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Bibliometric Analysis of Research Trends on Utilisation of *Low-Cost Sensor* (LCS) and *Internet of Things* (IoT) for PM2.5 Air Pollution Monitoring

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ABSTRAK

Penelitian ini menjelaskan kelemahan pada metodologi pemantauan polusi udara konvensional, mengadvokasi penerapan Sensor Berbiaya Rendah (LCS) dan Internet of Things (IoT) sebagai alternatif perintis, khususnya untuk pengawasan Particulate Matter 2.5 (PM2.5). Melalui analisis bibliometrik, penelitian ini berupaya untuk menilai evolusi literatur akademik dari tahun 2014 hingga 2023, dengan melihat tren utama, penulis terkemuka, negara terkemuka, dan jalan prospektif untuk penelitian. Keaslian penelitian ini diwujudkan dalam pengakuannya terhadap peningkatan yang nyata dalam domain ini, terutama sejak tahun 2019, bersamaan dengan semakin pentingnya LCS dan IoT sebagai solusi yang layak secara ekonomi untuk tata kelola kualitas udara. Para akademisi dari negara-negara berkembang, seperti Indonesia, digarisbawahi memiliki prospek yang berbeda untuk terlibat dalam bidang penelitian yang terus berkembang ini, terutama dalam bidang pengelolaan lingkungan. Metadata dikumpulkan secara sistematis melalui Scopus dengan menggunakan kata kunci yang relevan dan dianalisis menggunakan perangkat lunak Biblioshiny dan Vosviewer, yang menunjukkan adanya peningkatan jumlah publikasi, terutama pada tahun 2022. Penulis terkemuka termasuk Alam F, Ali S, dan Potgieter J. Hasil penelitian menunjukkan bahwa penelitian yang akan datang dan implementasi praktis LCS dan IoT untuk pemantauan PM2.5 memiliki janji yang besar, menghadirkan jalur yang bermanfaat untuk mengatasi masalah kualitas udara dalam skala global.

Kata Kunci: Bibliometrik; Sensor Berbiaya Rendah; Internet of Things; PM2,5

ABSTRACT

This investigation elucidates the inadequacies inherent in conventional air pollution monitoring methodologies, advocating for the implementation of Low-Cost Sensors (LCS) and the Internet of Things (IoT) as pioneering alternatives, specifically for the surveillance of Particulate Matter 2.5 (PM2.5). Through the execution of a bibliometric analysis, this research endeavors to assess the evolution of academic literature from 2014 to 2023, discerning principal trends, notable authors, leading nations, and prospective avenues for research. The originality of this study is manifested in its recognition of a marked escalation in this domain, particularly since 2019, alongside the burgeoning significance of LCS and IoT as economically feasible solutions for air quality governance. Scholars from emerging nations, such as Indonesia, are underscored as possessing distinctive prospects to engage in this proliferating field of inquiry, particularly in the realm of environmental management. Metadata was systematically amassed via Scopus utilizing pertinent keywords and subjected to analysis employing Biblioshiny and Vosviewer software, uncovering a pronounced increase in publications, notably in 2022. Distinguished authors include Alam F, Ali S, and Potgieter J. The results suggest that forthcoming research and practical implementations of LCS and IoT for PM2.5 monitoring possess substantial promise, presenting a fruitful pathway for tackling air quality issues on a global scale.

***Keywords**: Bibliometric; Low-Cost Sensor; Internet of Things; PM2,5*

I. INTRODUCTIONS

Deterioration of air quality constitutes a paramount environmental challenge across numerous nations globally (Huda et al., 2024; Yang et al., 2023; Zhao et al., 2022). The escalation of emissions stemming from industrial operations, vehicular transportation, and the combustion of fossil fuels has resulted in heightened concentrations of atmospheric pollutants, notably Particulate Matter (PM), particularly PM2.5, which comprises fine particles with a diameter measuring less than 2.5 micrometers (Alonso et al., 2021; Boeing et al., 2023; Kanu et al., 2021). PM2.5 has been recognized as one of the most hazardous pollutants concerning human health, primarily due to its diminutive size, which facilitates its infiltration into the respiratory system, potentially leading to an array of respiratory and cardiovascular ailments(Chen et al., 2023; Jaganathan et al., 2024; Ren et al., 2021).

