

# Bibliometric analysis of research trends in low-cost sensors for air pollution monitoring: innovations and future implications

**Yuli Dwi Astanti<sup>1</sup>, Berty Dwi Rahmawati<sup>2</sup>, Dian Hudawan Santoso<sup>3\*</sup>, Ahmad Taufiq Akbar<sup>4</sup>**

<sup>1,2</sup>Department of Industrial Engineering, Faculty of Industrial Engineering, Universitas Pembangunan Nasional Veteran Yogyakarta, Jl. Babarsari No. 2 Tambakbayan, Indonesia, 55282

<sup>\*3</sup>Department of Environmental Engineering, Faculty of Mineral Technology and Energy, Universitas Pembangunan Nasional Veteran Yogyakarta, Condongcatur, Sleman, Indonesia, 55283

<sup>4</sup>Department of Informatics Engineering, Faculty of Industrial Engineering, Universitas Pembangunan Nasional Veteran Yogyakarta, Jl. Babarsari No. 2 Tambakbayan, Indonesia, 55282

yulidwi.astanti@upnyk.ac.id<sup>1</sup>, berty.dr@upnyk.ac.id<sup>2</sup>, dian.hudawan@upnyk.ac.id<sup>3\*</sup>  
ahmadtaufiq.akbar@upnyk.ac.id<sup>4</sup>

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## ABSTRACT

Air quality monitoring is imperative due to the substantial health and environmental ramifications of atmospheric contamination. The present study endeavors to examine prevailing research trends in low-cost sensors, which offer an efficacious and attainable approach to evaluating air quality. A meticulous bibliometric meta-analysis was executed using data from multiple academic databases to identify publication patterns, prominent authors, and influential institutions in this domain. The methodology entailed the analysis of publication counts, citation metrics, and collaboration networks to underscore the expansion and pertinence of low-cost sensor research. The analysis was executed using Biblioshiny software. The findings indicate a marked increase in publications over recent years, reflecting heightened interest and innovation in this area. The present analysis employed a set of 233 articles published between 2011 and 2025, with all data exclusively sourced from Scopus. This study underscores the potential of low-cost sensors to enhance air quality monitoring efforts, providing valuable insights for future research and policy development aimed at mitigating air pollution and its associated risks.

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### Corresponding Author:

Dian Hudawan Santoso,

Department of Environmental Engineering, Faculty of Mineral Technology and Energy, Universitas Pembangunan Nasional Veteran Yogyakarta, Condongcatur, Sleman, Indonesia

dian.hudawan@upnyk.ac.id

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## 1. INTRODUCTION

Air pollution is a pervasive environmental problem that has profound consequences for human and ecosystem health. According to a report by the World Health Organization (WHO), approximately 7 million deaths per year can be attributed to exposure to air pollution, making it one of the leading causes of premature death [1], [2], [3]. In light of these findings, the importance

of air quality monitoring for identifying pollution sources and developing effective mitigation strategies becomes evident[4].

In recent years, there has been a notable increase in the use of low-cost sensors for air quality monitoring. These sensors offer a more affordable and flexible solution compared to traditional monitoring methods, which are often expensive and require complex infrastructure [5]. The ability to provide real-time data enables the collection of more extensive and detailed information on air quality at various locations[6].

Despite the considerable promise inherent in low-cost sensors, challenges related to accuracy and calibration persist as significant concerns. Research findings indicate that while these sensors can offer early indications of air quality, proper calibration is often essential to ensure the accuracy of the data they provide [7]. Consequently, conducting a bibliometric analysis is imperative to comprehend the prevailing research trends and advancements in the application of low-cost sensors for air pollution monitoring[8].

Bibliometric meta-analysis is a method of evaluating and analyzing extant literature in a given research field[9]. The present study employs this approach to identify trends, patterns, and gaps in research on low-cost sensors and air quality monitoring. Through this analysis, it is hoped that greater insight will be gained into future research directions.

The novelty of this study lies in the bibliometric approach used to explore research trends in the utilization of low-cost sensors. By collecting and analyzing data from various publications, this research will provide a comprehensive overview of the development of sensor technology and its application in air pollution monitoring. It is expected to identify areas that require further research and provide recommendations for better technology development.

The state of the art in this research includes the use of the latest sensor technologies and innovative data analysis algorithms. Several recent studies have demonstrated that the combination of low-cost sensors with machine learning techniques can yield superior results in comparison to traditional methods [10]. This research will build upon these findings and strive to make a significant contribution in the field of air quality monitoring.

The primary objective of this study is to conduct a bibliometric analysis of the extant literature regarding the utilization of low-cost sensors in air pollution monitoring. By achieving this objective, it is hoped that this research will provide new insights into research trends, as well as identify challenges and opportunities that exist within this field[11], [12], [13].

The findings of this study offer a wide range of benefits. By offering a more in-depth understanding of prevailing research trends, the study is poised to support researchers, policymakers, and practitioners in the development of more efficacious strategies for air quality monitoring. Furthermore, the results of this study are anticipated to foster collaboration among diverse disciplines and stakeholders, thereby addressing issues related to air pollution.

It is anticipated that this research will have a substantial impact on the implementation of low-cost sensors for air pollution monitoring. Furthermore, it is expected to establish a foundation for additional research in this domain. Consequently, the findings of this study will not only contribute to academic advancement but also have a beneficial effect on society and the environment.

## 2. METHOD

In this study, a bibliometric meta-analysis method was employed to evaluate research trends regarding the utilization of low-cost sensors in air pollution monitoring. The database utilized was Scopus, a leading database for scientific literature with extensive coverage in various disciplines, including environmental science, engineering, and computer science [14]). It is important to note that all articles analyzed were exclusively retrieved from the Scopus database. The document selection process commenced with a search employing relevant keywords, namely ("Low-Cost Sensor" OR "Low-Cost Air Quality Sensor") AND ("Air Quality Monitoring" OR

"Environmental Monitoring") AND ("Air Pollution Control" OR "Pollutant Detection").The initial search yielded 913 relevant documents.

Following the acquisition of the initial documents, the subsequent step entails subject area filtration.The search was constrained to the fields of "Environmental Science," "Engineering," "Computer Science," and "Chemistry." This process yielded 807 documents that were more focused on topics pertinent to this study [15]. This filtration process is instrumental in ensuring the analysis's specificity and relevance to the context of the research on low-cost sensors and air quality monitoring.

