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Twenty-Five Years of Satellite-Based Particulate Matter Estimation: A Bibliometric Analysis

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Abstract **–** Over the past two decades, the integration of remote sensing technologies for estimating particulate matter (PM) has increased rapidly, reflecting the global urgency of monitoring air pollution at large spatial scales. This study presents a bibliometric analysis of 4,155 journal articles published between 2000 and 2024, retrieved from the Scopus database. Only peer-reviewed English-language journal articles were included, while conference proceedings, reviews, and book chapters were excluded. By leveraging the Bibliometrix package in R, this analysis maps scientific trends in remote sensing applications for estimating particulate matter ($PM_{2.5}$ and PM_{10}). Results show that annual publications grew from fewer than 50 per year in the early 2000s to more than 500 by 2024, with China (n = 10,023), the United States (n = 6,501), and India (n = 1,325) emerging as leading contributors. Keyword co-occurrence and thematic clustering highlight the growing use of machine learning, data fusion, and health-linked applications. International collaboration networks reveal strong linkages among China, the USA, and Europe, while regions such as Africa and South America remain underrepresented. These findings suggest that future efforts should focus on targeted investments in the underrepresented areas and on integrating remote sensing, machine learning, and health data into air quality indices to enhance environmental monitoring and policy relevance.

Keywords *– Remote sensing; Bibliometric analysis; Co-occurrence analysis; Air pollution; Particulate matter*

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1.0 Introduction

Air pollution is one of the most critical environmental and health issues, especially in developing countries, due to industrialisation and urbanisation (Ranjan et al., 2020). Among the various pollutants, particulate matter (PM), specifically fine particulate pollution <2.5 μm ($PM_{2.5}$), is considered especially dangerous due to its ability to penetrate deep into the respiratory system for blood gas exchange (Schraufnagel, 2020). Exposure to high levels of $PM_{2.5}$ has been strongly linked to cardiovascular disease, impaired lung function, skin ageing and increased mortality (Ding et al., 2017; Pope III et al., 2020; Wang et al., 2018). Therefore, it is essential to monitor PM concentrations for safeguarding public health. Basically, ground-based monitoring stations have been used to measure air pollutant concentrations with high accuracy. However, many regions, particularly in developing or remote areas, lack a dense network of air quality monitoring stations due to financial, logistical, and technical constraints (Kanniah & Zaman, 2021). This uneven distribution of ground sensors limits the ability to assess the spatial variability of air pollution, especially during critical episodes (Zaman et al., 2021).

To address these limitations, satellite-based remote sensing has emerged as a powerful alternative for estimating surface-level PM concentrations. Instruments aboard satellites, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), the Medium Resolution Imaging Spectrometer (MERIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), the Advanced Himawari Imager (AHI), and the Sentinel-5P, capture atmospheric aerosol properties through parameters called Aerosol Optical Depth (AOD). AOD is a physical parameter that quantifies the amount of light absorbed and scattered by airborne particles throughout the vertical column of the atmosphere (Shtein et al., 2019). These data can be processed and calibrated against ground measurements to estimate PM concentrations at large spatial and temporal scales. Remote sensing offers cost-effective, continuous, and wide-coverage solutions for air quality assessment, particularly in areas lacking dense monitoring networks.

Over the past two decades, research on remote sensing applications for PM estimation has grown rapidly, particularly following the introduction of MODIS data in the early 2000s, which offered consistent global aerosol observations and reliable AOD products. In addition to MODIS, more recent milestones include the Himawari-8/9 geostationary satellites, which provide high-temporal-resolution AOD observations across the Asia-Pacific region. Meanwhile, the Sentinel-

5P mission has enhanced our ability to monitor trace gases and aerosols with higher spatial and spectral resolution.