The precise and timely surveillance of air quality is essential for the effective management and alleviation of the adverse effects of air pollution (Shihab, 2023; Sokolova et al., 2025). Nonetheless, the efficacy of advanced air monitoring instruments, such as reference technology-based air quality measurement devices, is frequently hindered by exorbitant costs, the necessity for rigorous maintenance, and insufficient geographical distribution, particularly in developing nations(Kosta et al., 2024; Suriano & Penza, 2022). Consequently, the advent of Low-Cost Sensors (LCS) and their incorporation with the Internet of Things (IoT) presents a viable alternative (Nourildean et al., 2022; Wang, 2022). LCS are capable of delivering real-time air quality data with broader geographic reach and at reduced costs in comparison to conventional reference instruments (González, 2025; Preux et al., 2023).

In recent years, scholarly inquiry pertaining to the application of LCS and IoT for the monitoring of air quality, particularly concerning PM2.5, has witnessed considerable advancement (Considine et al., 2023; Jo et al., 2020; Pang et al., 2023). This progress is evidenced by the increasing volume of scientific literature addressing this subject annually. The objective of this study is to investigate the trends in scientific publications regarding the utilization of LCS and IoT for air pollution monitoring, with an emphasis on PM2.5 parameters, while also identifying the predominant authors, journals, and nations engaged in this research. Furthermore, this study seeks to uncover potential avenues for innovation and the development of future topics, particularly in developing countries such as Indonesia.

II. METHODS

This research employs bibliometric methodologies to discern, scrutinize, and visually represent data. The bibliometric framework, which represents a quantitative approach to the examination of scientific literature, was initially conceived by Allen Richard in 1969, subsequent to the foundational contributions of Coles and Eales who pioneered this methodology in 1917(Feng et al., 2023; Hossain, 2020; Liu & Wang, 2024). The predominant merit of this approach lies in its ability to elucidate trends and advancements across various scientific fields. Bibliometric analysis provides an extensive viewpoint on the progression of a scientific domain, particularly within the realm of ambient air quality management, with an emphasis on fine particulate matter (particulate matter)(Joo et al., 2022; Lam et al., 2023; Senarathna et al., 2024).

The investigation was executed utilizing a plethora of methods, encompassing citation analysis, co-citation evaluation, geographic distribution, word frequency analysis, and author collaboration assessment. These methodologies were employed to scrutinize the progression of a designated field of inquiry. The data utilized in the current analysis is sourced from the Scopus database (https://www.scopus.com/search), which is esteemed as one of the most comprehensive scientific databases on a global scale(Maral, 2024; Sabda, 2024; Santoso et al.,2023). The phases of article retrieval encompass keyword searches, data aggregation, data organization and cleansing, analysis, interpretation, and visualization. Metadata was extracted from SCOPUS utilizing the keywords ‘Low-Cost Sensor’ OR LCS AND ‘Internet of Things’ OR IoT AND monitoring AND ‘air pollution’ OR ‘air quality’ AND Particulate Matter OR PM2.5, which concentrated on article titles, abstracts, and keywords, for the period spanning 2014-2023.

The data subjected to analysis included the annual publication count, journals featuring articles pertinent to Low-Cost Sensors & PM2.5, authors, authors' countries of origin, and research themes, which were subsequently examined.

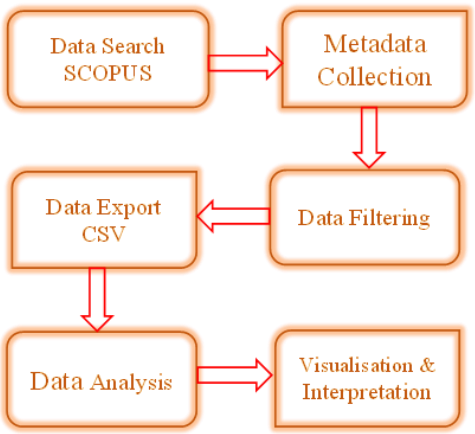

Figure 1. Research Flow Chart

The process of data filtration was executed without imposing restrictions on the subjects, yielding a total of 82 articles. Subsequent filtration was conducted by selecting document types specifically categorized as journal articles and conference proceedings, restricted solely to publications in the English language, which resulted in a refined set of 68 articles. The filtered dataset obtained from SCOPUS was exported in CSV format and subsequently analyzed using Biblioshiny (https://www.bibliometrix.org/home/) and Vosviewer(Ali Basah et al., 2024; Sklavos et al., 2024). While numerous bibliometric software options exist, including CiteSpace, BibExcel, VOSviewer, CiteNetExplorer, and Biblioshiny, this study opted for VOSviewer and Biblioshiny due to their distinct advantages and limitations in comparison to alternative software solutions (see Figure 1).

III. RESULTS AND DISCUSSION

This chapter engages in a comprehensive examination pertaining to the outcomes derived from the exploration of articles within the SCOPUS literature database, which encompasses an analysis of the trends and advancements in scholarly articles associated with the management of air quality and particulate matter.