Subsequently, a document type filter was implemented, excluding all documents not designated as "articles." This process reduced the number of documents to 532. The objective of this filter was to ensure that only peer-reviewed research articles were included in the analysis, thereby enhancing the quality and credibility of the data utilized [16]. Following this, a screening by publication stage was conducted, which resulted in 525 documents. This additional screening phase helped eliminate documents that were not yet fully published or under review.

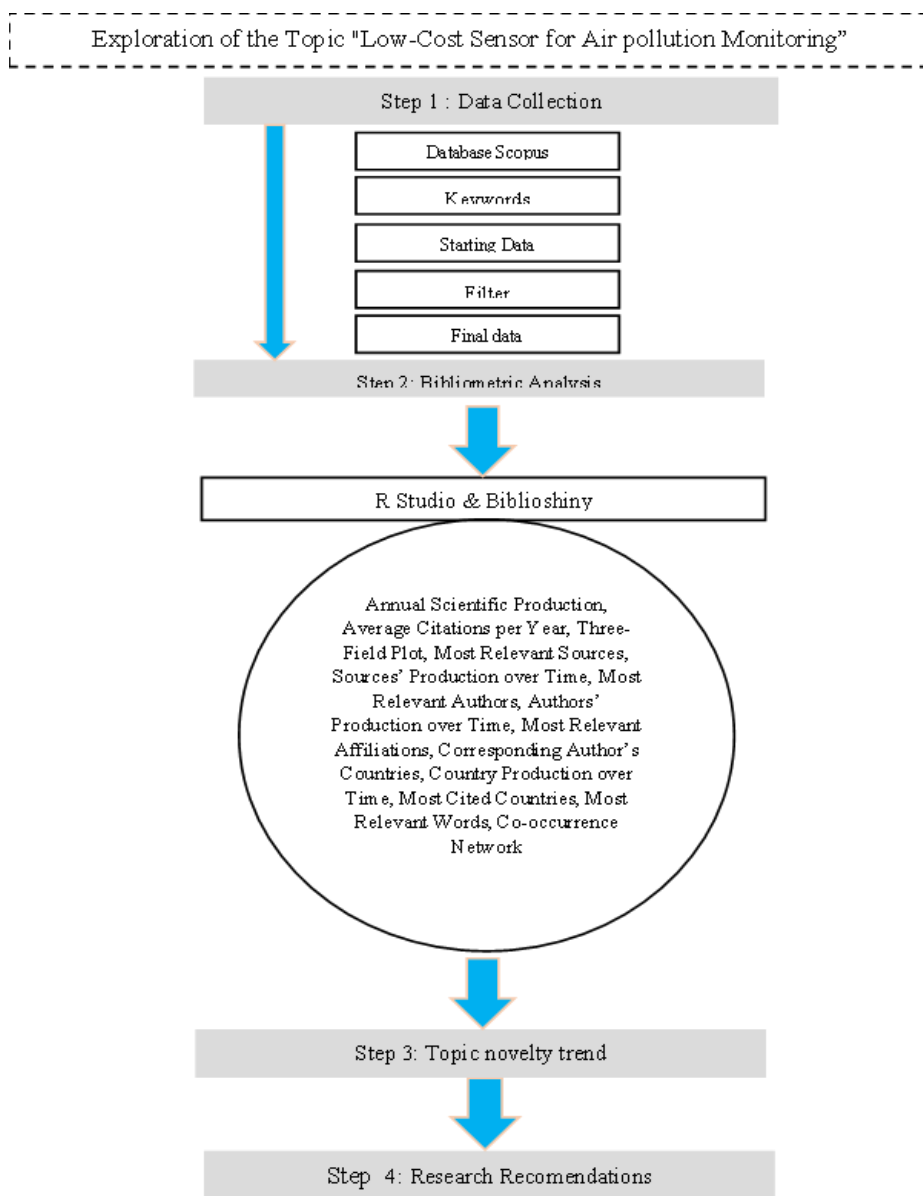


Figure 1. Steps of The Research

The filtration process was then executed by the removal of documents deemed irrelevant based on the keywords contained within the articles, which reduced the number of documents to 326. Subsequently, the selection was narrowed to journal-type sources exclusively, a decision that was made to ensure that the analysis focused on publications that are reputable and recognized in the scientific community [17]. Subsequently, the search was restricted to documents written in English because English has a very wide range of articles, yielding 320 documents. Finally, documents that were open access were selected, resulting in a final count of 233 documents used in this analysis. These steps were meticulously followed and reported in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement guidelines to ensure a transparent and reproducible selection process.

Figure 1 show the steps of the research. The process of document selection and filtering was executed through the utilization of biblioshiny software, a bibliometric analysis instrument that facilitates the efficient and effective execution of data analysis [13]. The employment of biblioshiny enables the seamless management and analysis of data derived from Scopus, in addition to the production of visualizations that substantiate the comprehension of research trends concerning the application of low-cost sensors for the purpose of air pollution monitoring.

### 3. RESULT AND DISCUSSION

Table 1 presents key information regarding the data obtained from the bibliometric analysis related to the utilization of low-cost sensors in air pollution monitoring. The study period, which spans from 2011 to 2025, saw the identification of a total of 233 documents, indicating a growing interest in this topic. The annual growth rate of 12.18% reflects a significant increase in related publications, which can be interpreted as a response to the pressing need to monitor air quality more effectively. The average document age of 3.86 years indicates that most of the existing research is the result of relatively recent studies, reflecting technological and methodological developments in this field.

Table 1. The Bibliometric Data Collected from The Years 1986 To 2025

Description	Results
Timespan	2011:2025
Sources (Journals, Books, etc)	74
Documents	233
Annual Growth Rate %	12.8
Document Average Age	3.86
Average citations per doc	21.67
References	9345
Keywords Plus (ID)	1752
Author's Keywords (DE)	726
Authors	1146
Authors of single-authored docs	5
Single-authored docs	5
Co-Authors per Doc	5.57
International co-authorships %	26.61
Article	233

The average citations per document of 21.67 indicates that these articles have a considerable impact within the scientific community, as evidenced by the large number of references, which suggests the relevance and high quality of the research. The analysis also demonstrates the diversity of publications, with 74 different sources, including a range of journals and books focusing on environmental science, engineering, and computer science. The international collaboration percentage of 26.61% signifies the presence of cross-country cooperation in these studies, which can enrich the perspectives and methodologies employed. This underscores the significance of global collaboration in addressing the universal issue of air pollution.

