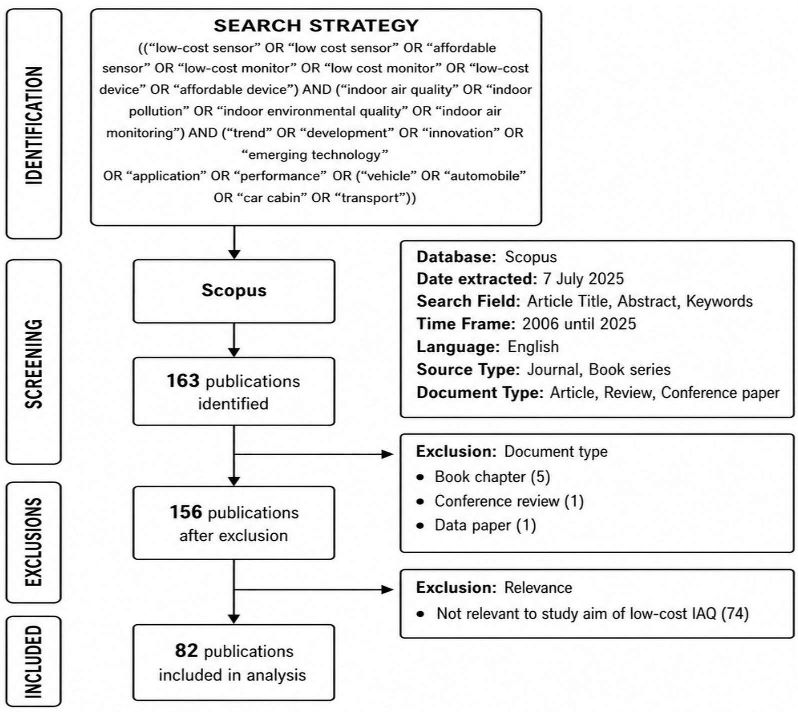

Fig. 1: The flowchart of the specific search strategy of the low cost IAQ on Scopus database.

of the relationship was indicated by the link strength (in numerical value). For co-authorship analysis, the link strength between the two countries indicates the number of publications co-authored. Similarly, in co-occurrence analysis, the link strength between two author keywords represents the number of articles in which the two keywords appear together where the thresholds used in VOSviewer is set at minimum number of three occurrences for keywords or minimum number of publications for countries.

RESULTS

Annual Publication Outputs and Document Type

Fig. 2 highlights the annual publications on low-cost IAQ from 2006 until 2025, with the earliest indexed record appearing in 2006. Annual output peaked in 2024, reflecting the post-pandemic emphasis on IAQ and falling sensor costs. The apparent decline in 2025 is likely a partial-year indexing artifact rather than a true contraction.

Across the 82 documents analyzed, research articles constituted the majority 53.7%, followed by conference papers 30.5% and review articles 15.9% **(Fig. 3).** This composition indicates a field driven primarily by original empirical work, complemented by conference dissemination and a smaller though nontrivial body of syntheses.

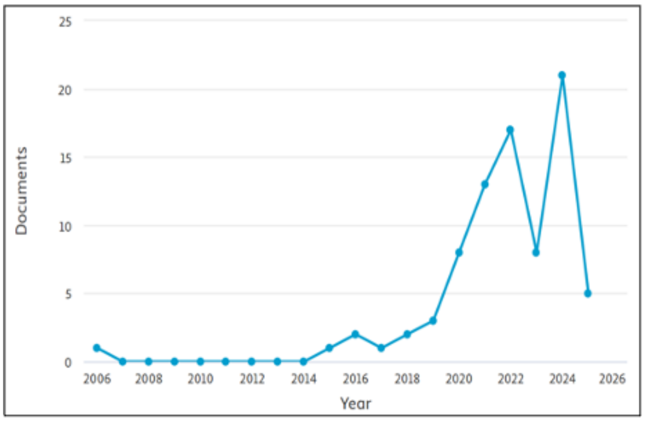

Fig. 2: The annual publications trends on low-cost IAQ from 2006 until 2025.

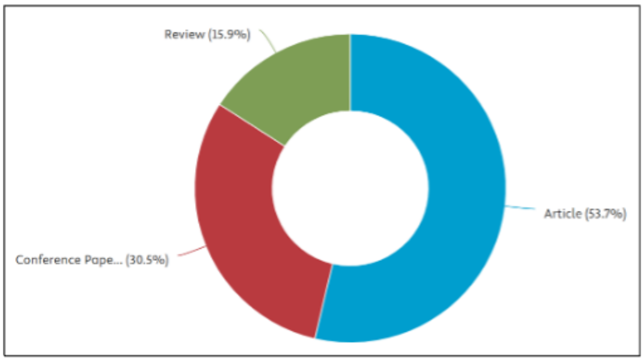

Fig. 3: The percentage distribution of low-cost IAQ document types analysed.