Scholars have explored diverse approaches, including empirical modelling, statistical regression, machine learning, and data fusion techniques that integrate satellite data with meteorological and land-use information (Chu et al., 2016; Ranjan et al., 2020; Shin et al., 2020). While the field has expanded, the distribution of research outputs and collaborations remains varied across regions and institutions. To better understand the development of this research field, bibliometric analysis provides a helpful method for mapping scientific trends, evaluating research productivity, and identifying key contributors (Shu et al., 2024). Through the study of citation patterns, collaboration networks, and keyword co-occurrence, it offers valuable insights into the evolution of research priorities, identifies influential publications, and uncovers knowledge gaps that require further exploration (Aria & Cuccurullo, 2017; Derviş, 2019). This approach is particularly valuable in rapidly evolving interdisciplinary domains, such as remote sensing and environmental monitoring. Previous bibliometric studies have demonstrated the utility of this approach in various domains related to air pollution. For example, global research on air pollution and cardiovascular diseases from 2012 to 2022 (Wen et al., 2024), global $PM_{2.5}$ exposure research trends (Jia et al., 2023), trend publication on air quality ($PM_{2.5}$), management strategies (Bulto et al., 2024; Santoso et al., 2024), and studies also examined the effects of $PM_{2.5}$ on asthma (Shu et al., 2024). Recently, bibliometric perspectives have also been applied to methodological approaches, for instance, the application of machine learning in air pollution research (Ansari & Quaff, 2024; Jain et al., 2022; Li et al., 2023).

However, none of these studies have specifically examined the specific role of remote sensing technologies in particulate matter estimation. This gap highlights the novelty of the present review, which provides the first bibliometric analysis dedicated to remote sensing–based PM estimation across 25 years (2000–2024). The chosen timeframe was deliberately selected to capture key technological and scientific milestones: the introduction of MODIS aerosol products in the early 2000s, which enabled the first consistent global AOD retrievals; the subsequent launches of MERIS, VIIRS, Himawari-8/9 and Sentinel-5P and the recent adoption of machine learning and data fusion approaches that have transformed PM estimation. Specifically, it seeks to: (1) analyse the growth of scholarly output over time; (2) identify leading countries and institutions; (3) examine keyword trends and thematic developments; and (4) explore collaboration

patterns in the scientific community. The insights from this review aim to support future research, highlight knowledge gaps, and provide direction for advancing geospatial approaches in air quality assessment.

2.0 Methods

2.1 Search Criteria

This study adopted a bibliometric approach to map and analyse scientific publications related to the estimation of particulate matter using remote sensing technology. The methodology was structured into three key stages: data retrieval, data cleaning, and bibliometric analysis. The data analysed in this study were obtained from the Scopus database, one of the largest and most comprehensive scientific databases available (Azer, 2017). Scopus is one of the largest bibliographic databases, indexing over 36,000 titles from nearly 12,000 publishers, including more than 34,000 peer-reviewed journals across the life, social, physical, and health sciences (Sabri et al., 2022), making it a reliable and valuable resource for conducting bibliometric research.

The search was conducted in Scopus on July 1, 2025, and restricted to journal articles published between 2000 and 2024. To ensure transparency and reproducibility, the exact Boolean string, including field tags and limits, is provided in Table 1. The query specifically targeted final-stage journal articles written in English and focused on topics combining remote sensing applications with air pollution, particularly particulate matter ($PM_{2.5}$ and PM_{10}). The search terms were applied to the title, abstract, and author keywords fields to ensure comprehensive retrieval of relevant documents. The search strategy and screening criteria are outlined in Table 1.

Table 1: Search strategy and criteria used for article selection

Criteria	**Details**
Database Used	Scopus
Date of Search	July 1, 2025
Keywords	(“remote sensing” OR “satellite data”) AND (“air pollution” OR “particulate matter” OR “PM_{10}” OR “$PM_{2.5}$”)
Time Span	2000–2024
Document Type	Journal articles only
Language	English
Search Fields	Title, Abstract, Keywords
Boolean string	TITLE-ABS-KEY ((“remote sensing” OR “satellite data”) AND (“air pollution” OR “particulate matter” OR “PM10” OR “PM2.5”)) AND PUBYEAR > 1999 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”))

While Table 1 outlines the initial search strategy, additional exclusion criteria were applied to refine the dataset and ensure alignment with the review objectives. These criteria involved removing non-peer-reviewed sources, specific document types, and other records that could introduce inconsistency or bias.

2.2 Exclusion Criteria

To maintain the quality and consistency of the dataset, certain types of publications were excluded, including conference proceedings, review articles, editorials, book chapters, and other non-peer-reviewed sources. In addition, only final and peer-reviewed journal articles were retained, while early-access and in-press items were excluded to avoid inconsistencies in indexing and citation counts. Besides that, only English-language journal articles were included in this review to ensure consistency in data processing and analysis. However, this introduces a potential language bias, as relevant studies published in languages other than English may not have been captured.