Table 1. Essential details of scholarly articles obtained from the Scopus literature database.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2014: 2024
Sources (Journals, Books, etc)	56
Documents	68
Annual Growth Rate %	24,57
Document Average Age	2,76
Average Citations per Doc	13,65
References	2629
Document Contents	
Keywords Plus (ID)	704
Author's Keywords (DE)	213
AUTHORS	
Authors	328
Authors of single-authored docs	1
AUTHORS COLLABORATIONS	
Single-authored docs	1
Co-Authored per Docs	5,25
International co-authorships %	23,53
DOCUMENT TYPES	
Article	49
Conference Paper	19

Table 1 presents the primary data aggregation concerning published articles that pertain to the implementation of Low-Cost Sensors (LCS) and the Internet of Things (IoT) in the monitoring of PM2.5 air pollution. The temporal scope of publication spans from the year 2014 to 2024, encompassing a total of 56 journal sources and yielding 68 documents, with an annual publication growth rate quantified at 24.57%. Additionally, the figure distinctly illustrates the total number of contributing authors, which amounts to 328 individuals. Furthermore, 23.53% of these authors are identified as international collaborators, with an average of 5.25 co-authors per document. The aforementioned data also reveal that there are 213 distinct author keywords, 2629 references cited, an average publication interval of 2.76 years, and an average citation count of 13.65 per document. This information suggests a burgeoning interest among researchers in the application of low-cost sensors and IoT technologies for air quality monitoring. In light of technological advancements and the constraints associated with monitoring expenditures, it can be posited that the design of sensors dedicated to air quality monitoring represents a viable alternative for effective air quality management initiatives.

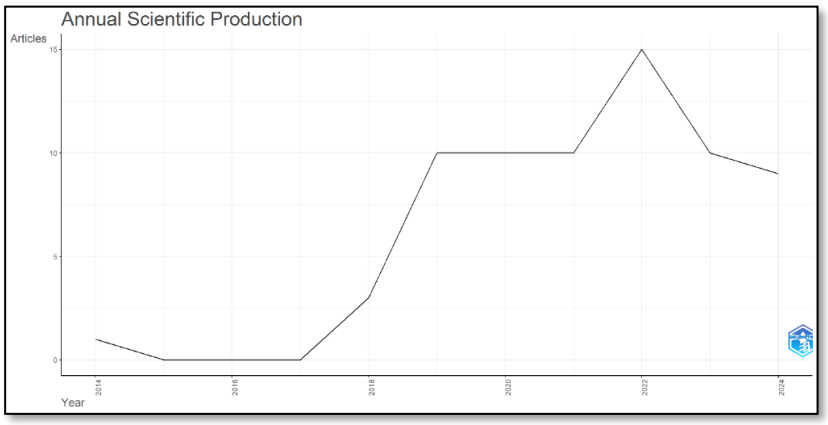

Figure 1. Annual Scientific Production Graph

It is evident from **Figure 1** that the scholarly output concerning the utilization of Low-Cost Sensors (LCS) and the Internet of Things (IoT) for the surveillance of PM2.5 air pollution has exhibited a notable increase over successive years. It is observable that between the years 2014 and 2017, the scholarly production fluctuated between 0 and 1 article. In 2018, there was a discernible escalation in the volume of articles, reaching a total of 3. From 2019 to 2021, the mean production of articles stabilized at approximately 10 articles per year. In 2022, the total number of published articles rose to 15, while in 2023, the output decreased to 10 articles. According to the data presented in Figure 2, there has been a discernible escalation in the academic output pertaining to the application of low-cost sensors and the Internet of Things in the context of air quality management. This trend may suggest that, year after year, the challenges associated with air quality monitoring technologies are amplifying; conversely, a plethora of scholarly articles propose diverse alternative solutions aimed at addressing the issues related to air quality management.

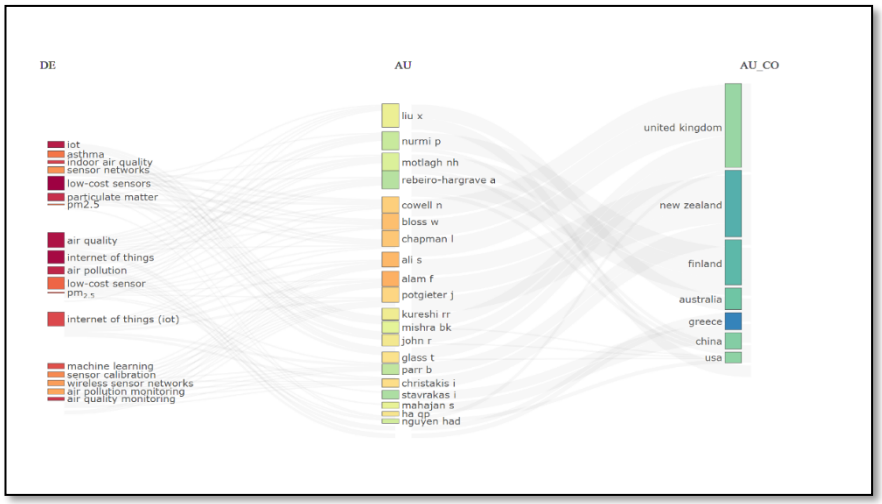

Figure 2. Correlation among keywords, authors, and country of origin.

