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Original Research Paper

Technology-Driven Solutions for Harmful Algal Bloom Monitoring and Prediction: A Bibliometric Analysis of Research Trends, Collaboration Networks, and Emerging Technologies in Southeast Asia

Lyndon A. Rosas
College of Information Technology Education, North Eastern Mindanao State University- Cantilan Campus, Cantilan Surigao del Sur, 8317, Philippines

Abstract

Harmful algal blooms (HABs) pose significant ecological, economic, and public health challenges across Southeast Asia, driving increasing interest in technology-enabled monitoring and prediction systems. Despite the rapid adoption of digital technologies, a comprehensive understanding of the region's research development remains limited. This study provides a bibliometric analysis of technology-driven research on HAB monitoring and prediction in Southeast Asia using publications indexed in the Scopus database. A total of 2,181 English-language publications published between 1997 and 2026 were analyzed following a systematic screening process. Bibliometric analyses were performed using Bibliometrix (RStudio 4.5.3) and VOSviewer (v1.6.20) to examine research productivity, citation trends, influential publication sources, authors, institutions, countries, scientific collaboration, and thematic evolution. The results reveal a marked increase in scientific output after 2015, with the research field currently approaching its peak growth stage based on logistic life-cycle analysis. Indonesia, Malaysia, and Singapore emerged as leading contributors, supported by extensive international collaboration involving the United States, China, Japan, and other research-intensive countries. Influential publication venues and authors highlight the multidisciplinary nature of the field, spanning environmental science, remote sensing, engineering, and artificial intelligence. Thematic evolution further demonstrates a transition from conventional environmental monitoring toward intelligent approaches integrating remote sensing, machine learning, artificial intelligence, deep learning, and the Internet of Things (IoT). These findings provide a comprehensive overview of the intellectual landscape of technology-driven HAB research and offer valuable insights for researchers, policymakers, and funding agencies in identifying collaboration opportunities and future research priorities for sustainable aquatic environmental management in Southeast Asia.

Keywords: Artificial intelligence; Bibliometric analysis; Harmful algal blooms; Remote sensing; Southeast Asia.

Introduction

Harmful algal blooms (HABs) have become one of the most pressing environmental challenges affecting aquatic ecosystems worldwide, posing significant threats to ecological integrity, public health, fisheries, aquaculture, tourism, and coastal economies (Choudhary, 2026). HABs occur when colonies of phytoplankton, cyanobacteria, or other microscopic algae proliferate rapidly under favorable environmental conditions, often producing toxins or causing severe ecological disturbances through oxygen depletion, reduced water quality, and habitat degradation (Anderson *et al*., 2025). While algal blooms are naturally occurring ecological phenomena that contribute to primary productivity in aquatic environments, the increasing frequency, intensity, duration, and spatial extent of HAB events over recent decades have raised global concern among scientists, environmental managers, and policymakers. Numerous studies have associated this increasing occurrence with accelerating anthropogenic pressures, including excessive nutrient loading from agricultural runoff, untreated wastewater discharge, coastal urbanization, industrial activities, and aquaculture intensification, which collectively alter nutrient dynamics and promote eutrophication (Mishra *et al*., 2025). These human-induced stressors, combined with climate-driven changes such as rising sea surface temperatures, altered precipitation regimes, ocean stratification, and extreme weather events, have further increased the complexity and unpredictability of HAB occurrences, making effective monitoring and forecasting increasingly important for sustainable aquatic resource management.

The ecological consequences of HABs extend well beyond localized water quality deterioration. Toxic algal species can accumulate in shellfish and other aquatic organisms, resulting in seafood contamination and various forms of shellfish poisoning that threaten human health and food

***Corresponding Author:**
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security (Choudhary, 2026). Large-scale bloom events frequently lead to mass fish mortalities, degradation of coral reef ecosystems, destruction of seagrass beds, and disruption of marine food webs, thereby reducing biodiversity and ecosystem resilience (Rossbach *et al*., 2023). Economically, HAB outbreaks impose substantial financial burdens on fisheries, aquaculture enterprises, tourism industries, and coastal communities through production losses, market restrictions, increased monitoring costs, and emergency management interventions (Tahiluddin *et al*., 2025). Consequently, HABs have evolved from isolated ecological incidents into complex environmental hazards requiring interdisciplinary solutions that integrate aquatic science, environmental engineering, computer science, remote sensing, and data-driven decision support systems.

The challenges associated with HABs are particularly significant in Southeast Asia, one of the world's most biologically diverse and economically productive marine regions. The region encompasses extensive coastlines, coral reef ecosystems, estuaries, mangrove forests, and highly productive coastal waters that support millions of people through fisheries and aquaculture. Southeast Asia contributes substantially to global aquaculture production, with countries such as Indonesia, the Philippines, Vietnam, Thailand, Malaysia, Singapore, and Brunei relying heavily on aquatic resources for food security, employment, and economic development (Zhang *et al*., 2023). However, rapid population growth, expanding coastal urbanization, intensive aquaculture practices, agricultural nutrient runoff, and increasing industrialization have significantly increased nutrient enrichment within many coastal environments, creating conditions favorable for HAB development (Sabdaningsih *et al*., 2023). In parallel, the region is experiencing accelerated climate change impacts, including warming ocean temperatures, changing monsoon patterns, increased rainfall variability, and more frequent extreme weather events, all of which further influence phytoplankton dynamics and bloom formation.

Recurring HAB events have been reported throughout Southeast Asia, causing severe environmental and socioeconomic consequences. Episodes of paralytic shellfish poisoning, extensive fish kills, and toxic red tides have affected coastal communities and commercial aquaculture operations across several countries within the region (Guillotreau *et al*., 2021). These recurring incidents highlight the vulnerability of Southeast Asian aquatic ecosystems and emphasize the importance of developing reliable monitoring, prediction, and early warning systems capable of supporting timely management interventions. As governments continue to promote sustainable fisheries, climate adaptation, and blue economy initiatives, improving technological capacity for HAB surveillance has become an important research and policy priority.

Historically, HAB monitoring has relied primarily on conventional field-based approaches, including manual water sampling, laboratory microscopy, phytoplankton identification, toxin analysis, and physicochemical water quality measurements. These methods provide valuable biological and chemical information regarding bloom composition and toxicity; however, they are often labor-intensive, time-consuming, expensive, and spatially constrained (Lo *et al*., 2026). Since field observations are typically conducted at discrete sampling locations and intervals, conventional monitoring approaches may fail to capture the rapid temporal and spatial variability that characterizes bloom initiation, expansion, and dissipation. Furthermore, the complex interactions among biological, chemical, hydrological, and meteorological factors influencing HAB formation make accurate forecasting difficult when relying solely on traditional observational techniques. These limitations have motivated researchers to explore innovative technological solutions capable of providing continuous, large-scale, and near real-time environmental monitoring.