2.3 Data Screening

After applying the exclusion criteria, a total of 4,683 records were initially retrieved. These records were then carefully screened to ensure their relevance to the scope of this review. In this process, the titles, abstracts, and keywords were examined, and publications not directly related to air pollution or particulate matter estimation were removed. For example, studies focusing on suspended particles in water, marine sediments, or other unrelated environmental topics were excluded. Following this screening step, the dataset was refined to 4,155 records, which were subsequently used for the bibliometric analysis in R.

2.4 Data Analysis and Visualisation

The bibliographic data exported from Scopus were imported into RStudio (version 2024.04.2) and converted into a dataframe using the convert2df() function in the Bibliometrix package (Aria & Cuccurullo, 2017). Subsequent analyses were conducted using Biblioshiny (version 5.0), the web-based graphical interface of Bibliometrix. Biblioshiny provides a user-friendly environment that facilitates interactive visualisation while ensuring statistical rigour and completeness in the results (Jain et al., 2022). Although Bibliometrix includes built-in visualisations, several graphs, such as

annual publication trends and country-level output, were further refined using custom R scripts to enhance readability and presentation quality.

2.5 Indicators and Metrics Used

This bibliometric analysis employed a series of quantitative indicators to explore the structural and intellectual patterns within the selected body of literature. In this study, full counting was applied, whereby each publication was counted once for every contributing author, institution, or country. This method provides a comprehensive overview of global research contributions. The following metrics were assessed:

i. **Annual Scientific Production**:
   The number of articles published each year from 2000 to 2024 was analysed to identify growth trends and shifts in research interest over time.

ii. **Most Productive Countries and Institutions**:
   Publication output was assessed based on the affiliation and country of the corresponding authors, highlighting the leading contributors in each area.

iii. **Citation Analysis**:
   Citation counts were used to assess the academic impact of individual publications, authors, and institutions within the field of study.

iv. **Keyword Frequency and Co-occurrence**:
   Author keywords were analysed to identify frequently studied topics and emerging research themes. Keyword co-occurrence networks were used to reveal thematic clusters and conceptual linkages.

v. **Collaboration Patterns**:
   Country-level co-authorship data were analysed to explore international collaboration trends in remote sensing research related to particulate matter.

Each of these indicators was visualised using customised plots created in R, based on the processed data. These visualisations provide deeper insight into the dynamics of remote sensing research related to particulate matter estimation.

3.0 Results and Discussion

3.1 Publication Trends

A clear upward trend in publication output is observed over the 25 years, reflecting the growing academic interest in particulate matter estimation using remote sensing (Figure 1). In total, 4,155 articles related to this topic were retrieved from the Scopus database for the period between 2000 and 2024. Between 2000 and 2008, the publication volume remained relatively low, with fewer than 100 articles published per year. This slow growth may reflect the limited accessibility of satellite data and early-stage research in remote sensing applications for air pollution. For instance, MODIS instruments aboard Terra (launched in 1999) and Aqua (2002) only began to provide reliable global AOD products in the early 2000s, and their integration into PM estimation frameworks required extensive validation against ground-based measurements such as AERONET (Choi et al., 2019).

A noticeable increase begins around 2010 (95 articles), with a more rapid acceleration evident after 2015 (175 articles). This trend can be attributed to the availability of new satellite sensors, such as Himawari-8 and Sentinel-5P, which provide higher spatial and temporal resolution data, significantly enhancing the monitoring of fine-scale pollution dynamics (Kikuchi et al., 2018; Veefkind et al., 2012). At the same time, the rapid rise of machine learning and data fusion methods enabled more accurate retrieval of PM2.5 from satellite observations (Di et al., 2016; Xue et al., 2019).