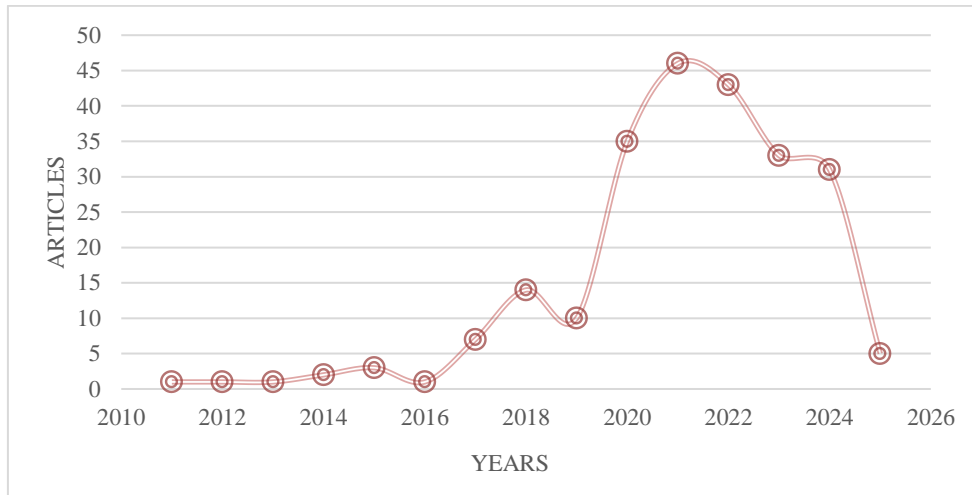


Figure 2. Annual Scientific Production

Figure 2 illustrates the annual scientific production related to the utilization of low-cost sensors in air pollution monitoring from 2011 to 2025. It is evident that the number of published articles experienced a significant increase starting in 2015, with the peak occurring in 2021, where more than 40 articles were published. This increase can be attributed to the mounting attention and interest in research on low-cost sensor technologies, which may be precipitated by the pressing need to effectively and cost-effectively monitor air quality, particularly in densely populated urban areas.

However, following the peak in 2021, a discernible decline in the number of publications was observed in subsequent years, suggesting fluctuations in research interest or potential challenges in the development of such technologies. This decline may be indicative of various factors, including potential research saturation or a shift in focus to alternative technologies or methods for air quality monitoring. Consequently, conducting further analysis is imperative to comprehend these dynamics and explore the factors that influence future publication trends.

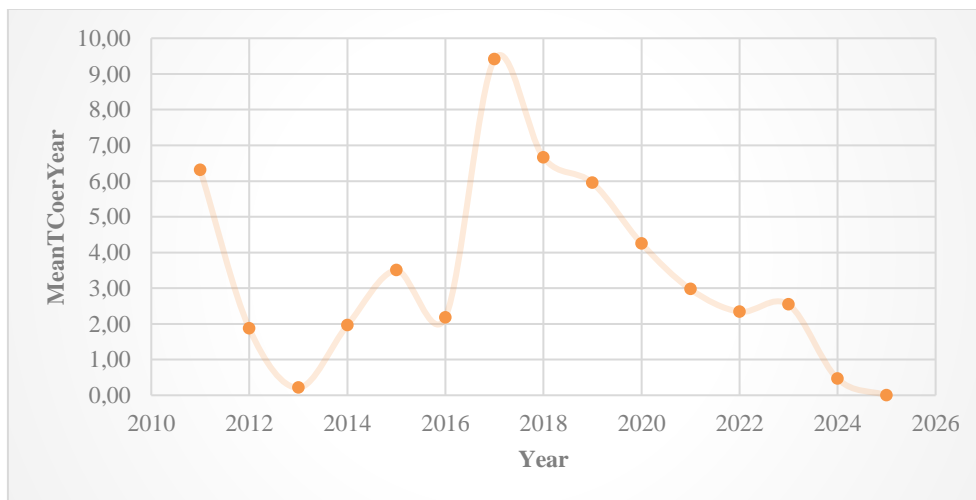


Figure 3. Average Citations per Year

Figure 3 illustrates the average number of citations per year for publications concerning the utilization of low-cost sensors in air pollution monitoring from 2011 to 2025. It is evident that the average citations exhibit significant fluctuations, with a notable peak in 2017, when the average citations exceeded 10. This increase may be indicative of the relevance and impact of the research published in that year, which can be attributed to technological advances and increased awareness of air pollution issues.

However, after 2017, there was a consistent decline in the average citations, indicating that while the number of publications increased, the citation impact of the articles tended to decrease. This decline may be attributable to several factors, including the increasing number of publications, which may have resulted in heightened competition among researchers for attention and citations. This decline may also indicate that although research on low-cost sensors is increasing, the quality or innovation of the research may not be proportional to the number of publications, thus affecting the citations received.

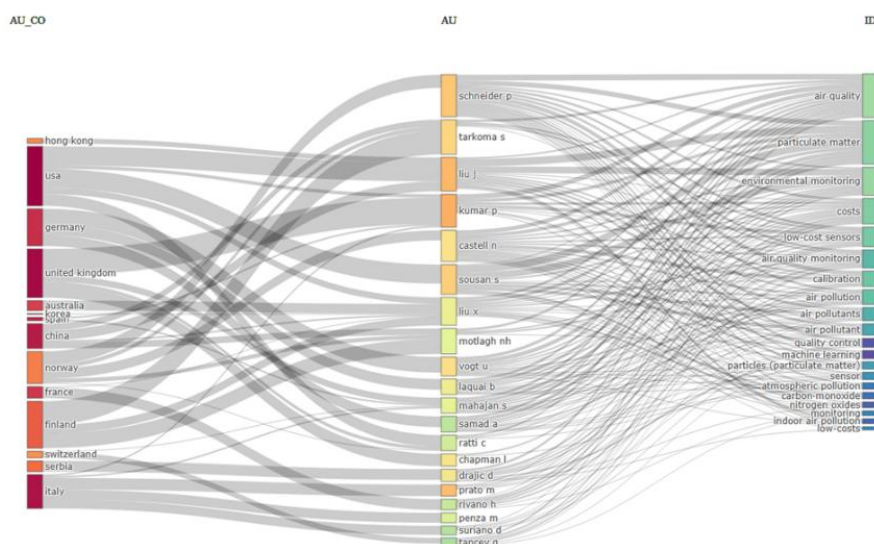


Figure 4. Three-Field Plot

Figure 4 presents the relationship between author country (AU\_CO) and author (AU) and research topic (ID) related to the utilization of low-cost sensors in air pollution monitoring. From this analysis, it can be seen that Hong Kong, the United States, and Germany are countries with significant author contributions in this field. The strong relationship between these countries and certain authors, such as Schneider and Tarkoma, suggests that research conducted in these countries has a significant impact on the development of sensor technology and air quality monitoring.