Authors, Institutions, and Countries Contributing to Global Publications on IAQ

Overall, 346 authors from different countries and institutions contributed to the increase in knowledge on technological developments and innovations in low-cost IAQ monitoring devices. A group of researchers from University of Porto (Portugal) published the highest number of publications (5) and received the highest co-citations (210). The prominence of the Porto group likely stems from a combination of early contributions to sensor validation, and cross-disciplinary collaborations.

In total, 32 countries and 31 institutions were engaged in IAQ research **(Fig. 4).** In accordance with the top authors, the most active country in IAQ research was the US with 20 publications, followed closely by the UK with 9 publications and Portugal with 8 publications. This may be contributed from strong funding and research infrastructure which enable faster, larger and multi-institution studies. Combined with the advantages of publishing in English and strong coverage in major databases, this boosts visibility and dissemination, leading to higher publication counts than in regions with fewer resources or non-English outlets.

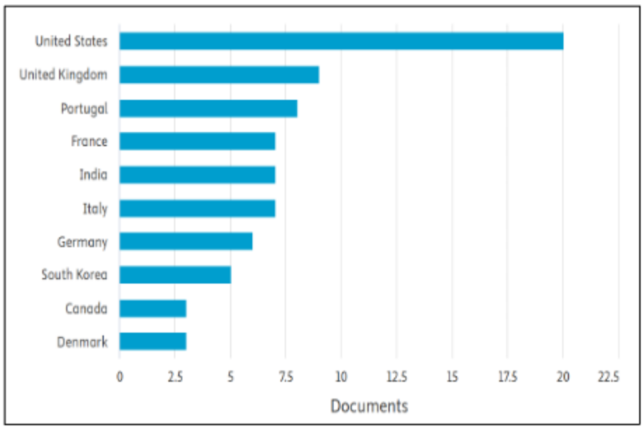

Fig. 4: The distribution of publications on low-cost IAQ by top ten countries.

Analysis of Co-Authorship and Co-Occurrence

The analysis of co-authorship included all 32 countries affiliated with 346 authors. The network visualisation option was selected to display the co-authorship among 17 related nations. Africa, Asia, Europe, North America, South America, and Oceania were the six continents to which the affiliated countries belonged.

Only 46 of 231 of the authors keywords were relevant enough to be included in the co-occurrence analysis. The network visualisation option was chosen to reveal connections within and across keyword clusters. Among the keywords are particulate matter, indoor air quality and low cost-sensor **(Fig. 5).**

Most Frequently Cited Articles

The top 10 highly cited articles on low-cost IAQ are listed in **Table I.** The total citations received by these articles ranged from 60 to 158. Out of the 10 articles listed,