Recent advances in digital technologies have fundamentally transformed the way HABs are monitored, analyzed, and predicted. Among these innovations, satellite remote sensing has emerged as one of the most widely adopted approaches for large-scale environmental observation. Earth observation platforms provide continuous measurements of ocean color, chlorophyll-a concentration, sea surface temperature, suspended sediments, turbidity, and other environmental indicators associated with bloom dynamics (Caballero *et al*., 2025; Wang *et al*., 2025). Satellite missions such as Landsat, MODIS, Sentinel, and other multispectral and hyperspectral sensors have substantially improved the spatial and temporal coverage of aquatic monitoring, enabling researchers to detect bloom development across extensive coastal and inland water bodies. The integration of remotely sensed observations with Geographic Information Systems (GIS) has further enhanced the visualization, mapping, and spatial analysis of HAB events, supporting environmental planning and resource management through improved geospatial decision-making.

Beyond advances in remote sensing, artificial intelligence (AI) has become an increasingly important driver of innovation in aquatic environmental monitoring. AI enables the analysis of large and complex environmental datasets that would be difficult to interpret using conventional statistical techniques alone. Machine learning algorithms including Artificial Neural Networks (ANN), Support Vector Machines (SVM), Random Forests (RF), Extreme Gradient Boosting (XGBoost), and Decision Trees have demonstrated considerable capability in modeling nonlinear relationships among meteorological, hydrological, and biological variables associated with HAB occurrence (Olawade *et al*., 2024). More recently, deep learning approaches such as Convolutional Neural Networks (CNNs), Long Short-Term Memory (LSTM) networks, recurrent neural networks, and hybrid neural architectures have significantly improved predictive accuracy by learning complex spatial and temporal patterns from multisource environmental data. These developments have shifted HAB research from descriptive environmental monitoring toward predictive environmental intelligence, allowing scientists to forecast bloom events before they reach critical stages.

The rapid expansion of the Internet of Things (IoT) has further accelerated technological innovation in HAB monitoring by enabling continuous environmental sensing through interconnected smart devices. IoT-based sensor networks are capable of collecting real-time measurements of key water quality parameters, including temperature, pH, dissolved oxygen, salinity, conductivity, turbidity, chlorophyll concentration, and nutrient levels, while transmitting these data through wireless communication technologies to cloud-based monitoring platforms (Muhammed *et al*., 2024). The integration of IoT with cloud computing, edge computing, and AI-driven analytics facilitates automated data processing, anomaly detection, and real-time environmental decision support, thereby improving the responsiveness and efficiency of aquatic monitoring systems. Such smart monitoring frameworks have become increasingly attractive for fisheries management, aquaculture operations, and environmental protection agencies seeking cost-effective and scalable solutions for HAB surveillance.

Although this rapid growth reflects significant scientific progress, it has also resulted in an increasingly fragmented knowledge landscape characterized by diverse research themes, methodological approaches, technological innovations, and collaborative networks. The multidisciplinary nature of this research makes it challenging for scholars, practitioners, and policymakers to obtain a comprehensive understanding of how the field has evolved, which technological approaches have gained prominence, who the leading contributors are, and where future research opportunities lie. While numerous review articles have synthesized advances in harmful algal bloom monitoring technologies, comparatively little attention has been given to systematically mapping the scientific development, intellectual structure, collaboration patterns, and emerging technological trends within this rapidly evolving domain, particularly in the context of Southeast Asia. These limitations underscore the need for a comprehensive bibliometric investigation capable of revealing the knowledge structures, research dynamics, and innovation trajectories that have shaped technology-driven HAB monitoring and prediction research across the region.

Bibliometric analysis has emerged as a rigorous quantitative approach for examining the evolution of scientific knowledge through publication metadata, citation relationships, collaboration networks, and keyword co-occurrence patterns (Sohail, 2026). Unlike traditional narrative or systematic reviews that primarily synthesize research findings, bibliometric techniques objectively evaluate the structural characteristics of a research field by identifying influential publications, prolific authors, leading institutions, collaborative partnerships, thematic development, and emerging research frontiers (Haghani, 2023; Ballesteros-Ballesteros and Zárate-Torres, 2025). The increasing availability of large bibliographic databases, together with the development of science mapping tools such as Bibliometrix and VOSviewer, has significantly enhanced the ability of researchers to visualize intellectual structures, conceptual relationships, and scientific collaboration within rapidly expanding multidisciplinary domains (Muis and Sintang, 2026). Consequently, bibliometric analysis has become an indispensable methodology for understanding the maturity, evolution, and future trajectory of scientific disciplines while providing evidence-based guidance for researchers, funding agencies, and policymakers.

Within aquatic and environmental sciences, bibliometric studies have increasingly been employed to investigate research trends related to marine pollution, climate change adaptation, coastal ecosystem management, aquaculture innovation, water quality monitoring, and environmental sustainability (Quan and Jin, 2024). Similar approaches have also been applied to evaluate emerging digital technologies, including artificial intelligence, machine learning, remote sensing, big data analytics, and the Internet of Things (IoT), highlighting their growing importance in environmental monitoring and resource management (Kamyab *et al*., 2023). These studies have demonstrated the value of bibliometric analysis in identifying influential scientific contributions, revealing interdisciplinary collaboration, and uncovering emerging research themes that may not be readily apparent through conventional literature reviews.

Research focusing specifically on harmful algal blooms has likewise expanded considerably over the past two decades. Existing review articles have examined bloom ecology, environmental drivers, phytoplankton dynamics, toxin production, mitigation strategies, and ecological impacts across marine and freshwater ecosystems (Anderson *et al*., 2025; Huang *et al*., 2025). More recently, scholarly attention has shifted toward the application of advanced technologies for HAB monitoring and prediction, including satellite remote sensing, hyperspectral imaging, autonomous sensor platforms, geographic information systems, artificial intelligence, machine learning, deep learning, and integrated environmental forecasting models (Yang, Tao and Wang, 2026). These technological innovations have substantially improved the spatial coverage, temporal resolution, and predictive capabilities of HAB monitoring systems, enabling more proactive and data-driven environmental management. However, most existing reviews remain technology-oriented, emphasizing algorithm development or monitoring methodologies rather than evaluating how the scientific field itself has evolved.

Although several bibliometric investigations have explored HAB research from a global perspective, they generally focus on ecological studies, marine biology, phytoplankton dynamics, or environmental management without explicitly examining the technological transformation of HAB monitoring and prediction. Likewise, bibliometric studies on artificial intelligence, remote sensing, and smart environmental monitoring frequently encompass a broad range of environmental applications, making it difficult to distinguish the specific scientific landscape associated with HAB research. Consequently, the intersection between aquatic environmental science and emerging digital technologies remains insufficiently explored from a bibliometric perspective. This limitation restricts a comprehensive understanding of how technological innovation has shaped the development of HAB monitoring and prediction research and where future technological opportunities may emerge.

The need for a regional assessment is particularly evident in Southeast Asia. As one of the world's leading regions for fisheries, aquaculture, and coastal biodiversity, Southeast Asia experiences recurring HAB events that pose substantial environmental, economic, and public health challenges (San Diego-McGlone *et al*., 2024). At the same time, governments, research institutions, and international organizations across the region have increasingly invested in digital transformation initiatives involving smart environmental monitoring, artificial intelligence, remote sensing, cloud computing, and IoT-enabled aquatic management systems (Pricopoaia *et al*., 2025). Despite these developments, the regional scientific landscape remains fragmented across multiple countries, institutions, and disciplines, with varying levels of research productivity, technological capacity, and collaborative engagement. Understanding these patterns is essential for strengthening regional research networks, promoting technology transfer, and supporting evidence-based environmental governance.