In addition, the graph also shows the most discussed research topics, such as "air quality," "particulate matter," and "environmental monitoring." The association between authors and these topics reflects the diverse research focus, ranging from technical aspects of sensors to practical applications in air pollution monitoring. This finding underscores the necessity of a multifaceted approach to research in this domain, encompassing not only technological development but also evaluation and implementation in the field, which is imperative for comprehensively understanding and addressing air pollution issues.

As illustrated in Figure 5, the analysis reveals that the journal "Sensors" is the leading publication, with 49 documented articles, signifying its preeminence as a platform for researchers to disseminate their findings in the domain of low-cost sensors for air pollution monitoring. This observation underscores the journal's substantial reputation and influence within the scientific community [18].

In addition, several other sources, including "Sensors (Switzerland)" and "Atmosphere," demonstrated substantial contributions, with 30 and 27 documents, respectively. These journals, along with "Aerosol and Air Quality Research" and "Indoor Air," underscore the interdisciplinary nature of research on low-cost sensors, encompassing diverse aspects related to air quality and environmental health. This diversity of sources underscores the significance of multidisciplinary collaboration in the context of air pollution research and air quality monitoring.

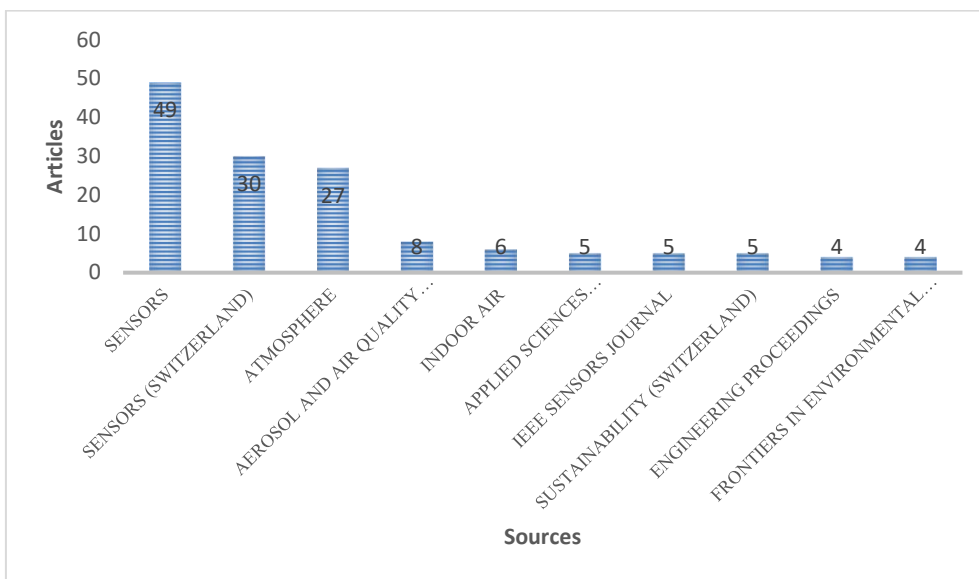


Figure 5. Most Relevant Sources

Figure 6 illustrates the cumulative development of publications from diverse sources pertaining to the utilization of low-cost sensors in air pollution monitoring from 2011 to 2025. It is evident that the journal "Aerosol and Air Quality Research" exhibits substantial growth, particularly after 2018, with the number of publications demonstrating a consistent increase. This observation is indicative of a growing interest and contributions in research focusing on air quality and sensor technologies, signifying that the journal is emerging as a prominent platform for research in these domains. The journals "Sensors" and "Sensors (Switzerland)" also demonstrate a positive growth trend, although at a rate that is less rapid than that observed in "Aerosol and Air Quality Research." Conversely, the journals "Indoor Air" and "Atmosphere" exhibit a more gradual growth pattern, yet they still contribute to the cumulative total of publications. The collective rise in publications from these diverse sources signifies an escalating focus within the scientific community on low-cost sensors and air pollution monitoring. This heightened interest has the potential to catalyze the evolution of advanced technologies and policies, thereby enhancing the efficacy of air quality management.