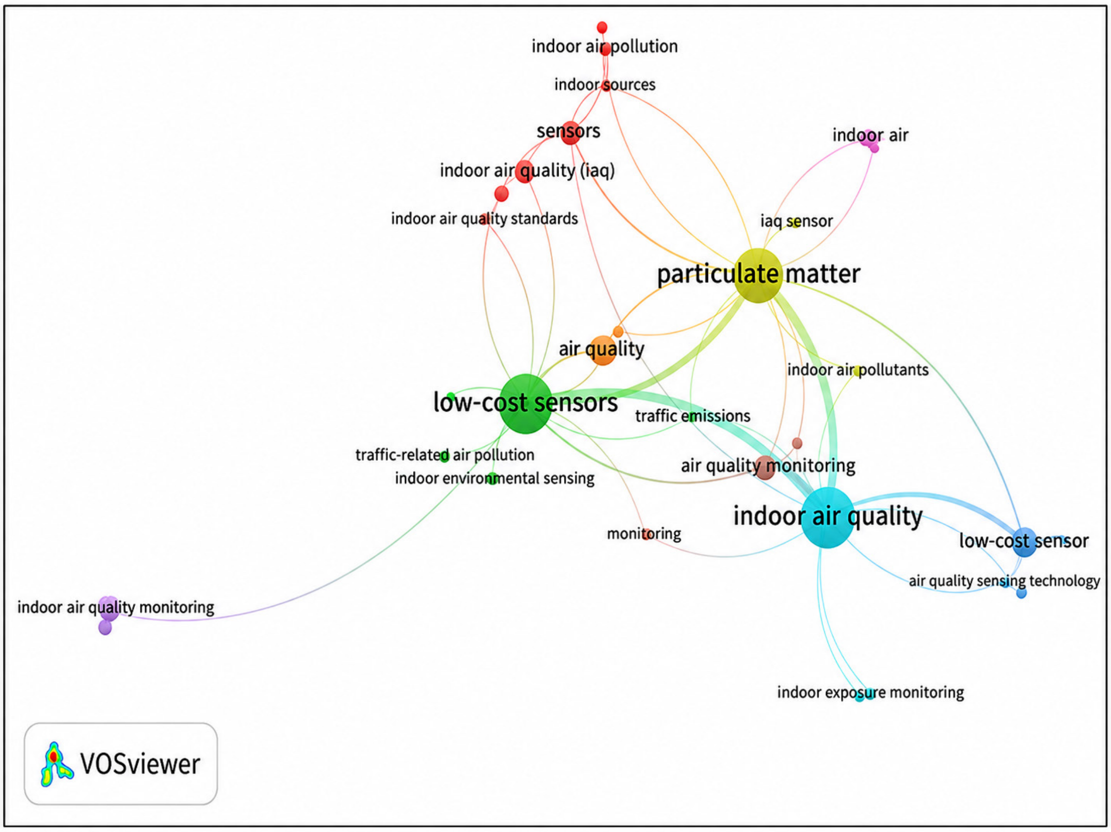

Fig. 5: The network visualisation map of keywords.

Most Frequently Cited Articles

The top 10 highly cited articles on low-cost IAQ are listed in **Table I.** The total citations received by these articles ranged from 60 to 158. Out of the 10 articles listed, seven were original articles while the remaining three were review articles. Four of the articles were published in journals with a CiteScore above 10. The paper by Chojer in 2020 (1) received the highest citation with 158 total citations. This paper was published in Science of the Total Environment (CiteScore = 16.4). The paper reviews the development of low-cost indoor air quality monitoring devices, highlighting challenges such as data reliability issues due to varied calibration and validation methods, lack of sensor performance testing, and limited studies on long-term stability and cross-sensitivity, but suggests that with standardized processes, these devices could be the future of IAQ monitoring. This suggestion is consistent with Demanega et al., study (11). The review was published in Building and Environment (CiteScore = 14.3) and received 122 citations. The article evaluates the performance of low-cost environmental monitors and single sensors under various indoor air quality and thermal conditions. The finding highlight that they can detect source events and measure temperature and humidity accurately, despite under-reporting particle measurements and poor VOC agreement, suggesting the potential for indoor air quality management. Meanwhile, at number three was an article by Shrestha et al., (12) with 114 citations. This review was published in International Journal of Environmental Research and Public Health (CiteScore = 8.5). This study finds that long-range wildfire plumes, road proximity, and human activity significantly increase indoor pollutant concentrations in low-income dwellings during wildfire seasons.

DISCUSSION

Bibliometric Analysis

The current bibliometric analysis focuses on analysis of research trends related to low-cost IAQ sensing technologies from 2001 to 2025 thorough review of papers pertaining to this subject matter. Following the release of the first article in 2006 on the low-cost sensors for balancing indoor air quality and energy usage (20), research output on low-cost IAQ sensing technologies was low and remained relatively flat until recently. The highest peak was observed in 2024 with 21 publications. This trend indicated that while low-cost IAQ sensing technologies continue to receive attention from researchers, the pace of research activity has become more gradual.

This could be due to several factors. Firstly, the field may be reaching a point of technological maturity, where foundational research on sensor performance, calibration methods, and deployment strategies has been largely established (21, 22). Secondly, research trends attention has possibly shifted toward other pressing global challenges, such as AI-driven environmental analytics (23). These factors collectively indicate that