Furthermore, the rapid emergence of interdisciplinary technologies has fundamentally reshaped the conceptual foundations of HAB research. The field has evolved beyond conventional ecological observation toward integrated environmental intelligence systems that combine Earth observation satellites, in situ sensor networks, hydrodynamic modeling, artificial intelligence, deep learning, cloud computing, and decision-support platforms. This convergence has created new research clusters, interdisciplinary partnerships, and innovation pathways that are difficult to capture through conventional review methodologies alone. A bibliometric approach provides a systematic means of revealing these hidden knowledge structures by examining scientific productivity alongside citation influence, collaboration networks, thematic evolution, and conceptual relationships. Such analyses not only document the historical development of the field but also identify emerging technologies and research priorities that are likely to shape future scientific investigations.

Despite the increasing importance of technology-driven HAB monitoring, no comprehensive bibliometric study has systematically mapped the scientific landscape of technology-enabled HAB monitoring and prediction research within Southeast Asia using science mapping techniques. Existing reviews provide valuable technological or ecological insights but offer limited evidence regarding publication growth, influential contributors, institutional leadership, regional collaboration, conceptual knowledge structures, thematic evolution, and emerging technological directions. This absence of a regional bibliometric perspective represents an important knowledge gap because Southeast Asia possesses unique environmental conditions, socioeconomic dependencies, and scientific priorities that differ substantially from those of other geographic regions. Addressing this gap will enable researchers and decision-makers to better understand the evolution of regional research capacity while identifying opportunities for stronger interdisciplinary collaboration and technological innovation.

In response to these research gaps, the present study conducts a comprehensive bibliometric analysis of Scopus-indexed publications on technology-driven solutions for harmful algal bloom monitoring and prediction in Southeast Asia. Using Bibliometrix and VOSviewer as complementary science mapping tools, the study systematically evaluates the evolution of scientific production and citation performance, identifies the most influential authors, institutions, countries, and publication sources, examines patterns of scientific collaboration across the region, and maps the intellectual, social, and conceptual structures that characterize this multidisciplinary research field. The study further investigates thematic evolution and keyword co-occurrence to identify emerging technologies and evolving research priorities while highlighting future directions that can strengthen innovation in HAB monitoring and prediction. By providing an evidence-based overview of the regional research landscape, this study contributes to the growing body of knowledge on smart aquatic environmental monitoring, supports strategic research planning and interdisciplinary collaboration, and offers valuable insights for researchers, environmental managers, funding agencies, and policymakers seeking to develop resilient, technology-driven solutions for protecting aquatic ecosystems in Southeast Asia.

Methodology

Research Design

This study employed a quantitative bibliometric research design to examine the scientific landscape of technology-driven solutions for harmful algal bloom (HAB) monitoring and prediction in Southeast Asia. Bibliometric analysis is a systematic and reproducible quantitative approach that evaluates scientific publications through bibliographic metadata to assess research productivity, citation performance, collaboration networks, and the intellectual and conceptual development of a research field (Sohail, 2026; Aryawati *et al*., 2024). Compared with conventional literature reviews, bibliometric methods provide objective insights into the evolution of scientific knowledge by combining performance analysis with science mapping techniques.

The study adopted two complementary analytical approaches. First, performance analysis was conducted to evaluate publication productivity, citation impact, influential authors, institutions, countries, and publication sources. Second, science mapping was performed to visualize collaboration networks, keyword co-occurrence, conceptual structures, thematic evolution, and citation relationships. Together, these approaches provide a comprehensive understanding of the development and emerging directions of technology-driven HAB monitoring and prediction research within Southeast Asia.

Data Source and Search Strategy

The bibliographic data were retrieved exclusively from the Scopus database, which is recognized as one of the largest multidisciplinary citation databases covering high-quality peer-reviewed publications across environmental science, marine biology, engineering, computer science, remote sensing, and related disciplines. Scopus was selected because of its extensive journal coverage, standardized bibliographic metadata, and compatibility with bibliometric software such as Bibliometrix and VOSviewer.

The literature search was performed using the TITLE-ABS-KEY search field to maximize the retrieval of publications related to technology-driven approaches for harmful algal bloom monitoring and prediction. The search strategy incorporated keywords associated with harmful algal blooms together with technological concepts, including remote sensing, artificial intelligence, machine learning, deep learning, Internet of Things (IoT), sensor networks, geographic information systems (GIS), environmental monitoring, forecasting, and predictive modeling. To ensure regional relevance, the search was further restricted to publications affiliated with Southeast Asian countries, namely Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. The search parameters used in this study are summarized in Table 1, while the complete Scopus search query is presented below.

TITLE-ABS-KEY(("harmful algal bloom*"OR HAB*OR "harmful algae"OR "algal bloom*"OR "red tide*"OR cyanobacteri*OR "cyanobacterial bloom*"OR phytoplankton*) AND (monitor* OR detect* OR predict* OR forecast* OR surveillance OR "early warning" OR "decision support" OR assessment) AND (technolog* OR innovation* OR "smart technolog*" OR "digital technolog*" OR AI OR "artificial intelligence" OR "machine learning" OR "deep learning" OR "computer vision" OR "neural network*" OR "convolutional neural network*" OR CNN OR LSTM OR transformer* OR robotics OR drone* OR UAV* OR "internet of things" OR IoT OR sensor* OR biosensor* OR "wireless sensor network*" OR "remote sensing" OR satellite* OR GIS OR blockchain OR "digital twin*" OR autonomous OR automation))

Table 1. Scopus Search Strategy and Inclusion Criteria

Item	Description
Item	Description
Database	Scopus
Search Date	09 July 2026
Search Field	TITLE-ABS-KEY
Initial Search Results	50,516
Document Type Filter	Articles, Conference Papers, Reviews, Book Chapters, Conference Reviews, Books
Records after Document Type Filter	49,978
Language	English and Southeast Asian Country Filter
Final Dataset	2,181
Export Format	CSV
Analysis Software	Bibliometrix (RStudio) and VOSviewer

Data Screening and Eligibility

The identification and selection of publications followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent and reproducible screening process.

The initial Scopus search identified 50,516 records. To improve dataset quality and maintain consistency, only peer-reviewed scholarly document types commonly used in bibliometric studies were retained, including articles, conference papers, review papers, book chapters, conference reviews, and books. This filtering step reduced the dataset to 49,978 publications. Subsequently, only English-language publications were retained to ensure consistency in bibliometric analyses and keyword standardization, resulting in 47,523 publications. Finally, an affiliation-based geographic filter was applied to retain publications associated with Southeast Asian countries. After this screening process, the final dataset comprised 2,181 publications, which served as the basis for all bibliometric analyses conducted in this study.