The interrelationship among keywords, authors, and the authors' respective countries of origin in the context of producing scholarly articles pertaining to the utilization of Low-Cost Sensors (LCS) and the Internet of Things (IoT) for the monitoring of PM2.5 air pollution is illustrated in **Figure 2**. It has been established that certain principal keywords that frequently emerge in discussions surrounding the deployment of LCS and IoT for the monitoring of PM2.5 air pollution include IoT, Low-Cost Sensors, air quality, Internet of Things, machine learning, and wireless sensor networks. Furthermore, it has been noted that several authors whose names frequently recur in the literature related to the application of LCS and IoT for PM2.5 air pollution monitoring are Petteri Nurmi, Naser Hossein Motlagh, Andrew Rebeiro-Hargrave, Sasu Tarkoma, Nicole Cowell, Lee Chapman, William Bloss, Sharafat Ali, Fkhrul Alam, Johan Potgieter, and Bhupesh Kumar Mishra. Additionally, it is recognized that the authors' countries of origin are predominantly represented by individuals from the United Kingdom, New Zealand, Finland, China, Greece, and Australia. Scholars hailing from the United Kingdom exhibit the highest prevalence in publishing articles pertinent to low-cost sensors. This observation suggests that advancements in air quality monitoring and measurement methodologies, particularly those employing low-cost sensors, have commenced in the United Kingdom in comparison to other nations. This assertion is substantiated by the preeminence of authors affiliated with institutions in the United Kingdom.

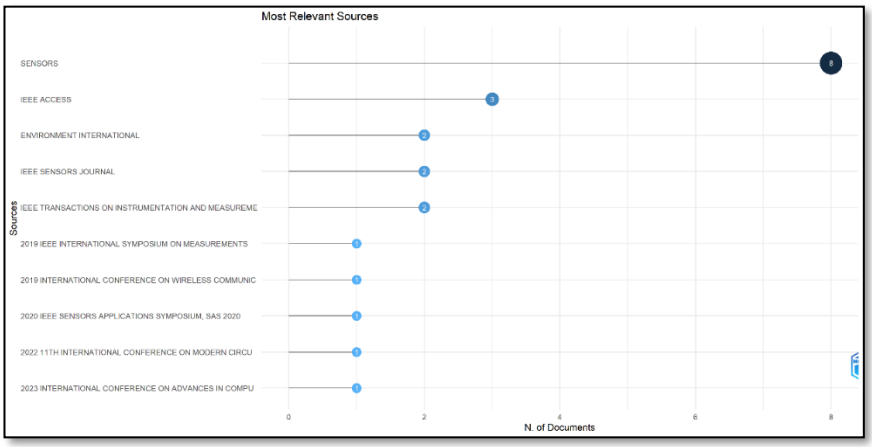

Figure 3. The Most Pertinent Reference Materials

The most pertinent reference materials are illustrated in **Figure 3**. It is well-established that numerous scholarly journals that primarily disseminate articles concerning the application of Low-Cost Sensors (LCS) and the Internet of Things (IoT) for the monitoring of PM2.5 air pollution encompass Atmospheric Chemistry and Physics with 45 published articles, Journal of Geophysical Research: Atmospheres with 16 published articles, Environmental Science and Pollution Research with 12 published articles, Transactions on Ecology and the Environment with 12 published articles, Aerosol and Air Quality Research with 11 published articles, Geophysical Research Letters with 10 published articles, and the American Journal of Environmental Science with 9 published articles.