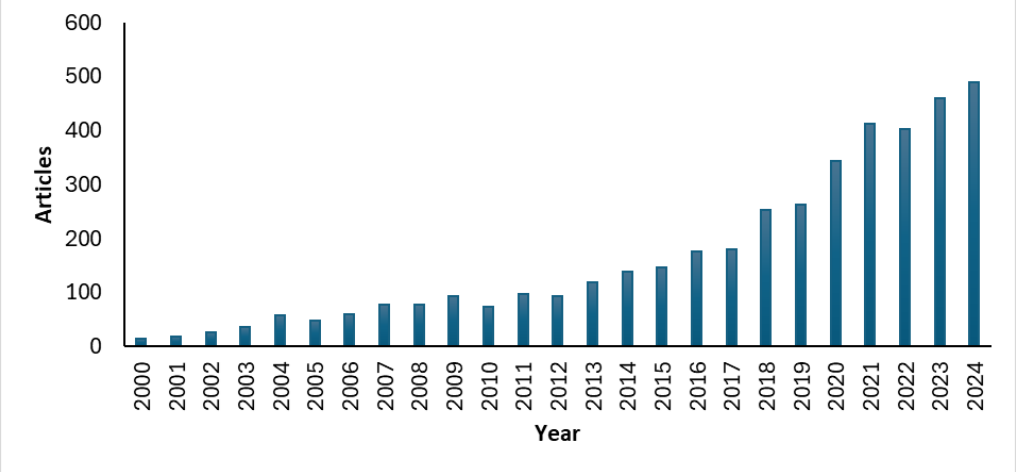

Figure 1: Annual publication trends for 2000 – 2024

Between 2018 and 2021, the number of publications nearly doubled, indicating a significant increase in academic and institutional interest in air quality monitoring technologies. This surge coincides with increased public attention to urban pollution, global climate agreements, and the integration of satellite data with machine learning models for environmental monitoring. The publication peak in 2024, reaching over 540 articles, further illustrates the rapid expansion of this research domain. Overall, the pattern demonstrates that remote sensing for PM estimation has evolved into a well-established and expanding field of study.

3.2 Productive Countries Based on Publication Output

Based on the distribution of research publications (Figure 2), it is evident that a small number of countries account for the majority of the scientific output in the field of particulate matter estimation using remote sensing. Figure 2a presents a world map showing the distribution of article production by country, while Figure 2b highlights the top 10 contributing countries based on the number of published articles.

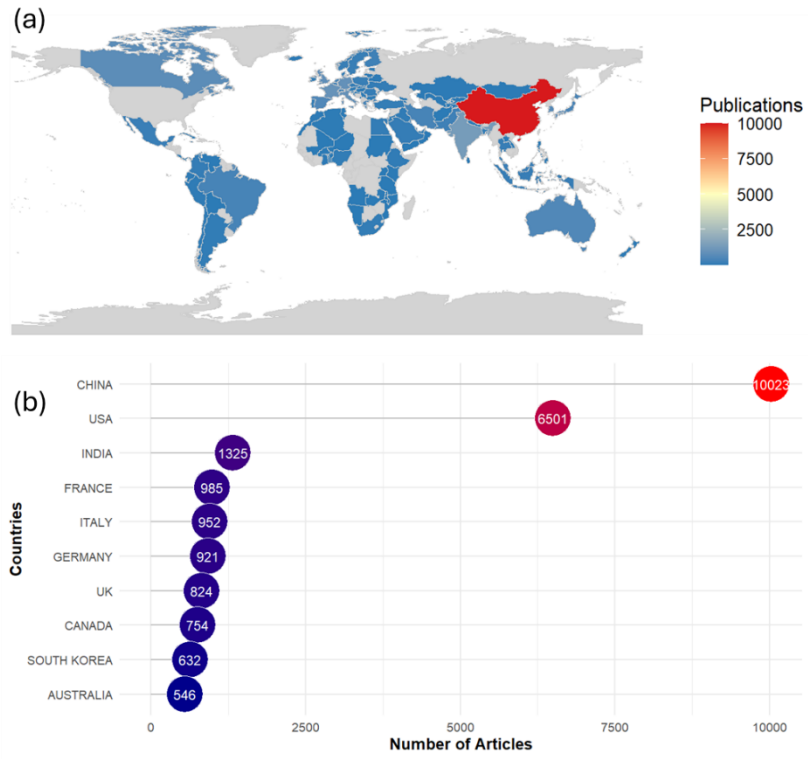

Figure 2: (a) Global distribution of publication output related to remote sensing applications for PM estimation (2000–2024) and (b) Top 10 countries by number of articles published