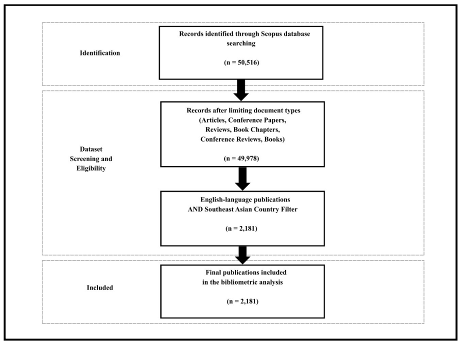

Figure 1. PRISMA Flow Diagram of the Literature Selection Process.

Data Preparation

The final dataset was exported from Scopus in comma-separated values (CSV) format containing complete bibliographic metadata, including publication titles, abstracts, author keywords, indexed keywords, author names, institutional affiliations, countries, publication sources, references, and citation information.

Prior to analysis, the dataset underwent preprocessing to improve consistency and analytical accuracy. Variations in author names, institutional affiliations, country names, abbreviations, spelling variants, singular and plural keyword forms, and synonymous terminologies were standardized where appropriate. A thesaurus file was used during network visualization to merge equivalent terms and reduce fragmentation within collaboration and keyword networks. This preprocessing step enhanced the reliability of both performance analysis and science mapping results.

Bibliometric Analysis

Descriptive bibliometric analysis and performance evaluation were conducted using the Bibliometrix package implemented in RStudio version 4.5.3. Bibliometrix is an open-source R package designed specifically for comprehensive bibliometric analysis and science mapping, offering a wide range of analytical techniques for evaluating scientific production and knowledge structures.

Performance analysis included the assessment of annual scientific production, annual citation trends, document characteristics, source productivity, leading authors, productive institutions, country scientific production, collaboration indices, and the most globally cited publications. These indicators provide quantitative evidence regarding the growth, productivity, and scientific influence of technology-driven HAB monitoring and prediction research in Southeast Asia.

Bibliometrix was also used to generate conceptual structure analyses, thematic maps, thematic evolution, trend topics, and historiographic networks, thereby facilitating the identification of research hotspots, thematic development, and emerging areas of investigation.

Science Mapping and Network Visualization

Science mapping was performed using VOSviewer version 1.6.20 to visualize relationships among authors, institutions, countries, publications, and research topics. VOSviewer employs distance-based visualization algorithms that cluster closely related research entities into interconnected knowledge networks.

The analyses included co-authorship analysis to examine scientific collaboration among authors, institutions, and countries; keyword co-occurrence analysis to identify dominant research themes and emerging technologies; citation analysis to determine influential publications; bibliographic coupling to identify publications sharing common references; and co-citation analysis to reveal the intellectual foundations of the research field. Network visualizations were interpreted using node size, link strength, cluster membership, and network connectivity. Larger nodes indicate greater scientific productivity or influence, while thicker links represent stronger collaborative or conceptual relationships between research entities. The integration of Bibliometrix and VOSviewer enabled a comprehensive assessment of both bibliometric performance indicators and the structural evolution of technology-driven HAB monitoring and prediction research within Southeast Asia.

Results

Research Productivity, Citation Trends, and Research Life Cycle

This section addresses RQ1, which examines the publication trends and citation patterns of technology-driven research on harmful algal bloom (HAB) monitoring and prediction in Southeast Asia. The temporal distribution of scientific publications reveals a substantial increase in research productivity throughout the study period. As illustrated in Figure 2, the earliest publication indexed in the Scopus database appeared in 1997, followed by relatively low annual scientific production during the succeeding years. Publication output gradually increased from the mid-2000s and entered a period of accelerated growth after 2015. Annual scientific production increased from 48 publications in 2017 to 83 in 2018, 108 in 2019, 128 in 2020, 159 in 2021, 167 in 2022, 224 in 2023, and 297 in 2024. The highest annual scientific production was recorded in 2025, with 390 publications, while 211 publications were indexed for 2026, representing a partial publication year at the time of data retrieval.

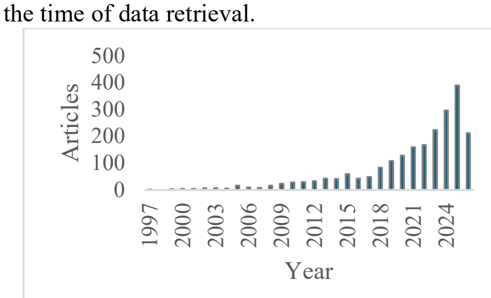

Figure 2. Annual Scientific Production of Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction in Southeast Asia (1997–2026).

The citation performance of the retrieved publications is presented in Figure 3. The annual citation trend indicates that publications from earlier years accumulated higher average citation counts than more recent publications. Conversely, publications produced in recent years exhibited lower average citations per article because they have had a shorter period to accumulate scholarly citations. Despite these differences in citation accumulation across publication years, the increasing volume of annual scientific production demonstrates sustained research activity throughout the study period.

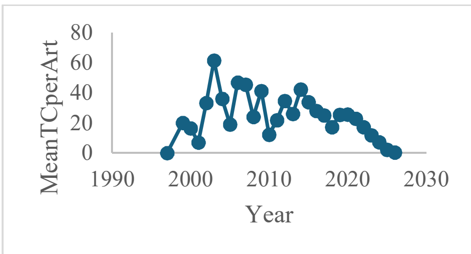

Figure 3. Average Citations per Article by Publication Year.

To further characterize the developmental trajectory of the research field, a logistic growth model was fitted to both the annual and cumulative publication data. As shown in Figure 4A, the annual publication life cycle follows a bell-shaped logistic distribution with a strong model fit ($R^2 = 0.915$). The fitted model estimates that annual scientific production reaches its maximum growth at approximately 2025.5, corresponding to an estimated peak of 291 publications. The observed publication output during 2025 exceeded the fitted value, reaching approximately 390 publications, indicating a higher-than-predicted annual research output during the most recent observation period.

The cumulative publication growth likewise follows a characteristic S-shaped logistic curve, as illustrated in Figure 4B. The fitted model estimates a carrying capacity (K) of approximately 3,452 cumulative publications, representing the projected upper limit of scientific production under the current growth trajectory. The observed cumulative publication trend closely follows the fitted logistic curve and indicates that the field is currently approaching the model's inflection point, where cumulative scientific production experiences its highest growth rate before gradually slowing toward the projected saturation level.

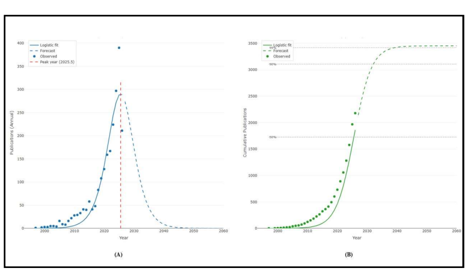

Figure 4. Research life cycle of technology-driven solutions for harmful algal bloom monitoring and prediction in Southeast Asia. (A) Annual publication life cycle based on the logistic growth model. (B) Logistic cumulative growth curve of scientific production.