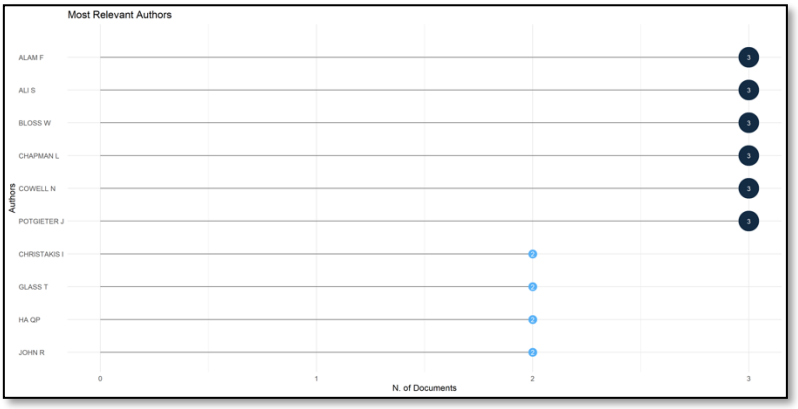

Figure 4. Authors of Paramount Significance

The most pertinent authors of articles are delineated in **Figure 4**. It is established that a number of preeminent authors have disseminated scholarly works pertaining to the application of LCS and IoT for the surveillance of PM2.5 air pollution, notably including Fakhrul Alam, Sharafat Ali, William Bloss, Lee Chapman, Nicole Cowel,

and Johan Potgieter, each contributing three articles, followed by Christakis, Tyrell Glass, Huang P. Ha, and Reena John, who each authored two articles.

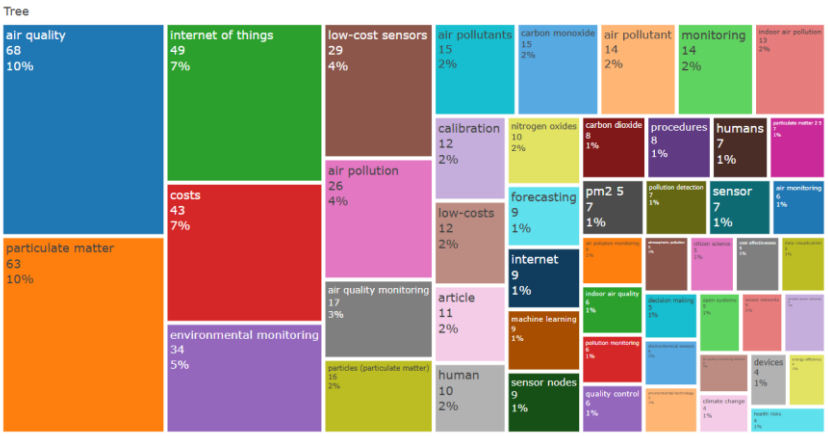

Figure 5. Keyword distribution

Several prominent and pertinent keywords associated with scholarly articles concerning the application of LCS and IoT for the surveillance of PM2.5 air pollution are illustrated in **Figure 5**. It is established that the keyword "air quality" emerges as the most prevalent, encompassing 68 articles, which constitutes 10% of the total. The keyword "particulate matter" ranks as the second most significant term, represented in 63 articles, also accounting for 10%. The term "internet of things" is notable, appearing in 49 documents, which corresponds to 7%. Conversely, the keywords pertinent to the employment of LCS and IoT for the monitoring of PM2.5 air pollution, albeit limited in number, include "sensors" (1%), "internet" (1%), "devices" (1%), "quality control" (1%), "climate change" (1%), "air pollution monitoring" (1%), and "health risks" (1%). This analysis indicates that the aforementioned keywords possess substantial potential for further investigation and development within research themes related to the utilization of LCS and IoT for the monitoring of PM2.5 air pollution, as the corpus of documents or articles remains relatively scarce.

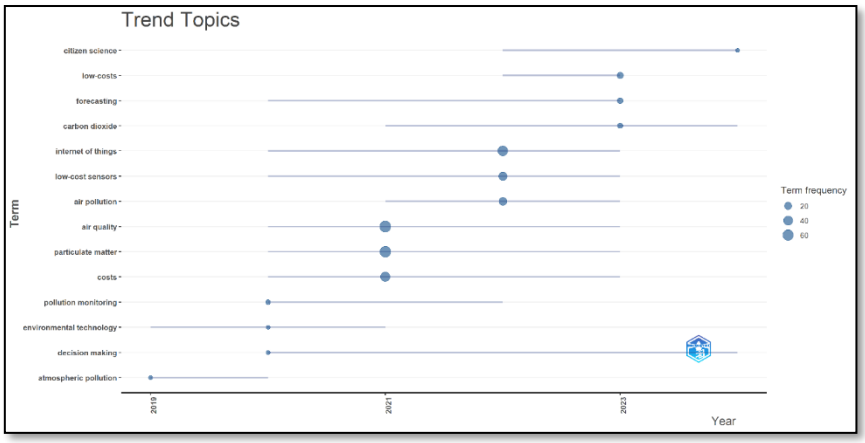

Figure 6. Evolution of Subjects Pertaining to The Governance Of Air Quality And Particulate Matter