Table I: Ten top highly cited papers in low-cost IAQ innovations research

Title (sources)	Journal / Document type	Cite-Score / Total citation	Study focus	Device type	Monitoring parameters	Validation method	Main conclusion
Development of low-cost indoor air quality monitoring devices: Recent advancements (1)	Science of the Total Environment / Review	16.4 / 158	Review of low-cost indoor air quality (IAQ) device development, calibration, and performance	Multi-parameter devices (various, often Arduino/ Raspberry Pi-based)	Temperature, relative humidity (RH), carbon dioxide (CO_2), carbon monoxide (CO), volatile organic compounds (VOCs), particulate matter (PM), formaldehyde, ozone, nitrogen dioxide (NO_2), ammonia, benzene, toluene, nitric oxide (NOx)	Varied; some used reference instruments (TSI Qtrak, DustTrak), others used known pollutant concentrations	Lack of data reliability due to insufficient calibration and validation are the main challenge with low-cost sensor technology. The results are potential to high measurement errors as most studies did not perform sensor performance tests or calibration (1).
Performance assessment of low-cost environmental monitors and single sensors under variable indoor air quality and thermal condition (11)	Building and Environment / Article	14.3 / 122	Laboratory assessment of low-cost monitors/ sensors under variable IAQ and thermal conditions	Multi-parameter Monitors; Air Visual, Awair, Foobot,andsingle parameter sensors; Sensirion SCD40 (SCD40), CO2meter K30 (K30), Alphasense OPC-N3 (OPC–N3), NovaFitness SDS018 (SDS018)	PM, CO_2, total VOCs (TVOCs), temperature, RH	Controlled chamber; correlation with reference data; no explicit calibration method	The majority of low-cost devices under-reported particulate matter by up to 50% but were strongly correlated with reference data, suggesting suitability for indoor air quality management. The performance of these devices was comparable across different seasons, with slight variations in accuracy depending on the parameter being measured (11).
Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons (12)	International Journal of Environmental Research and Public Health / Article	8.5 / 114	Impact of outdoor air pollution on indoor air quality in low-income homes during wildfire seasons.	Dylos monitors for PM2.5, aethalometers for BC, Y-Pods for CO and humidity, Ogawa passive samplers for NO2	$PM_{2.5}$, black carbon (BC), CO, NO_2	Co-location experiments with federal reference monitors, post-processing algorithm for calibration.	Proximity to roadways significantly increased indoor concentrations of BC, CO, and NO_2 in homes closer to roads. The type of kitchen stove hood and window opening behavior affected indoor pollutant concentrations, with exhaust hoods reducing $PM_{2.5}$ and window opening increasing BC (12).
Highly sensitive and selective VOC sensor systems based on semiconductor gas sensors: How to? (13)	Environments – MDPI / Article	5.7 / 107	Metal oxide semiconductor gas sensors for VOC monitoring	Metal oxide semiconductor gas sensors	VOCs like formaldehyde, naphthalene, and benzene at low concentrations	Calibration, including efficient factory and on-site calibration methods	Metal oxide semiconductor gas sensors are highly sensitive but lack selectivity. Dynamic operation improves both sensitivity and selectivity, addressing the three key aspects of chemical sensor systems: sensitivity, selectivity, and stability (13).
Application of the low-cost sensing technology for indoor air quality monitoring: A review (14).	Environmental Technology and Innovation / Review	16.1 / 83	Review of low-cost sensing technology for IAQ monitoring	Multi-parameter devices (e.g., Speck, Dylos, Foobot, Sharp GP2Y1010AU0F)	$PM_{2.5}$, CO_2, CO	Regular calibration recommended; trimonthly/ monthly; often compared to reference instruments	Some low-cost sensors/devices demonstrated good performance, especially in laboratory settings, and are reliable for qualitative analysis in indoor environments. Thus, the use of low-cost sensing technology is encouraged due to its advantages such as lower costs, less noise, and lower electricity consumption (14).
Sensors for indoor air quality monitoring and assessment through Internet of Things: a systematic review (15).	Environmental Monitoring and Assessment / Review	5.0 / 81	Review of sensors for IAQ and internet of thing (IoT) integration	No information available	CO, thermal comfort, others	Not mention	A significant portion (45.7%) of the 71 sensors analyzed are available for under \$20, indicating cost-effectiveness. The study highlights that 77.5% of the literature lacks calibration details, and 39.4% of sensors have missing accuracy specifications, indicating a need for improved sensor reliability (15).