Influential Sources, Authors, Institutions, and Countries

The distribution of publications across scientific sources demonstrates that research on technology-driven solutions for harmful algal bloom (HAB) monitoring and prediction is disseminated through a wide range of multidisciplinary journals and conference proceedings. As illustrated in Figure 5, the IOP Conference Series: Earth and Environmental Science emerged as the leading publication source with 82 publications, followed by AIP Conference Proceedings (31 publications) and the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (ISPRS Archives) (23 publications). Other major publication venues include PLOS ONE, Proceedings of SPIE – The International Society for Optical Engineering, and Science of the Total Environment, each contributing 21 publications. Additional influential sources include the ACM International Conference Proceeding Series, Biodiversitas, and IEEE Access, highlighting the multidisciplinary nature of research dissemination across environmental science, remote sensing, engineering, geospatial science, and artificial intelligence.

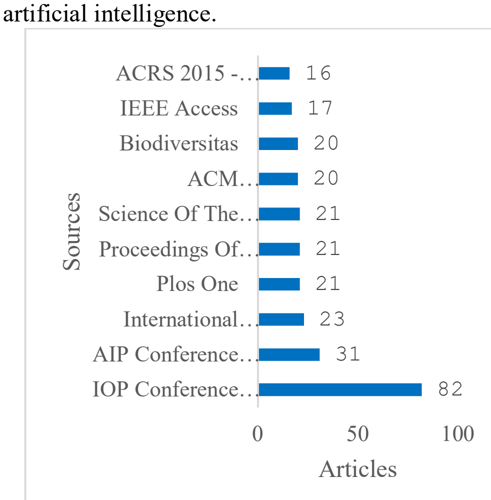

Figure 5. Most Productive Publication Sources in Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction in Southeast Asia.

The scientific influence of authors was evaluated using bibliometric impact indicators, including the h-index, g-index, m-index, total citations (TC), and number of publications (NP). As presented in Table 2, Hossain M.S. demonstrated the highest scholarly impact with an h-index of 9, a g-index of 15, 513 total citations, and 15 publications. Zainuddin M. ranked second with an h-index of 8, g-index of 17, 362 total citations, and 17 publications, representing the largest publication output among the leading authors. Hashim M. also exhibited substantial scientific influence, accumulating 436 citations with an h-index of 7 across 14 publications.

Several other researchers demonstrated strong bibliometric performance, including Pradhan B., Wang Y., Nurdin N., and Zhang J., each recording an h-index of 6 or higher and substantial citation counts. Notably, Zhang J. accumulated 478 total citations, indicating a considerable scholarly influence despite publishing fewer articles than some of the highest-producing authors. These results demonstrate that scientific influence within the field is distributed among a relatively small group of researchers who have consistently produced highly cited contributions over an extended period.

Table 2. Most Influential Authors in Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction in Southeast Asia Based on Bibliometric Performance Indicators.

Author	h_index	g_index	m_index	TC	NP
Hossain Ms	**9**[a]	15	**0.7500000**[a]	**513**[a]	15
Zainuddin M	8	**17**[a]	0.421053	362	**17**[a]
Hashim M	7	14	0.500000	436	14
Nurdin N	7	11	0.466667	194	11
Pradhan B	7	8	0.466667	363	8
Wang Y	7	13	0.583333	173	13
Komatsu T	6	8	0.400000	79	9
Li X	6	9	0.315789	116	9
Li Y	6	8	0.500000	78	8
Liu X	6	7	0.500000	78	7

[a] Highest value for the corresponding bibliometric indicator; TC = Total Citations; NP = Number of Publications.

The institutional distribution of scientific production is presented in Figure 6. The National University of Singapore emerged as the leading institution with 124 publications, followed by Universiti Kebangsaan Malaysia (73 publications), Universiti Teknologi Malaysia (70 publications), Universiti Putra Malaysia (65 publications), and both IPB University and Universiti Sains Malaysia, each contributing 64 publications. Other highly productive institutions include Nanyang Technological University, Universiti Teknologi MARA, Universitas Gadjah Mada, and Hasanuddin University. The institutional distribution indicates that research activities are concentrated within several established universities across Singapore, Malaysia, and Indonesia, reflecting their significant contributions to technology-driven aquatic environmental research in Southeast Asia.

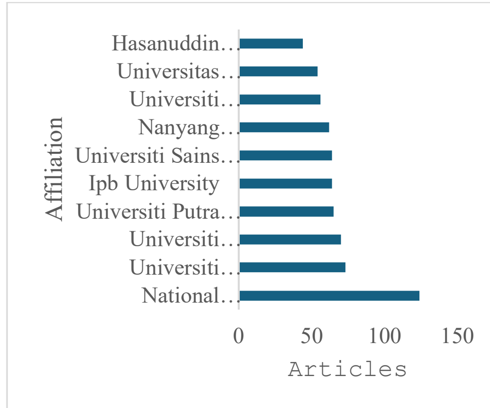

Figure 6. Most Influential Research Institutions in Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction in Southeast Asia.

Country Scientific Production

The geographical distribution of scientific production is illustrated in Figure 7. The results reveal that Indonesia produced the largest number of publications (1,624), followed by Malaysia (1,275). Outside Southeast Asia, the United States (582 publications) and China (440 publications) also demonstrated substantial contributions, reflecting active international participation in research related to technology-driven HAB monitoring and prediction within the region. Among Southeast Asian countries, the Philippines (467 publications), Thailand (466 publications), and Singapore (378 publications) also recorded considerable scientific productivity.

The global distribution presented in Figure 7 further indicates that although the study focuses on Southeast Asia, research output involves extensive international participation, with contributions originating from North America, Europe, East Asia, and Oceania.

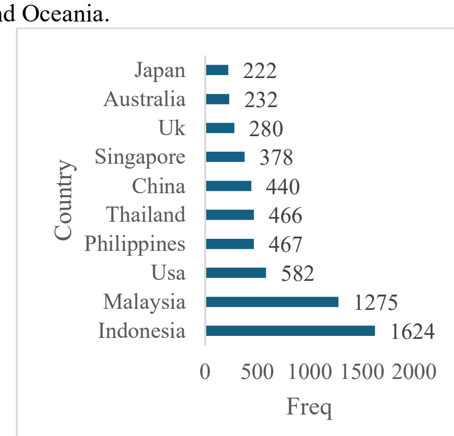

Figure 7. Country Scientific Production in Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction.

Scientific Collaboration Networks

The international collaboration network among countries is presented in Figure 8. The network reveals a highly interconnected pattern of scientific collaboration involving Southeast Asian countries and numerous international research partners. Countries are organized into several collaborative clusters, each represented by different colors, indicating groups of nations with relatively stronger co-authorship relationships.

Indonesia, Malaysia, Singapore, the United States, China, Thailand, the Philippines, Japan, and the United Kingdom emerged as the most prominent nodes within the collaboration network, as evidenced by their relatively larger node sizes and extensive linkages with other participating countries. Indonesia and Malaysia occupy central positions within the network, reflecting their substantial contribution to collaborative research on technology-driven harmful algal bloom (HAB) monitoring and prediction. Likewise, Singapore demonstrates extensive collaborative connections with countries in Europe, North America, and Asia, indicating its important role in facilitating international scientific partnerships.

The network further illustrates that research collaboration extends well beyond Southeast Asia. Strong collaborative relationships are evident among countries from North America, Europe, East Asia, the Middle East, and Oceania, reflecting the international character of technology-driven HAB research. Several smaller clusters also indicate the participation of emerging research countries that contribute to regional and international scientific cooperation.