As shown in Figure 2b, China stands out as the most prolific contributor, accounting for 10,023 articles, followed by the United States with approximately 6,501 articles, and India with around 1,325 articles. These three countries alone represent a significant portion of global research activity in this domain. This high level of productivity reflects each country's investment in satellite infrastructure, environmental monitoring programs, and policy-driven research agendas. China's extensive national programs in atmospheric observation and satellite development have significantly enhanced its contributions to this field. The United States' long-standing leadership in remote sensing, through agencies such as the National Aeronautics and Space Administration (NASA), continues to support a steady output of high-quality publications. India's growing engagement in this area is also noteworthy, reflecting both domestic air quality concerns and increasing access to global satellite data. Other countries making substantial contributions include France, Germany, Italy, and the United Kingdom, as well as Canada, South Korea, and Australia. Their outputs, although lower than those of the top three, consistently reflect strong participation in geospatial and environmental sciences. In contrast, regions such as Southeast Asia remain underrepresented, highlighting an ongoing disparity in research capacity and access to satellite-based environmental data. Similar patterns have been mentioned by Tursumbayeva et al. (2023), as there are limited studies and knowledge regarding air quality variation in this Asian region.

Table 2: Top 10 contributing institutions

Affiliation	**Articles**
Wuhan University	373
Peking University	332
Beijing	295
Sun Yat-Sen University	270
University of Maryland	224
Beijing Normal University	223
Nanjing University of Information Science and Technology	223
University of California	215
Emory University	208
Zhejiang University	191

Analysis of institutional affiliations reveals that research on particulate matter estimation using remote sensing, as shown in Table 2, is dominated by a combination of leading Chinese and

U.S.-based universities. Among the top 10 contributing institutions, Wuhan University ranks highest with 373 articles, followed closely by Peking University (332) and Beijing-based institutions, including Beijing Normal University and the City of Beijing, which serves as a regional research entity. Chinese institutions occupy 7 of the top 10 positions, reflecting the country's strong national investment in geospatial science and environmental health research. This dominance aligns with China's broader leadership in publication output, as noted in earlier sections, and may be attributed to centralised air quality initiatives and robust satellite programs such as FengYun, Gaofen, and Daqi-1.

In contrast, the United States is represented by the University of Maryland (224 articles), the University of California system (215 articles), and Emory University (208 articles). These institutions have long been involved in satellite-based environmental research and often lead studies on aerosol modelling, AOD-PM calibration, and integration of NASA data with public health assessments (Dickerson et al., 2024; Vadrevu et al., 2019). This mix of institutional leadership highlights the interplay between national policy support and academic excellence in driving research productivity.

3.3 Citation Analysis

Figure 3 shows the average citations per article by publication year between 2000 and 2024. In the early 2000s, the average number of citations fluctuated between 0.99 (in 2001) and 4.76 (in 2000) per article. After 2002, citation rates stabilised between 3.88 and 5.61 citations per article per year. A temporary low occurred in 2008, with an average of 3.15 citations per article, before gradually increasing again.

From 2015 onwards, the average number of citations rose sharply, with values of 5.85 (2015), 7.57 (2016), and 7.43 (2017). The peak was recorded in 2018, with an average of 9.54 citations per article, the highest across the 25 years. This indicates that articles published around 2017–2018 have become highly influential references in the field. After 2020, citation averages began to decline, falling to 4.18 (2022), 3.62 (2023), and 2.43 (2024). This reduction is expected, as newer publications have had insufficient time to accumulate citations.