Figure 6 delineates the annual trajectory of scholarly articles pertaining to air quality management that have been disseminated in international journals cataloged by Scopus. Analyzing **Figure 6** reveals a periodic evolution of themes associated with air quality management. Research endeavors encompassing the keywords "internet of things" and "low-cost sensors" have garnered considerable attention from 2020 to 2023, yet the corpus of articles utilizing the keyword "internet of things" approximates 40, in contrast to the volume of articles employing the keyword "low-cost sensors." Additionally, three keywords have emerged as focal points for investigation by academics towards the conclusion of 2023, namely "citizen science," "carbon dioxide," and "decision making." It is evident that research characterized by the keyword "air quality" possesses the highest document count among articles associated with alternative keywords, exceeding 60 documents. The preceding analysis indicates that inquiries centering on the theme of "internet of things" are consistently intertwined with "decision making" and "air quality," thereby presenting avenues for further research development in these domains.

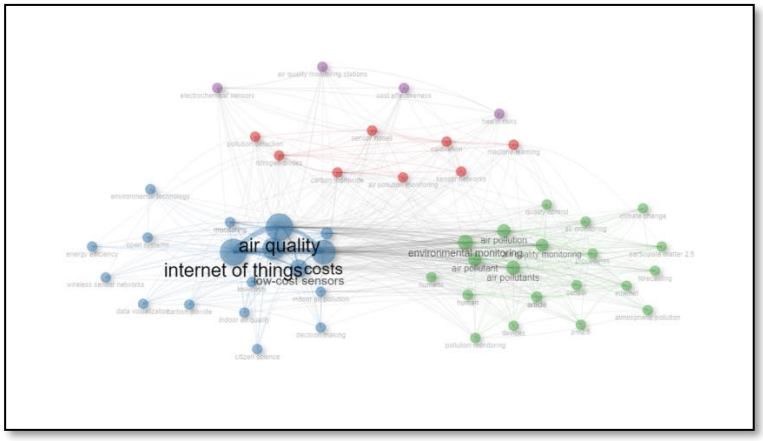

Figure 7. Visualization of the network pertaining to co-occurrence dynamics.

Figure 7 illustrates a network visualization pertaining to co-occurrence, elucidating the interconnection or association of one term with another within the scholarly discourse surrounding the application of Low-Cost Sensors and the Internet of Things (IoT) for the monitoring of PM2.5 air pollution. Numerous articles cataloged in the Scopus database can be classified into four distinct clusters, which are discernible through the chromatic differentiation of the nodes corresponding to each keyword. Cluster 1, represented in blue, signifies a compilation of articles centered on the primary theme of the Internet of Things. Cluster 2, represented in green, denotes a collection of articles wherein the prevailing keyword pertains to environmental monitoring. Cluster 3, represented in red, encompasses a set of articles focused on the subject of sensors. Lastly, Cluster 4, depicted in purple, addresses the principal theme of health risks.

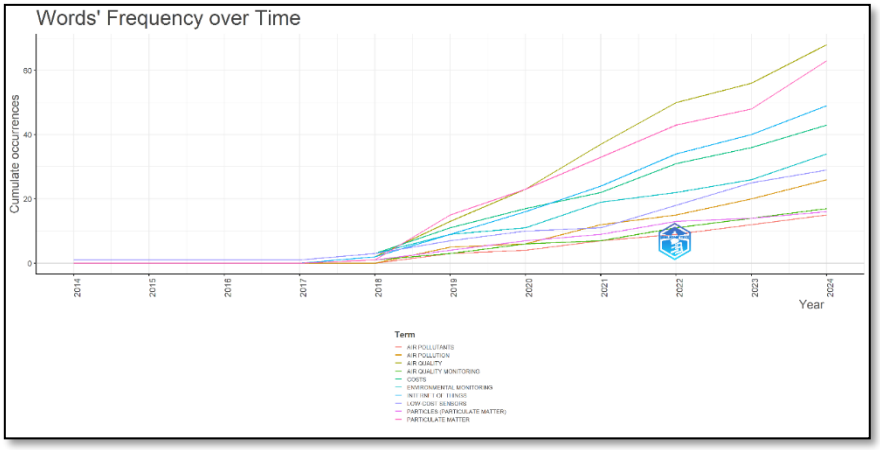

Figure 8. Illustrates The Temporal Distribution Of Word Frequency

Figure 8 indicates that scholarly investigations utilizing the keywords "internet of things," "air pollution," "air quality," "low-cost sensors," and "particulate matter" can be categorized into two distinct temporal intervals. During the period from 2014 to 2018, scholarly output pertaining to these subjects was rather minimal, with the emergence of fewer than three publications annually. Conversely, from 2018 to 2024, research associated with these topics began to witness a notable escalation in scholarly activity. By the year 2024, studies focusing on the keywords "air quality" and "particulate matter" were documented to exceed sixty publications. Additionally, research incorporating the keywords "environmental monitoring" and "internet of things" demonstrated a substantial uptick, with the total number of publications surpassing forty. This trend underscores the potential for innovation and advancement in air quality surveillance, particularly regarding particulate matter, through the application of low-cost sensors and the integration of internet of things technology.