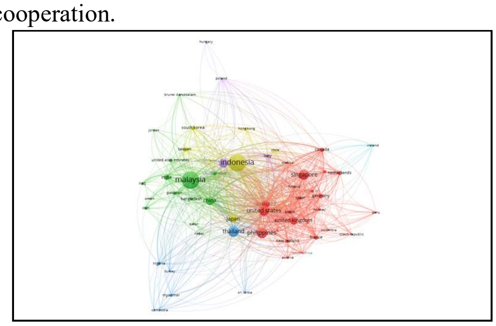

Figure 8. Country Collaboration Network in Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction.

To examine the conceptual structure of technology-driven research on harmful algal bloom (HAB) monitoring and prediction, a keyword co-occurrence analysis was performed using VOSviewer. As illustrated in Figure 9, the network consists of several interconnected thematic clusters representing the dominant research topics and emerging technological directions within the field.

The largest cluster is centered on machine learning, which exhibits extensive connections with artificial intelligence, deep learning, random forest, support vector machine, classification, and prediction, indicating the central role of data-driven analytical techniques in HAB monitoring and prediction research. A second major cluster is organized around remote sensing, linking closely with water quality, chlorophyll-a, MODIS, Sentinel-2, and eutrophication, highlighting the widespread application of satellite-based environmental monitoring technologies.

Additional thematic clusters emphasize GIS, climate change, biodiversity, conservation, and phytoplankton, reflecting the integration of geospatial analysis with ecological assessment. Another cluster focuses on Internet of Things (IoT), technology adoption, UTAUT2, and behavioral intention, indicating increasing attention toward smart environmental monitoring systems and technology acceptance. Smaller clusters further illustrate emerging applications involving unmanned aerial vehicles (UAVs), Google Earth Engine, aquaculture, mangroves, and coral reef ecosystems, demonstrating the expanding technological scope of HAB monitoring and prediction research. Collectively, the keyword co-occurrence network reveals that machine learning, remote sensing, artificial intelligence, GIS, and IoT constitute the dominant conceptual foundations of technology-driven HAB monitoring and prediction research in Southeast Asia.

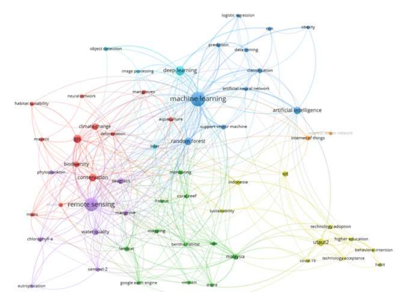

Figure 9. Keyword Co-occurrence Network of Technology-Driven Research on Harmful Algal Bloom Monitoring and Prediction.

Research Themes and Emerging Technologies

To examine the evolution of research themes over time, a thematic evolution analysis was conducted using authors' keywords. The analysis divides the research landscape into two time periods, 1997–2023 and 2024–2026, allowing the identification of thematic continuity, transformation, and the emergence of new technological directions. As illustrated in Figure 10, several research themes persisted across both periods, while others evolved or gave rise to new technology-oriented topics.

During the period 1997–2023, the dominant research themes included machine learning, remote sensing, water quality, conservation, aquaculture, random forest, and UTAUT2. Among these, machine learning, remote sensing, water quality, and conservation formed the principal thematic foundations of the research field, exhibiting strong connections with subsequent themes observed in the later period. The thematic evolution from 2024–2026 demonstrates the continued prominence of remote sensing, which remained one of the most persistent research themes throughout the study period. Likewise, machine learning continued to evolve and maintained strong thematic continuity while establishing connections with artificial intelligence and deep learning, indicating increasing adoption of advanced computational techniques for HAB monitoring and prediction. The theme water quality likewise persisted across both periods, reflecting its continuing importance in environmental assessment and aquatic ecosystem monitoring.

Several new themes also emerged during the most recent period. Artificial intelligence, deep learning, and the Internet of Things (IoT) became increasingly associated with the earlier technology-oriented themes, suggesting an expansion of intelligent and automated monitoring approaches. Similarly, mangrove appeared as a distinct research theme connected to earlier studies on conservation, indicating growing attention toward ecosystem-based environmental monitoring and coastal habitat management (Rashid and Kausik, 2024). The thematic evolution further indicates that earlier themes such as aquaculture, random forest, and UTAUT2 contributed to the development of more specialized research topics in the later period through multiple thematic linkages. The continuity of major environmental themes alongside the emergence of advanced digital technologies illustrates the progressive integration of artificial intelligence, machine learning, remote sensing, and IoT into HAB monitoring and prediction research.

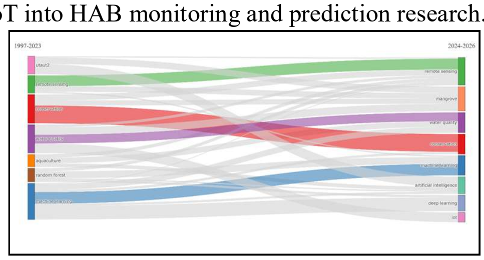

Figure 10. Thematic evolution of technology-driven research on harmful algal bloom monitoring and prediction in Southeast Asia from 1997–2023 to 2024–2026.

Discussion

Research Productivity, Citation Trends, and Research Life Cycle

RQ1. *How has technology-driven research on harmful algal bloom monitoring and prediction evolved in Southeast Asia in terms of scientific productivity, citation performance, and research life-cycle characteristics?*

The bibliometric findings indicate that research on technology-driven solutions for harmful algal bloom (HAB) monitoring and prediction in Southeast Asia has experienced substantial growth over the past three decades, with particularly rapid expansion beginning around 2015. This pattern reflects the increasing recognition of HABs as a major environmental and socioeconomic challenge in coastal and freshwater ecosystems, alongside the rapid advancement of digital technologies that have transformed aquatic environmental monitoring. The relatively low publication output observed during the early years suggests that technological applications for HAB monitoring were initially limited, relying primarily on conventional field sampling, laboratory analysis, and ecological observations. As computational capabilities, remote sensing platforms, and environmental sensing technologies became more accessible, research activity accelerated considerably, reflecting a transition from traditional monitoring approaches toward intelligent, data-driven environmental management systems (Lim *et al*., 2023).

The pronounced increase in publication output after 2015 coincides with major technological developments in artificial intelligence, machine learning, deep learning, cloud computing, Internet of Things (IoT), and satellite remote sensing. These technologies have significantly enhanced the capability to monitor environmental conditions continuously, process large volumes of heterogeneous data, and generate predictive models capable of supporting early warning systems for HAB events. The convergence of these digital technologies with aquatic environmental science has expanded opportunities for interdisciplinary collaboration among marine scientists, environmental engineers, computer scientists, and geospatial analysts, thereby contributing to the rapid growth of scientific production observed in this study (Park *et al*., 2025). In Southeast Asia, this increasing research activity may also reflect regional priorities related to sustainable aquaculture, coastal resource management, climate adaptation, and food security, all of which have intensified the demand for advanced monitoring and forecasting technologies.