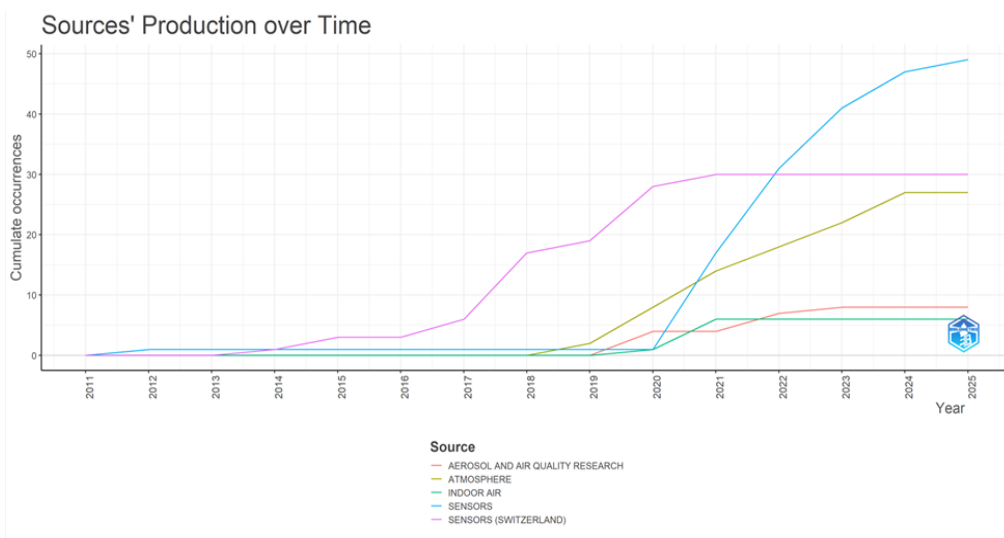


Figure 6. Sources' Production over Time

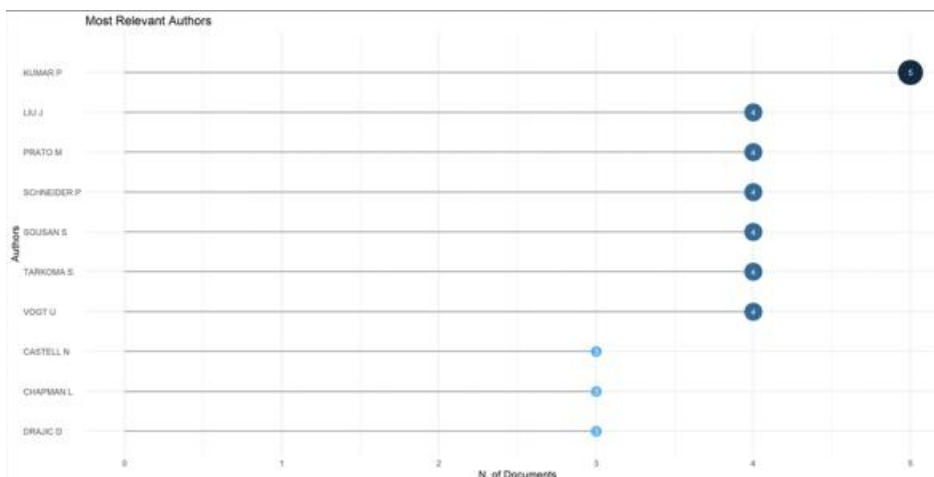


Figure 7. Most Relevant Authors

The figure 7 presented is a graphical representation of the number of documents written by the most relevant authors in a particular field of research. The vertical axis denotes the names of the authors, while the horizontal axis indicates the number of documents they produced. The analysis reveals that the author with the initials "KUMAR P" has the highest number of documents at five, indicating a significant contribution to the field. Other authors, such as "LIU J," "PRATO M," and "SCHNEIDER P," have four documents each, indicating that they also contributed substantially, although not to the same extent as KUMAR P. Further analysis revealed that other authors, such as "SOUSAN S," "TARKOMA S," and "VOGT U," also had the same number of documents, four, indicating collaboration or similar research focus between them. Conversely, authors with fewer documents, such as "CASTELL N," "CHAPMAN L," and "DRAJIC D," have three or two documents each, which may reflect a narrower specialization or more recent involvement in the field. In conclusion, this graph provides valuable insights into the distribution of author contributions in the academic literature, which may form the basis for further research or future collaborations.

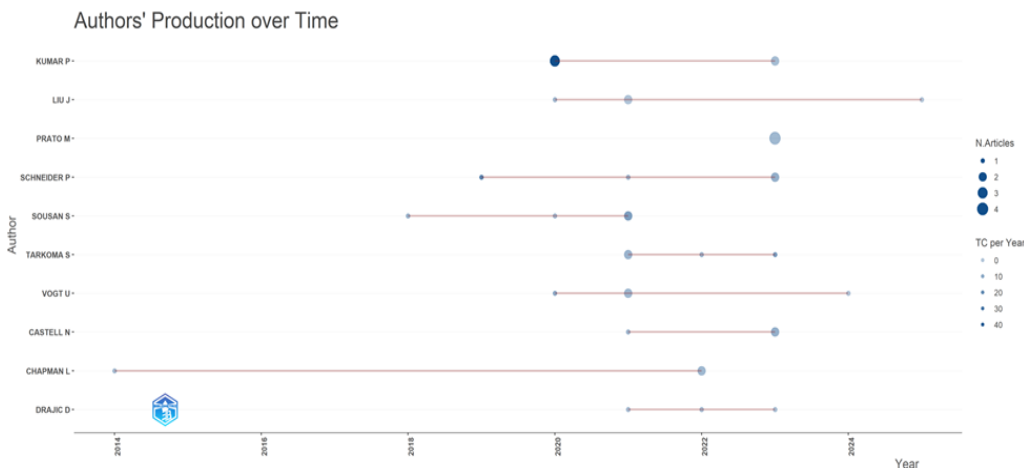


Figure 8. Authors' Production over Time

Figure 8 illustrates the production of articles by relevant authors over time, focusing on the year of publication and the number of articles produced. On the vertical axis, the names of the

authors are indicated, while the horizontal axis shows the publication years from 2014 to 2024. Each dot on the graph represents the number of articles published by each author, with different dot sizes indicating the total citations (TC) per year. The author "KUMAR P" demonstrates the most substantial production, exhibiting a consistent publication pattern from year to year, indicative of sustained contributions within this research domain. Other authors, including "LIU J," "PRATO M," and "SCHNEIDER P," also exhibit active publication patterns, though with variations in the number of published articles.

Further analysis reveals that authors "SOUSAN S" and "TARKOMA S" demonstrate relatively stable production, with multiple articles published within the same time span. Conversely, authors "VOGT U," "CASTELL N," "CHAPMAN L," and "DRAJIC D" exhibit a lower number of publications, which may be indicative of a more specific research focus or more recent involvement in the field. This graph provides valuable insights into the dynamics of author contributions in the academic literature, as well as showing trends in research production that can form the basis for further collaboration and development in the future.