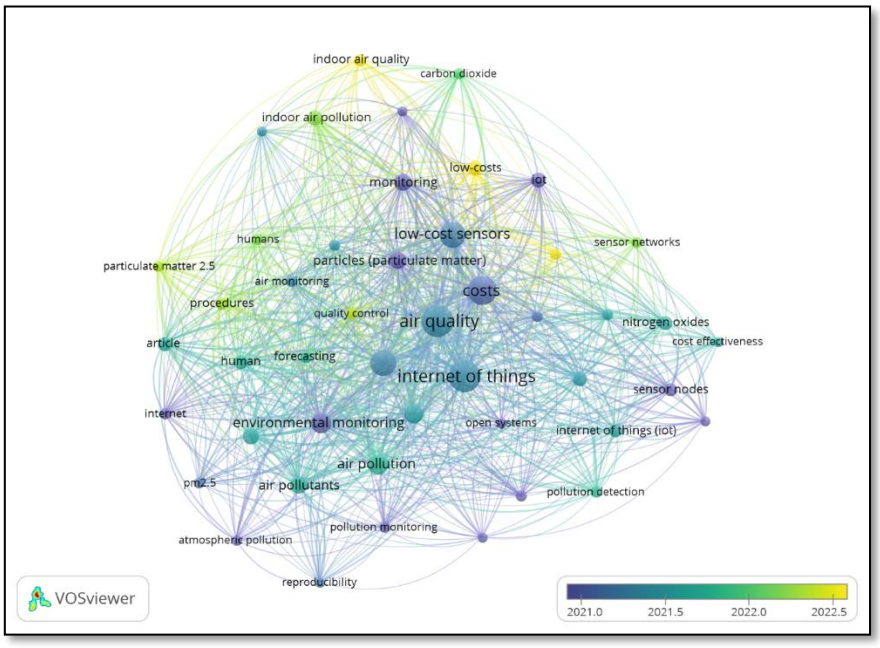

Figure 9. Composite Visualization

Following the identification of the mapping and clustering within the domain of air quality management strategy through network visualization, the subsequent phase involves the mapping and clustering of research trajectories predicated on historical data or the year of publication, utilizing the Vosviewer tool. The insights derived from the Overlay visualization illustrated in **Figure 9** can serve as a reference point to ascertain and delineate the current state of research pertinent to the Utilization of Low-Cost Sensors and IoT for Monitoring PM2.5 Air Pollution during the temporal span from 2014 to 2024.

As a result of the bibliometric analysis conducted via the Scopus metadata integrated into the Vosviewer software, an Overlay visualization was generated. Within this visualization, the coloration of the node signifies the keyword corresponding to the year of publication. For instance, the keyword 'internet of things' is represented by a green node, indicating that the article featuring this keyword was published between the years 2021 and 2022. Conversely, the term 'low cost' is represented in the Overlay visualization by a yellow node, signifying that the term 'low cost' appeared in the research published in 2022 and thereafter.

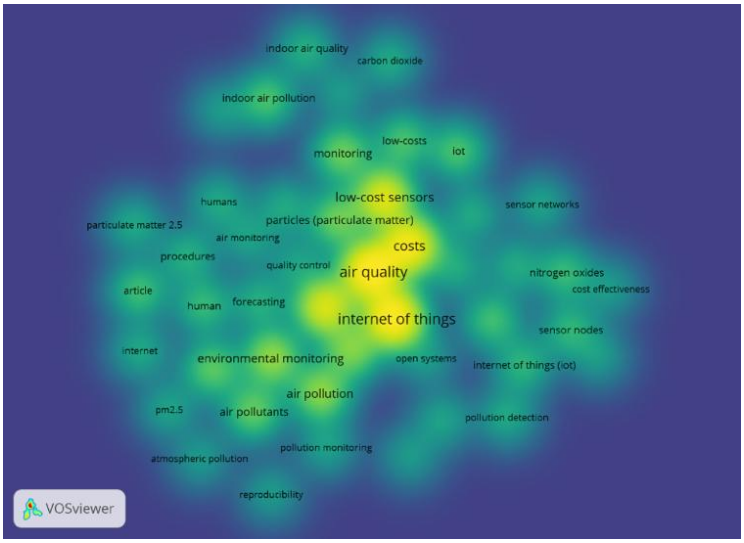

Figure 10. Visualization of density in relation to co-occurrence.