The citation trends further illustrate the developmental characteristics of the research field. Older publications accumulated higher average citation counts because they have remained available within the scientific literature for a longer period, allowing greater opportunities for scholarly recognition and knowledge diffusion. Conversely, more recent publications generally exhibited lower citation averages due to shorter citation windows rather than reduced scientific relevance. Such citation behavior is commonly observed in rapidly evolving research fields where publication growth substantially outpaces the time required for citations to accumulate. Therefore, the lower citation performance of recent publications should be interpreted cautiously, as many of these studies are likely to gain greater scholarly influence as the field continues to mature (Giordano, Misuraca and Restaino, 2025).

The logistic growth analysis provides additional evidence regarding the developmental stage of technology-driven HAB research. The strong goodness-of-fit obtained from the logistic model (R^2 = 0.915) indicates that the observed publication trajectory closely follows the characteristic life cycle of an emerging scientific field. The estimated inflection points around 2025.5 suggests that the field is currently experiencing its period of maximum scientific expansion, characterized by accelerated publication output, increasing interdisciplinary participation, and heightened technological innovation. Scientific disciplines often exhibit similar logistic growth patterns as research interest expands, collaborative networks strengthen, and methodological innovations stimulate further investigation before the field gradually progresses toward maturity (Choudhary and Yadav, 2026).

An important observation is that the actual publication output recorded in 2025 exceeded the value predicted by the fitted logistic model. This deviation suggests that the research field is currently expanding more rapidly than expected based on historical publication trends. Several factors may explain this accelerated growth. First, recent advances in generative artificial intelligence, explainable AI, digital twins, autonomous monitoring platforms, and edge computing have substantially broadened the range of technological solutions available for environmental monitoring. Second, increasing global concern regarding climate change, coastal ecosystem degradation, harmful algal bloom outbreaks, and sustainable aquaculture has likely intensified research funding and interdisciplinary collaboration in this area. Finally, the growing availability of open-access satellite imagery, cloud-based geospatial platforms, and environmental big data has reduced technological barriers, enabling broader participation by researchers across developing countries, including those within Southeast Asia (Majidi Nezhad *et al*., 2025).

The cumulative logistic growth curve further suggests that technology-driven HAB research remains in an active expansion phase rather than having reached full scientific maturity. Although the model projects an eventual carrying capacity of approximately 3,452 cumulative publications, the observed publication trajectory continues to closely follow or slightly exceed the fitted logistic curve. This finding implies that the field has not yet exhausted its research potential and is likely to continue generating substantial scientific output over the coming years. Rather than indicating a decline in scientific relevance, the projected slowing of publication growth reflects the natural evolution of research domains as foundational knowledge becomes established and scientific efforts gradually shift toward methodological refinement, interdisciplinary integration, and practical implementation.

From a regional perspective, the continued expansion of technology-driven HAB research presents significant opportunities for Southeast Asia. The region is characterized by extensive coastlines, highly productive fisheries, rapidly expanding aquaculture industries, and increasing vulnerability to climate-induced environmental changes. Consequently, sustained research investment in intelligent monitoring systems, predictive analytics, and integrated environmental decision-support technologies is essential for strengthening ecosystem resilience and supporting evidence-based resource management. Future technological developments are expected to increasingly emphasize multimodal data integration, real-time sensor networks, artificial intelligence-assisted forecasting, explainable machine learning, digital twin ecosystems, and autonomous environmental monitoring platforms capable of providing more accurate and timelier HAB predictions. Collectively, these advances indicate that technology-driven HAB monitoring is evolving from isolated technological applications toward comprehensive smart aquatic environmental management systems that will play an increasingly important role in supporting sustainable development across Southeast Asia.

Influential Sources, Authors, Institutions, and Countries

RQ2.*Who are the most influential publication sources, authors, research institutions, and countries contributing to technology-driven research on harmful algal bloom monitoring and prediction in Southeast Asia?*

The distribution of publication sources shown in Figure 5 highlights the multidisciplinary nature of technology-driven research on harmful algal bloom (HAB) monitoring and prediction. The prominence of the *IOP Conference Series: Earth and Environmental Science* and *AIP Conference Proceedings* suggests that emerging technological innovations are frequently disseminated through conference venues, where new methodologies, computational techniques, and prototype monitoring systems are often introduced before being refined for publication in peer-reviewed journals (García Márquez, Peinado Gonzalo and Papaelias, 2026). Concurrently, the inclusion of established journals such as *Science of the Total Environment*, *PLOS ONE*, and *IEEE Access* among the leading publication sources (Figure 5) reflects the increasing integration of environmental science, artificial intelligence, remote sensing, engineering, and geospatial technologies in addressing HAB-related environmental challenges. This publication landscape demonstrates that advances in HAB monitoring are increasingly driven by interdisciplinary research spanning multiple scientific domains.

The bibliometric indicators presented in Table 2 provide further evidence that scientific influence is determined by both research productivity and citation impact. Although Zainuddin M. produced the largest number of publications, Hossain M.S. achieved the highest h-index, m-index, and total citation count, indicating broader scholarly recognition of his research contributions. This distinction illustrates the value of employing multiple bibliometric performance indicators when evaluating scientific influence, as publication counts alone do not necessarily reflect intellectual impact within a research field (Hashem *et al*., 2023). Likewise, the strong performance of Hashim M., Nurdin N., Pradhan B., Wang Y., and other leading authors listed in Table 2 suggests the presence of a relatively small group of researchers who have consistently contributed influential work on technology-enabled HAB monitoring and prediction. Such concentrations of scholarly expertise are frequently observed in developing research fields, where a limited number of authors establish foundational knowledge that subsequently guides future investigations (Mohamad Zaki *et al*., 2025).

The institutional distribution presented in Figure 6 indicates that scientific production is concentrated within several established universities in Singapore, Malaysia, and Indonesia. The leading position of the National University of Singapore, together with the strong performance of Malaysian and Indonesian institutions, reflects substantial research capacity in environmental science, marine studies, engineering, artificial intelligence, and remote sensing. These institutions have benefited from sustained investments in research infrastructure, international collaboration, and technological innovation, enabling them to become major contributors to the advancement of intelligent environmental monitoring systems within Southeast Asia (Roy and Akbar, 2026). The concentration of productive institutions shown in Figure 6 also suggests that institutional research capacity plays a critical role in driving technological innovation and facilitating interdisciplinary collaboration within the region.

The geographical distribution of scientific production shown in Figure 7 identifies Indonesia as the leading contributor to research output, followed by Malaysia, the Philippines, Thailand, and Singapore. Indonesia's dominant position is likely associated with its extensive coastal ecosystems, large aquaculture industry, and recurring harmful algal bloom events, all of which necessitate continuous research on monitoring and prediction technologies (Putera *et al*., 2022). Similarly, the strong research productivity of Malaysia, the Philippines, Thailand, and Singapore reflect increasing national investments in environmental sustainability, digital transformation, coastal resource management, and smart monitoring technologies. The substantial contributions from countries outside Southeast Asia, particularly the United States and China, further indicate that research on HABs within the region has attracted considerable international scientific attention. This pattern is consistent with the transboundary nature of harmful algal blooms, which require collaborative expertise in oceanography, environmental science, artificial intelligence, remote sensing, and engineering to develop effective monitoring and forecasting systems (Choudhary, 2026).