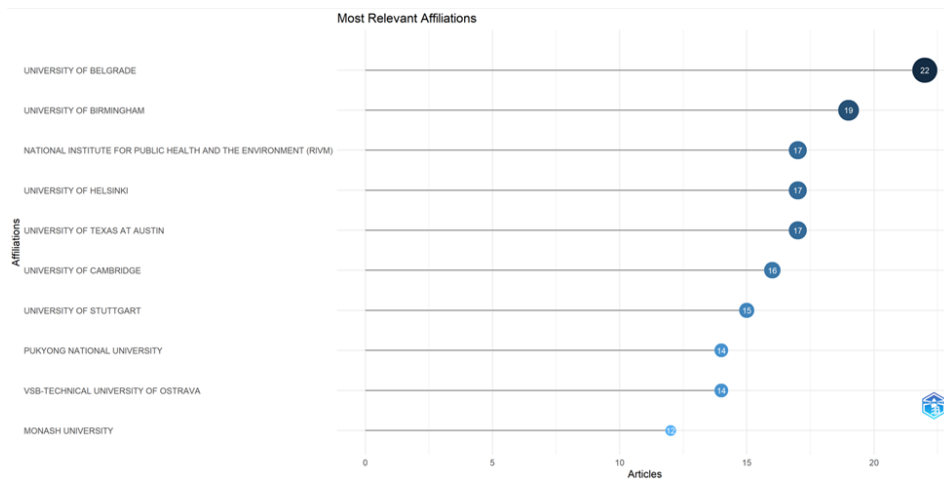


Figure 9. Most Relevant Affiliations

As Illustrated In Figure 9, The Analysis Focuses On The Most Relevant Institutional Affiliations In The Context Of The Publication Of Scientific Articles, Emphasizing The Number Of Articles Produced By Each Institution. The Vertical Axis Denotes The Names Of The Institutions, While The Horizontal Axis Indicates The Number Of Articles Published. The Analysis Reveals That "UNIVERSITY OF BELGRADE" Has The Highest Number Of Articles At Twenty-Two, Signifying A Substantial Contribution To The Research Area Under Study. Other Institutions, Such As The University Of Birmingham And The National Institute For Public Health And The Environment (RIVM), Also Demonstrate Noteworthy Results, With Nineteen And Seventeen Articles, Respectively.

Furthermore, Institutions Such As "UNIVERSITY OF HELSINKI," "UNIVERSITY OF TEXAS AT AUSTIN," "UNIVERSITY OF CAMBRIDGE," And "UNIVERSITY OF SUTTART" Each Had The Same Number Of Articles, Seventeen, Reflecting The Strong Collaboration And Similar Research Focus Between Them. Conversely, Institutions Such As "PUKYONG NATIONAL UNIVERSITY," "VSB-TECHNICAL UNIVERSITY OF OSTRAVA," And "MONASH UNIVERSITY" Exhibited A Comparatively Lower Number of Publications, With Each Institution Producing Between Fourteen and Sixteen Articles. This Graph Provides Valuable Insights into The Distribution Of Institutional Contributions In The Academic Literature, Which Can Serve As A Basis For Future Research Collaborations.

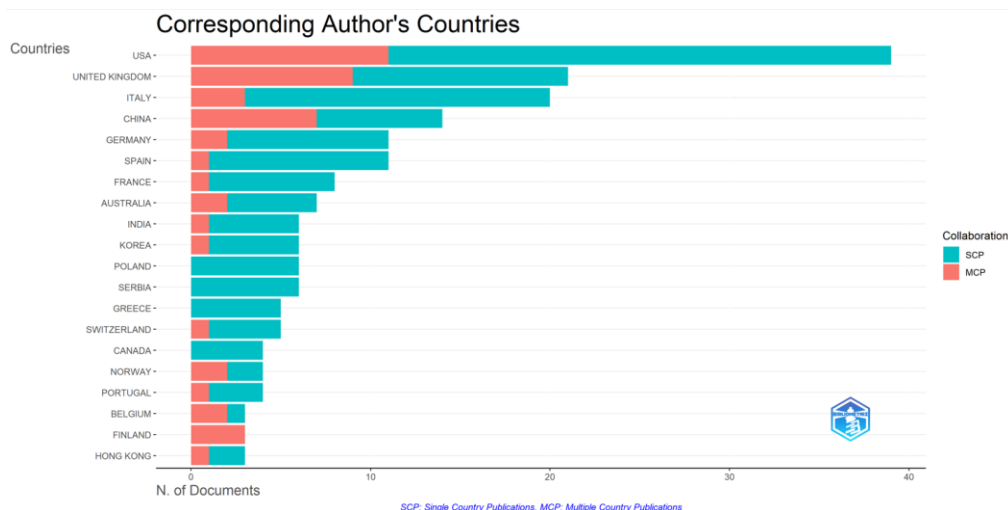


Figure 10. Corresponding Author's Countries

Figure 10 provides an overview of the countries of origin of authors contributing to scientific publications, with a focus on the number of documents produced. The vertical axis shows the names of the countries, while the horizontal axis shows the number of documents published. From this analysis, it can be seen that the United States dominates with the highest number of documents, followed by the United Kingdom and Italy. This finding indicates that these countries have significant contributions to the research field under study, with a large number of publications produced. Additionally, countries such as China, Germany, and Spain show substantial results, reflecting active involvement in international research collaborations.

Furthermore, this graph distinguishes between publications produced by authors from a single country (Single Country Publications, SCP) and publications involving collaboration between countries (Multiple Country Publications, MCP). It is evident that nations with a high volume of publications, such as the USA and the United Kingdom, also exhibit a substantial proportion of collaborative endeavors. This suggests that the research undertaken is not solely local but is also characterized by international collaboration. In contrast, nations with a smaller number of publications, such as Belgium, Finland, and Hong Kong, demonstrate a more limited engagement in international cooperation. This graph offers valuable insights into the dynamics of research collaboration at the global level and the potential for further collaborative development in the future.

Figure 11 illustrates the scientific article production of China, Italy, Spain, the United Kingdom, and the USA over time from 2011 to 2025. The vertical axis indicates the number of articles published, while the horizontal axis designates the year of publication. The analysis reveals that China demonstrates a substantial increase in the number of publications, with the curve ascending steeply since 2017.

This indicates an augmentation in China's research capacity and scientific collaboration, potentially propelled by substantial investments in research and development. In contrast, the United States and the United Kingdom demonstrate more stable growth patterns, though they too exhibit a consistent increase in the number of publications. Italy and Spain exhibit a more moderate growth trajectory compared to China, yet they still demonstrate a substantial increase in the number of articles published.