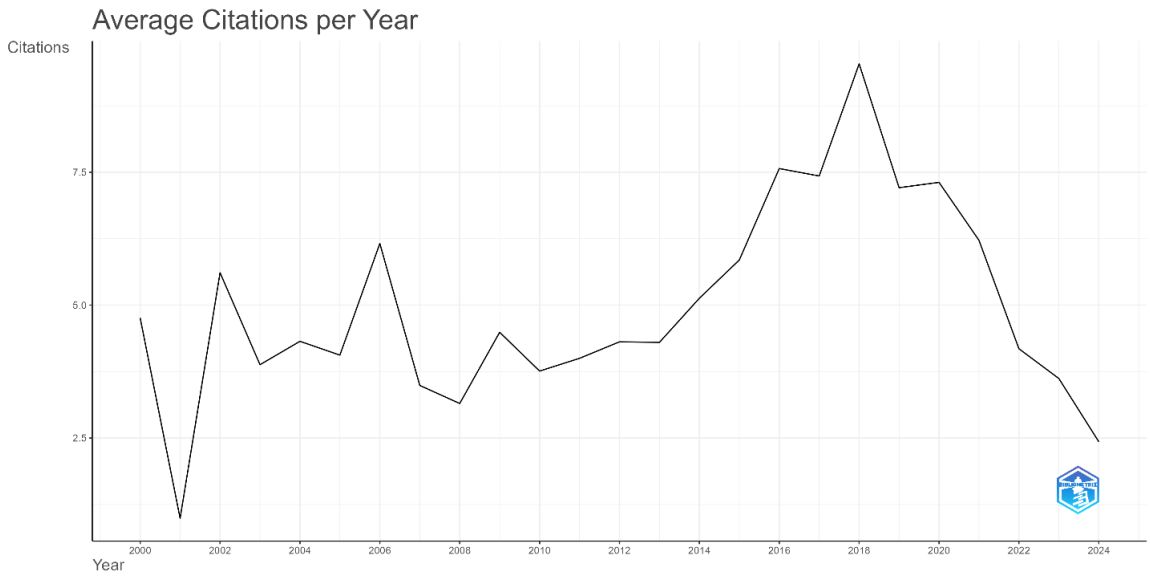

Figure 3: Average citations per article by year of publication (2000–2024)

3.4 Keyword Frequency and Co-occurrence

The word cloud in Figure 4 visualises the most frequently occurring author keywords across the 4,966 articles analysed. The most prominent keywords include "remote sensing," "particulate matter," "air pollution," and "satellite data", which reflect the core intersection of geospatial technology and air quality research. The prominence of "atmospheric pollution," "air quality," and "aerosol optical depth" further confirms the widespread use of satellite-derived aerosol metrics as proxies for $PM_{2.5}$ and PM_{10} concentrations.

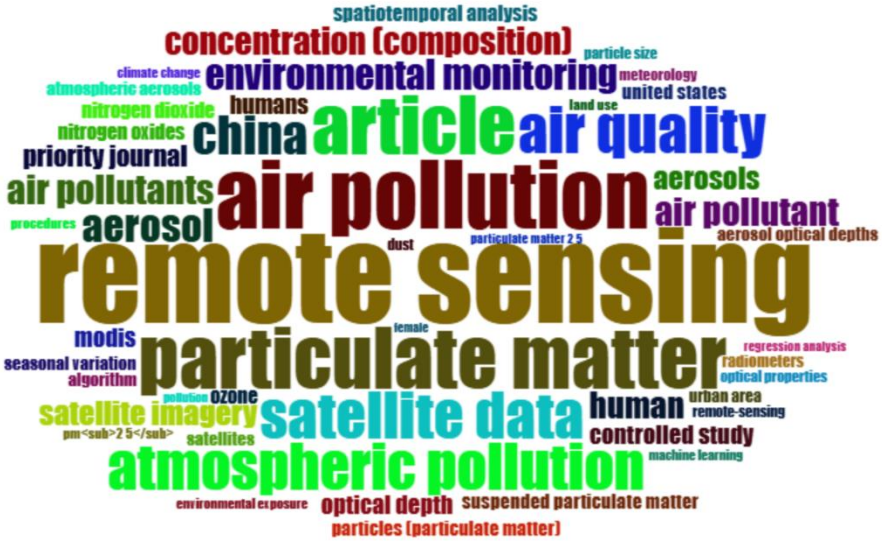

Figure 4: Word cloud of most frequent author keywords

Terms such as “MODIS,” “satellite imagery,” and “optical depth” indicate the popular satellite platforms and retrieval parameters utilised in these studies (Kamarul Zaman & Kanniah, 2020). “Environmental monitoring” and “spatiotemporal analysis” suggest that much of the research is oriented toward understanding the distribution and dynamics of air pollution over time and space. The presence of “China,” “United States,” and “urban area” among the top keywords implies a strong geographical and contextual focus on heavily polluted urban centres in major contributing countries. Additionally, keywords such as “human exposure,” “health impact,” and “controlled study” suggest an increasing trend toward interdisciplinary work that links environmental monitoring with public health assessments. It is also notable that terms such as “machine learning,” “regression analysis,” and “algorithm” appear in the cloud, indicating the growing integration of data-driven modelling and computational approaches in this field, a trend reported in recent literature (Doreswamy et al., 2020; Subramaniam et al., 2022; Vignesh et al., 2023; Xu et al., 2021).