Table I: CONTINUE

Temporal and spatial variation of PM2.5 in indoor air monitored by low-cost sensors (16).	Science of the Total Environment Article	16.4 77	Monitoring spatio-temporal variation of indoor $PM_{2.5}$	Low-cost sensors particle counters (PM-Model-II) from Green Built EnvMent, and laser scattering sensors (Plantower PMS3003)	Each sensor has a steady-speed fan to control the rate of airflow through the air channel where PM concentrations are measured. $PM_{2.5}$ concentrations in three particle size ranges (0.3-1.0 μm, 1.0-2.5 μm, and 2.5-10 μm)	Calibration against a continuous particle monitor (Thermo Scientific Model FH 62 C14) for 50 hours	Indoor $PM_{2.5}$ was predominantly generated from outdoor infiltration and cooking. Regression model explained 79% of the spatiotemporal variation in indoor $PM_{2.5}$, with outdoor and cooking sources contributing 36% and 64%, respectively (16).
Particulate Matter Measurement Indoors: A Review of Metrics, Sensors, Needs, and Applications (17).	Environmental Science and Technology Article	18.1 71	Review of PM metrics and sensors for indoor air quality monitoring	Pmass is measured using gravimetric and optical methods. Pnum is measured using Optical Particle Counters (OPCs) and Condensation Particle Counters (CPCs)	Pmass, Pnum, Psd, surface area	Comparison against reference grade equipment (e.g., gravimetric samplers)	Indoor air pollution is a significant global health risk, with over 4.3 million premature deaths attributed to it annually. Measuring indoor PM is challenging due to its variable levels and requires high spatial and temporal resolution. Therefore, low-cost sensors are crucial for improving indoor air quality monitoring and management, particularly in balancing health and energy efficiency (17).
Indoor household particulate matter measurements using a network of low-cost sensors (18).	Aerosol and Air Quality Research Article	9.1 62	Deploying a network of low-cost sensors and research-grade instruments in home environments to evaluate performance, characterize activities affecting PM concentrations, and assess impact on PM levels in different rooms.	Low-cost sensors (Dylos DC1100 Pro, Plantower PMS sensor), research-grade instruments (GRIMM, DustTrak, MiniVol)	PM_1, $PM_{2.5}$, PM_{10} concentrations; temperature; humidity; CO; NO_2	Comparison with research-grade instruments using linear-regression modeling against mass-adjusted DustTrak PM2.5 concentrations.	Frying food and spraying aerosol products significantly increase PM levels in the kitchen and bedroom, affecting adjacent rooms as well. The high outdoor PM concentrations during cold air pool episodes increase indoor PM levels while low-cost PM sensors can be useful for personal exposure management despite their limitations in accuracy due to varying optical properties of PM sources (18).
Long-term evaluation of a low-cost air sensor network for monitoring indoor and outdoor air quality at the community scale (19).	Science of the Total Environment Article	16.4 60	Long-term evaluation of a low-cost air sensor network for monitoring indoor and outdoor air quality at the community scale.	PurpleAir II (PA-II) sensor, a low-cost optical particle counter	Mass concentrations of PM_1, $PM_{2.5}$, and PM_{10}; particle number counts for various sizes	Quality assurance/quality control measures outlined in comparison with EPA FEM measurements.	Main data quality concerns were related to outdoor sensor data incompleteness. Indoor and outdoor sensors effectively detected resident activities and traffic pollution. This enable community-maintained low-cost sensors can produce accurate $PM_{2.5}$ pollution data (19).

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This could be due to several factors. Firstly, the field may be reaching a point of technological maturity, where foundational research on sensor performance, calibration methods, and deployment strategies has been largely established (21, 22). Secondly, research trends attention has possibly shifted toward other pressing global challenges, such as AI-driven environmental analytics (23). These factors collectively indicate that although interest remains, the trajectory of research in this area is evolving toward more specialized or integrated applications.

Key Technological Developments and Innovations in Low-Cost IAQ Monitoring Devices

Recent advancements in low-cost sensor technology have shown promise for indoor air quality (IAQ) monitoring. These devices are portable, low-maintenance, and can contribute to citizen science projects (1). However, challenges persist in sensor accuracy and reliability as stated by Chojer in 2020 results are potential to high measurement errors as most studies did not perform sensor performance tests or calibration necessitating regular calibration and validation against reference instruments (1). However, Sб JP in 2022, highlights that some low-cost sensors demonstrated good performance, especially in laboratory settings, and are reliable for qualitative analysis in indoor environments (14). Hence, it is confirmed that studies have shown moderate correlations between low-cost sensors and comparison instruments, suggesting sufficient precision for qualitative analysis in indoor environments.

The proliferation of low-cost IAQ monitoring devices has been significantly propelled by several key technological advancements, notably in sensor technology, microelectronics, and data analytics. The integration of electrochemical sensors, non-dispersive infrared (NDIR) sensors, and metal oxide semiconductor sensors has enabled the detection of a wide array of indoor air pollutants, including particulate matter, volatile organic compounds, carbon dioxide, and nitrogen oxides, at increasingly lower costs (1).