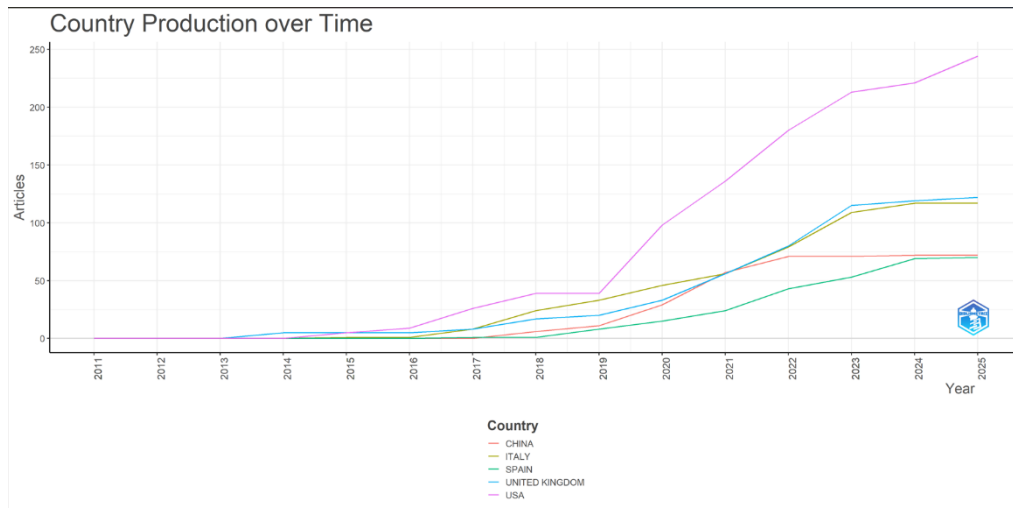


Figure 11. Country Production over Time

This finding underscores the notion that, while not as assertive as China, both nations continue to make significant contributions to the global scientific literature. The presented graph offers invaluable insights into the dynamics of research production in diverse nations and demonstrates how publication trends can be a reflection of research priorities and scientific policies in each country. Consequently, this analysis can serve as a foundation for comprehending research advancements on an international scale and potential future collaborations.

As demonstrated in Figure 12, the figure illustrates the number of citations received by the most cited countries in the scientific literature. The vertical axis denotes the names of the countries, whilst the horizontal axis indicates the number of citations received by each nation. The analysis reveals that the United States of America (USA) dominates with the highest number of citations at 870, followed by the United Kingdom (UK) with 703 citations.

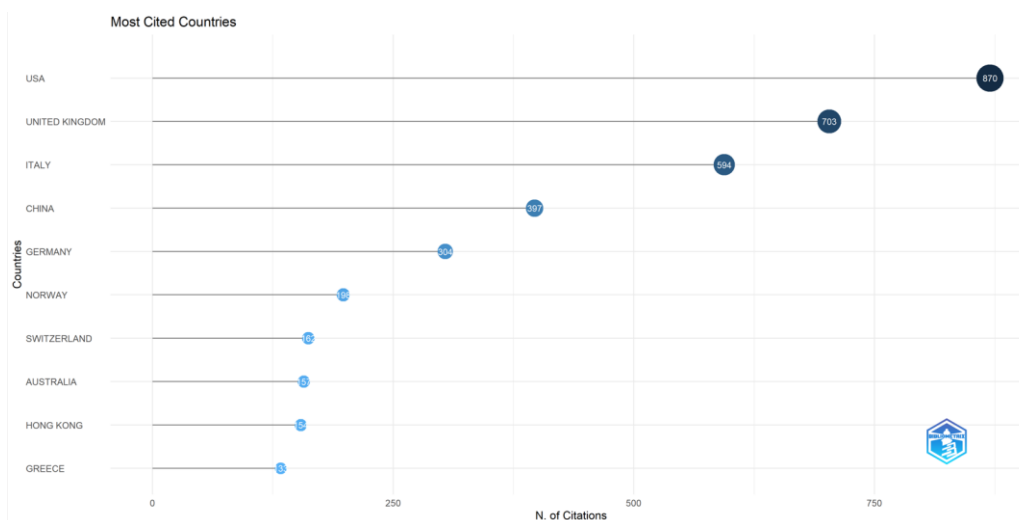


Figure 12. Most Cited Countries

This finding is indicative of the substantial influence exerted by research conducted in these countries, a influence that may be ascribed to the high calibre of research undertaken and the extensive international collaboration networks in place. Significant contributions are also evident from countries such as Italy and China, with 594 and 397 citations respectively, underscoring their role in the global research landscape.

Furthermore, a lower but still significant number of citations was shown by countries such as "GERMANY," "NORWAY," and "SWITZERLAND," with 304, 95, and 86 citations received, respectively. This finding indicates that, despite not being as prominent as the leading countries, research conducted in these nations nevertheless exerts a substantial influence on the scientific community. The graph provides valuable insight into the distribution of citations among countries, which can reflect the quality and relevance of the research produced. Consequently, this analysis can function as a foundation for comprehending the dynamics of research influence on an international scale and the potential for future collaborations.

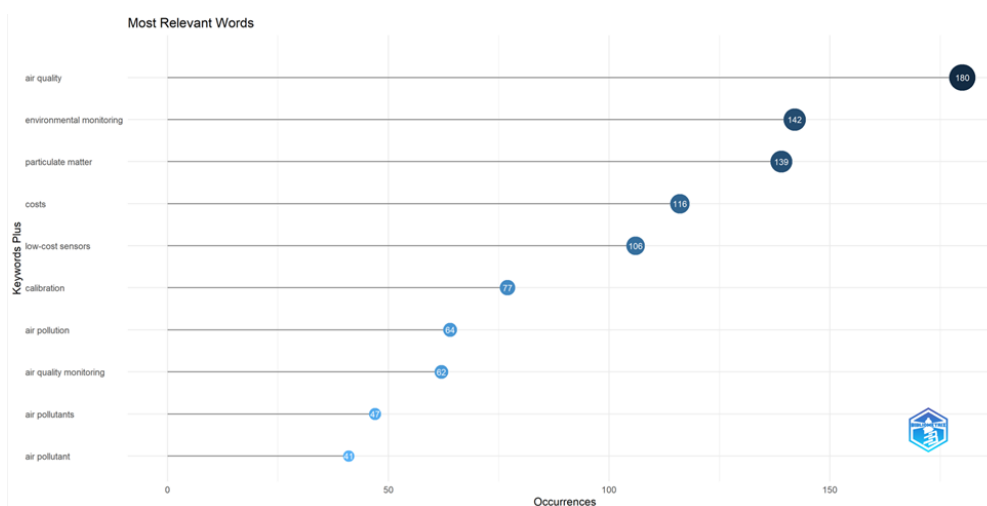


Figure 13. Most Relevant Words

As illustrated in Figure 13, the most salient keywords in the domain of research on air quality and environmental monitoring are delineated. The vertical axis enumerates the keywords, while the horizontal axis indicates the frequency with which each keyword is mentioned in the extant literature. The analysis reveals that the keyword "air quality" is the most prevalent, with 180 occurrences, reflecting the primary focus of the research. The analysis also reveals significant occurrences of keywords such as "environmental monitoring" (142 instances) and "particulate matter" (139 instances), underscoring the prominence of air quality and pollution-related issues in the extant literature.