The co-occurrence network visualisation (Figure 5) reveals the thematic landscape of research at the intersection of remote sensing and air pollution. Two distinct yet interconnected clusters emerge: one focused on technical methodologies (blue cluster) and the other on applied environmental issues (red cluster).

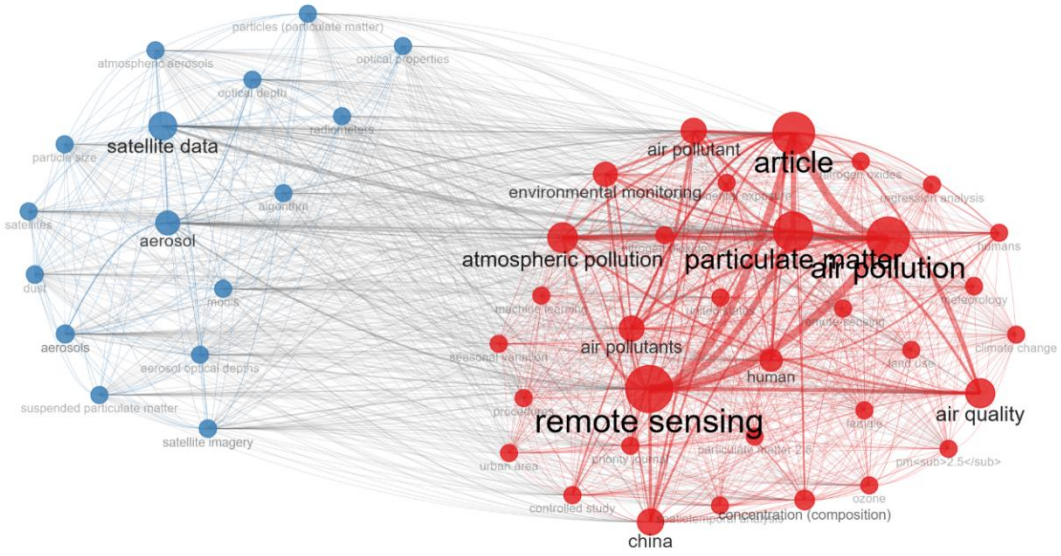

Figure 5: Keyword co-occurrence network

The technical cluster (blue cluster), dominated by terms such as satellite data, aerosol, and optical depth, reflects the foundational role of remote sensing technologies in air quality monitoring. This includes the use of satellite platforms, such as Sentinel-5, for retrieving pollutant concentrations, including NO_2, SO_2, CO, and aerosols, through spectral and spatial analysis (Mokarram et al., 2023). These techniques often leverage neural networks and regression models to predict spatial-temporal pollutant dynamics with high accuracy. The application-driven cluster (red cluster) centres on keywords such as particulate matter, pollution, and remote sensing, indicating a strong research emphasis on utilising satellite observations to assess air quality and human health risks. Numerous studies apply these tools to urban environments, examining the correlation between land surface temperature, urbanisation, and pollution levels (Bodor et al., 2022; Mazeli et al., 2023; Othman et al., 2022; Stafoggia et al., 2019; Yang et al., 2022). The red cluster's dense connectivity suggests a high degree of interdisciplinarity and practical relevance, particularly in areas such as environmental monitoring and public policy.

Bridging terms like atmospheric pollution and environmental monitoring serve as conceptual connectors, indicating the integration of technical capabilities with applied environmental goals. This transition is reflected in bibliometric reviews that track the evolution of research from basic imaging techniques to complex semantic segmentation and deep learning applications in environmental science (Lin, 2024). In short, the co-occurrence network highlights an increasingly synergistic research ecosystem, where remote sensing technologies are not only

advancing technically but also becoming central to addressing critical pollution challenges worldwide.

3.5 Collaboration Pattern

The country co-authorship network visualisation (Figure 6) reveals the global collaboration patterns in the research domain related to air pollution and remote sensing. Node size represents the publication volume of each country, line thickness reflects the strength of collaboration (co-authored publications), and node colours indicate clusters of countries with stronger intra-group linkages. The most prominent nodes in the network are China and the USA, signifying their dominant roles in this research field. Their large node sizes and extensive interconnections indicate both high research output and strong international collaboration. The USA is a central hub with widespread connections across all clusters, including Europe, Asia, and developing countries, reflecting its global reach in scientific partnerships. Similarly, China maintains robust collaborative links, particularly with Asian nations such as India, South Korea, and Thailand, as well as with several European and developing countries. These findings are consistent with prior bibliometric studies in related topics. For instance, Jain et al. (2022) similarly report that China and the USA are leading contributors to global air pollution research.