Concurrently, advancements in microelectronics have facilitated the miniaturization of sensor modules and the development of highly integrated systems-on-chips that combine sensing, processing, and communication functionalities into a single compact device (11). Furthermore, the integration of sophisticated data analytics algorithms, including machine learning techniques, has allowed for real-time data processing, calibration, and correction of sensor drift, thereby improving the accuracy and reliability of low-cost IAQ monitoring devices (1). The development of user-friendly interfaces and data visualization tools has also contributed to the widespread adoption of these devices, making them accessible to both technical and non-technical users.

Potential Impact of Low-Cost IAQ Sensors in Vehicle Settings

Exposure to particulate matter (PM) air pollution is recognized as a major contributor to human morbidity and mortality (24). Air pollution, stemming from both natural and anthropogenic sources, poses serious risks to human health and the environment (25). As people typically spend 90% of their time indoors, exposure to indoor particulate matter is particularly concerning, as it has been associated with millions of premature deaths globally (17). Prolonged time spent indoors, for example at home or in vehicles, therefore, increases the potential for adverse health effects due to sustained exposure to indoor air pollutants.

Poor indoor air quality, particularly due to particulate matter (PM1, PM2.5, and PM10), has been linked to various adverse health effects. Traditionally, air quality monitoring has been constrained by the high cost and bulkiness of conventional monitoring stations. However, recent advancements in low-cost sensor technologies have enabled more affordable, scalable, and real-time monitoring solutions, which are especially valuable for indoor environments that can experience rapid fluctuations in pollutant levels (26).

Over the past decade, significant progress has been made in the development and application of these low-cost sensors. The low-cost sensors can provide individuals with personalized information about indoor air quality (IAQ), empowering them to take actions to reduce exposure to particulate matter. This technology also helps reconcile the challenge of maintaining healthy IAQ while pursuing energy-efficient building designs (1).

The integration of low-cost indoor air quality sensors within vehicle environments presents a multifaceted array of potential impacts, spanning from enhanced passenger health and safety to the optimization of HVAC system performance and the generation of valuable data for urban air quality monitoring. These sensors, while often associated with design compromises that may affect data reliability (1), offer the distinct advantage of enabling near real-time, continuous monitoring of critical air quality parameters within the confined space of a vehicle cabin. This capability holds significant implications for mitigating exposure to harmful pollutants and creating a healthier in-cabin environment, particularly for vulnerable populations such as children and individuals with respiratory sensitivities (27).

The deploying of these sensors operators supports air quality proactively through timely alerts triggered by increases in particulate matter (PM2.5, PM10), volatile organic compounds, carbon dioxide, and nitrogen oxides (28). This real-time feedback empowers vehicle occupants to take immediate corrective actions, such as adjusting ventilation settings, recirculating air, or even rerouting to avoid areas with high pollution concentrations (29).

Furthermore, the data collected from these sensors can be leveraged to optimize the operation of vehicle HVAC systems, enabling demand-controlled ventilation strategies that minimize energy consumption while maintaining acceptable IAQ levels (29). Hence, low-cost sensor technology offers an ultimate transformative approach, enabling the deployment of extensive networks of air quality monitors at a fraction of the expense associated with conventional techniques (30).

Future Research Directions

These findings can be used as a reference for future studies. The results from this study indicate a clear picture of the integration of low-cost indoor air quality sensors within vehicle environments. The deployment of these sensors allows for a proactive approach to managing air quality by providing timely alerts regarding elevated levels of pollutants like particulate matter. The low-cost sensor technology offers an ultimate transformative approach, enabling the deployment of extensive networks of air quality monitors at a fraction of the expense associated with conventional techniques. This guide policymakers toward targeted measures and enable industry to implement practical controls to reduce in-cabin pollution.

CONCLUSION

This study presents, to our knowledge, the first bibliometric mapping of global patterns and technological trajectories in low-cost indoor air quality (IAQ) research. Our findings suggest that research on low cost IAQ will continue to be a significant and developing area of academic study. The emergence of advanced technology innovation has also facilitated the development of the measurement technology within this field. The evidence indicates a vibrant and expanding field, with output led by the United States, and a thematic landscape dominated by clusters on low-cost IAQ sensors particularly calibration and validation. Co-occurrence analysis also reveals clear research gaps, limited evidence for in-vehicle deployments. Our findings serve as a valuable point of reference for scholars who are inclined towards undertaking further investigations within this specific topic.

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