In addition, keywords such as "costs," "low-cost sensors," and "calibration" demonstrated high relevance, with 116, 77, and 64 occurrences, respectively. This finding underscores the significance of incorporating practical and technical facets of air quality monitoring, such as costs and sensor calibration, into the prevailing discourse within the academic literature. Despite having a lower frequency of occurrence, keywords such as "air pollutants" and "air pollutants" underscore the significance of comprehending the diverse categories of pollutants that impact air quality. The graph provides valuable insights into the key themes in air quality research, which can form the basis for further research, development and future collaborations.

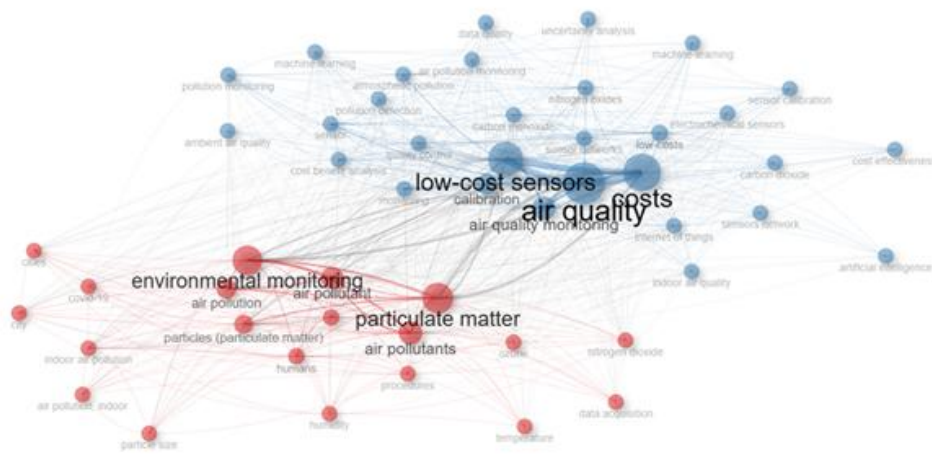


Figure 14. Co-occurrence Network

As illustrated in Figure 14, a visual depiction of the relationship between relevant keywords in the domain of air quality and environmental monitoring research is provided. In this graph, keywords of greater magnitude are indicative of a higher frequency of occurrence, whilst the lines connecting the keywords reflect the linkages between the concepts. The analysis reveals that the keywords "low-cost sensors" and "air quality" are at the centre of this network, indicating a current focus on the use of affordable sensors for air quality monitoring. The interrelationships between keywords such as "costs," "calibration," and "air quality monitoring" demonstrate that the technical and economic aspects of air quality monitoring are of major concern in the literature.

Moreover, the group of keywords related to "environmental monitoring" and "particulate matter" demonstrates that issues pertaining to air pollution and its impact on human health represent a significant focal point of this study. The high relevance of keywords such as "air pollution," "particles (particulate matter)," and "air pollutants" reflects the necessity to comprehend the diverse categories of pollutants that impact air quality. Additionally, the utilisation of technology-related keywords, such as "machine learning" and "data acquisition," signifies the growing adoption of technology-based approaches in this research domain. The graph provides valuable insights into the key themes and interconnections in air quality research, which can form the basis for further research development and future collaborations.

In the contemporary era, air quality monitoring has emerged as a critical issue, particularly with the growing awareness of the impact of air pollution on human health and the environment. The images presented illustrate significant trends in research related to air quality, emphasizing the use of low-cost sensors and innovative monitoring techniques[19]. Research by Chan et al. [20], [21] indicates that low-cost sensors can provide valuable data for environmental monitoring, making it feasible to implement widespread air quality assessments in various settings. This democratization of air quality monitoring technology allows for greater public engagement and awareness, which is essential for addressing air pollution challenges.

However, the reliance on low-cost sensors is not without its criticisms[5]. Some scholars argue that these sensors may lack the accuracy and reliability of traditional monitoring equipment, potentially leading to misleading data [22], [23]. The calibration and maintenance of low-cost sensors are also critical factors that can affect their performance. As highlighted in the visual data, the keyword "calibration" appears prominently, underscoring the necessity for rigorous validation protocols to ensure that the data collected is both accurate and actionable. This debate highlights the need for a balanced approach that considers both the benefits and limitations of low-cost sensor technology in air quality research.

Furthermore, the network analysis of keywords reveals a strong interconnection between various themes, such as "environmental monitoring," "particulate matter," and "air pollution." This interconnectedness suggests that a multidisciplinary approach is essential for comprehensively addressing air quality issues. For instance, integrating machine learning techniques with traditional environmental monitoring can enhance data analysis and interpretation, leading to more effective policy recommendations [24], [25]. The emphasis on collaboration across disciplines is a novel aspect of this research, as it encourages the synthesis of knowledge from various fields to tackle complex environmental challenges.

In conclusion, the findings from the visual data and the associated literature underscore the importance of advancing air quality monitoring through innovative technologies while also addressing the inherent challenges. The novelty of this research lies in its focus on the integration of low-cost sensors and advanced analytical techniques, which can significantly enhance our understanding of air quality dynamics. As the discourse surrounding air quality continues to evolve, it is imperative to foster collaboration among researchers, policymakers, and the public to develop effective strategies for mitigating air pollution and its associated health risks.

#### 4. CONCLUSION

This study successfully achieved its objectives by conducting a comprehensive bibliometric analysis of research trends in low-cost sensors for air quality monitoring. The findings reveal a significant increase in publications, highlighting the growing interest and relevance of this field in addressing air pollution challenges. The analysis underscores the importance of international collaboration, as evidenced by the diverse contributions from various countries and institutions. Furthermore, the integration of low-cost sensors with advanced analytical techniques presents a novel approach that enhances our understanding of air quality dynamics. Future research should focus on refining sensor technology, ensuring data accuracy through rigorous calibration, and fostering interdisciplinary collaborations to develop effective strategies for mitigating air pollution and its associated health risks.

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#### CONFLICT OF INTEREST

The author states that there are no financial or non-financial conflicts of interest that could affect the results or interpretation of this study.

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