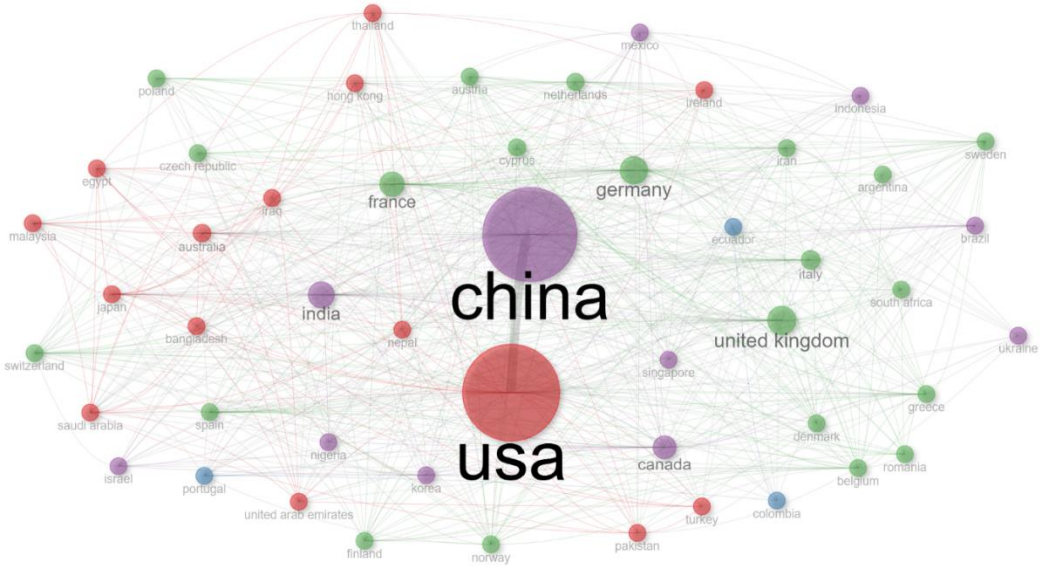

Figure 6: Global collaboration network on remote sensing–based PM estimation

Europe forms a dense and interconnected cluster, with countries such as the United Kingdom, Germany, France, Spain, and Italy often collaborating, likely supported by large-scale EU research initiatives. Meanwhile, India and other South Asian countries (e.g., Bangladesh, Pakistan) form a distinct cluster, connected through collaborations with both China and Western countries. Although smaller in scale, Latin American countries (Brazil, Mexico, and Argentina) and African countries (South Africa and Nigeria) are visible on the map, demonstrating growing engagement in this field. Overall, the network suggests that while a few leading nations dominate the output, collaboration is broadening, with an increasing number of countries contributing to the field over time.

4.0 Conclusion

This bibliometric analysis highlights the growing importance of satellite-based remote sensing in estimating particulate matter over the past 25 years. Publication output has increased markedly, with China (n = 10,023) and the United States (n = 6,501) emerging as the most productive contributors, reflecting sustained national investment in environmental monitoring and data infrastructure. Keyword analysis reveals the thematic convergence of technical methods and public health applications, with machine learning, aerosol optical depth, and human exposure emerging as key research fronts. Moreover, the international collaboration network indicates an evolving multipolar ecosystem, offering opportunities for more inclusive global partnerships. These findings suggest that funding agencies and policymakers should prioritise support for underrepresented regions, particularly in Southeast Asia, Africa, and Latin America, to promote more equitable global participation. Furthermore, integrating machine learning with health data into air quality indices could strengthen the relevance of satellite-based monitoring for public health decision-making. This study relies solely on Scopus data and focuses on journal articles, which may underrepresent some emerging topics. Future reviews could be enhanced by integrating multiple databases, expanding language coverage, and combining bibliometric with systematic review approaches to provide a more comprehensive perspective. Overall, this study provides a timely reference point for understanding the dynamics of particulate matter estimation research and offers a foundation for future work integrating geospatial technologies with environmental health and policy.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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