The subsequent section presents a bibliometric analysis utilizing density visualization. The visualization outcomes depicted in **Figure 10** reveal the presence of concentrated regions or areas exhibiting high density between distinct nodes. The saturation level discerned in the keywords highlighted in yellow signifies that the corresponding area

represents a subject of extensive research and has been cataloged by Scopus; for instance, the keywords air quality, low-cost sensors, and internet of things exemplify this phenomenon. Conversely, the nodes characterized by darker hues suggest that these subjects have not been subjected to thorough investigation. This scenario presents opportunities for scholarly inquiry into these topics, such as the keyword sensors network in relation to air quality. By developing an air quality model, this could contribute to an overarching air quality management strategy. The bibliometric analysis employing density visualization, which indicates low strain and intensity, reflects that research pertaining to air quality modeling in connection with air quality management strategies remains comparatively sparse, thereby indicating substantial scope for further exploration within this field.

This investigation elucidates significant prospects for more economical and efficient air quality monitoring, particularly within developing nations. The distinctive aspect of this study resides in the implementation of low-cost sensors (LCS) in conjunction with IoT technology to address the challenges posed by traditional monitoring instruments that are both costly and challenging to maintain. In recent years, a notable surge in publications related to LCS has been observed, indicating an increasing global interest in this domain, with a pinnacle of innovation recorded in 2022. These substantial advancements not only expedite the adoption of LCS technology but also foster opportunities for international research collaborations(Moradi & Sormunen, 2023; Nwokolo et al., 2024). Morawska et al. (2018) recognized the potential of LCS in broadening monitoring coverage; however, they emphasized the necessity for enhancing the accuracy of these sensors beyond that of reference technologies. Nevertheless, research such as that conducted by Castell et al. (2017) demonstrates that LCS can serve as an effective solution for real-time air quality monitoring across a broader geographic scope at a reduced cost. Future research avenues may concentrate on augmenting the precision of these sensors, integrating machine learning for enhanced air quality predictions, as well as exploring applications in under-researched regions such as Southeast Asia and Africa.

IV. CONCLUSION

Air pollution presently constitutes a significant global challenge and remains a focal point of extensive discourse among scholars. The assessment of air quality necessitates sophisticated instrumentation and substantial financial investment; however, the advent of economically viable sensors and the proliferation of the Internet of Things (IoT) present a viable alternative solution. The progression of research pertaining to the application of Low-Cost Sensors and IoT for the monitoring of PM2.5 air pollution may yield opportunities for diverse innovations and further advancements. To elucidate the evolution of research associated with the application of Low-Cost Sensors and IoT for PM2.5 air pollution monitoring, predicated on co-authorship (authors) and co-occurrence (keywords), a bibliometric analysis was conducted utilizing Biblioshiny and Vosviewer software. Initially, the dataset was compiled through metadata indexed by Scopus, encompassing a total of 68 published documents. The findings from bibliometric mapping, employing Biblioshiny and Vosviewer through network, overlay, and density visualizations, indicate that between 2014 and 2024, research concerning the application of Low-Cost Sensors and IoT for PM2.5 air pollution monitoring has experienced a year-on-year increase. The utilization of Scopus for article searches is advantageous, as all publications feature comprehensive metadata, thereby facilitating researchers' efforts to analyze the trajectory of research developments. The most significant increase in publication output was observed in 2022 and the subsequent years, during which the mean annual production of scientific articles exceeded 40, whereas the least prolific period was from 2014 to 2018, characterized by a production of fewer than three articles. The trajectory of research concerning air quality management strategies aligns with emergent findings within the domain. Bibliometric analysis has pinpointed authors engaging with the theme of the application of Low-Cost Sensors and IoT for PM2.5 air pollution monitoring who have established collaborative relationships with one another. Among the prominent authors frequently cited in articles related to the application of Low-Cost Sensors and IoT for PM2.5 air pollution monitoring are Fakhrul Alam, Sharafat Ali, William Bloss, Lee Chapman, Nicole Cowel, and Johan Potgieter. The practical implications of this study reveal that this research area is predominantly explored in European and East Asian nations, notably China and Japan. Conversely, research in Africa, West Asia, and Southeast Asia remains relatively underexplored. This presents a substantial opportunity for scholars from these regions to pursue analogous research endeavors. Furthermore, the study reveals a lack of collaborative research initiatives between authors residing in developed and developing nations, such as Indonesia, indicating potential avenues for future collaboration.

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