The combined bibliometric evidence presented in Figure 5, Table 2, Figure 6, and Figure 7 indicates that the advancement of technology-driven HAB monitoring and prediction in Southeast Asia is supported by a well-established network of multidisciplinary publication outlets, influential researchers, research-intensive universities, and internationally engaged countries. Rather than reflecting isolated research efforts, these patterns suggest the existence of interconnected scientific communities that collectively contribute to technological innovation in aquatic environmental monitoring. The concentration of influential contributors within several leading institutions and countries also highlights the importance of expanding regional research partnerships and strengthening international collaboration to promote knowledge exchange, accelerate technological development, and enhance the application of intelligent monitoring systems for sustainable aquatic ecosystem management (Fu *et al*., 2022).

Scientific Collaboration Networks

RQ3. *What are the patterns of scientific collaboration among countries engaged in technology-driven research on harmful algal bloom monitoring and prediction in Southeast Asia?*

The international collaboration network presented in Figure 8 demonstrates that research on technology-driven solutions for harmful algal bloom (HAB) monitoring and prediction is characterized by extensive cross-national scientific cooperation. The dense interconnections among countries indicate that the development of intelligent monitoring technologies has increasingly relied on multidisciplinary and international research partnerships. Such collaborative patterns are expected in environmental research, where the complexity of HAB dynamics requires expertise spanning marine science, environmental engineering, remote sensing, artificial intelligence, geospatial analysis, and aquatic resource management (Tian *et al*., 2026; Alotaibi and Nassif, 2024).

The central positions occupied by Indonesia, Malaysia, Singapore, the United States, China, Thailand, the Philippines, Japan, and the United Kingdom in Figure 8 suggest that these countries serve as major hubs within the global research network. Their extensive collaborative linkages reflect not only high scientific productivity but also strong participation in multinational research projects, joint publications, and knowledge exchange initiatives. Previous bibliometric studies have shown that countries occupying central positions within collaboration networks often exhibit higher research visibility, greater citation impact, and increased opportunities for scientific innovation because collaborative research facilitates access to complementary expertise, research infrastructure, and financial resources (Lu *et al*., 2025).

Among the Southeast Asian countries, the strong collaborative roles of Indonesia, Malaysia, and Singapore are particularly noteworthy. Indonesia's central position is likely influenced by its extensive coastal ecosystems, diverse marine biodiversity, and frequent occurrence of HAB events, which provide numerous opportunities for environmental monitoring and technological innovation. Malaysia and Singapore similarly possess well-established research infrastructures and have made substantial investments in digital technologies, remote sensing, and environmental sustainability, enabling them to establish productive international partnerships. These collaborative relationships strengthen regional research capacity by facilitating the exchange of technical knowledge, environmental datasets, and advanced analytical methodologies (Raihan, 2024).

The network illustrated in Figure 8 also reveals substantial collaboration between Southeast Asian researchers and institutions from North America, Europe, East Asia, and Oceania. Such international participation reflects the global significance of harmful algal blooms as transboundary environmental phenomena that threaten fisheries, aquaculture, coastal ecosystems, public health, and food security. Because HABs are influenced by interconnected climatic, oceanographic, and anthropogenic factors, international collaboration enables researchers to integrate diverse datasets, compare environmental conditions across geographic regions, and develop more robust monitoring and predictive models (McKinley *et al*., 2024).

Another notable characteristic of the collaboration network is the presence of multiple interconnected clusters rather than isolated country groups. This structure suggests that scientific collaboration is not restricted to bilateral partnerships but instead occurs through broader multinational research communities. Collaborative clusters facilitate interdisciplinary knowledge exchange and accelerate the transfer of emerging technologies, including artificial intelligence, machine learning, satellite remote sensing, Internet of Things (IoT) systems, and environmental sensor networks, into practical HAB monitoring applications. Such collaborative environments are particularly important for addressing complex environmental challenges that require coordinated scientific efforts across institutional and national boundaries (Tiggeloven *et al*., 2025).

The collaboration patterns observed in Figure 8 further suggest opportunities for expanding scientific participation among emerging research institutions within Southeast Asia. While several countries occupy central positions within the collaboration network, other nations appear to maintain relatively limited international linkages. Strengthening regional partnerships through collaborative research programs, shared environmental monitoring initiatives, researcher mobility, and joint technology development could broaden scientific participation and improve the regional capacity to develop intelligent HAB monitoring and prediction systems. Expanding these collaborative networks may also contribute to more standardized monitoring frameworks, enhanced data sharing, and improved evidence-based management of aquatic ecosystems across Southeast Asia (Ding *et al*., 2024).

Research Themes and Emerging Technologies

RQ4. *What are the dominant research themes and emerging technologies shaping technology-driven research on harmful algal bloom monitoring and prediction in Southeast Asia?*

The thematic evolution presented in Figure 10 illustrates the progressive transformation of technology-driven research on harmful algal bloom (HAB) monitoring and prediction from conventional environmental monitoring approaches toward increasingly intelligent, data-driven technologies. The persistence of remote sensing, machine learning, water quality, and conservation across both time periods indicates that these themes constitute the core knowledge base of the research field. Their continued presence suggests that technological innovation has not replaced traditional environmental monitoring concepts but has instead strengthened their analytical capabilities through advances in computational methods and digital technologies (Essamlali, Nhaila and El Khaili, 2024).

Among the dominant themes, remote sensing exhibited the strongest thematic continuity throughout the study period (Figure 10). This finding reflects the growing reliance on satellite-based observation systems for monitoring large-scale aquatic environments where conventional field sampling alone is often insufficient. Recent advances in multispectral and hyperspectral satellite imagery, together with improved spatial and temporal resolutions, have substantially enhanced the ability to detect chlorophyll concentrations, water quality parameters, and environmental conditions associated with HAB formation (Bentivogli *et al*., 2026). Consequently, remote sensing has become one of the most widely adopted technological approaches for supporting early detection and continuous environmental surveillance.

The sustained evolution of machine learning into more specialized themes, including artificial intelligence and deep learning, further demonstrates the increasing sophistication of predictive modeling within the research field. As shown in Figure 10, machine learning remained one of the principal research themes while establishing strong thematic connections with newly emerging computational approaches. This progression reflects broader developments in environmental informatics, where traditional statistical models are increasingly complemented by advanced artificial intelligence techniques capable of processing large, heterogeneous environmental datasets and improving predictive accuracy (Albahri *et al*., 2024). The emergence of deep learning further suggests an increasing emphasis on automated feature extraction, image analysis, and complex pattern recognition for HAB forecasting and environmental monitoring.

Another notable finding is the emergence of the Internet of Things (IoT) as a distinct technological theme during the most recent period (Figure 10). Although IoT was not among the dominant themes during the earlier years, its appearance in recent research reflects the growing adoption of interconnected environmental sensor networks capable of supporting real-time data acquisition and continuous aquatic ecosystem monitoring. The integration of IoT technologies with artificial intelligence and cloud-based analytical platforms has created opportunities for developing intelligent early warning systems that provide more responsive and adaptive HAB monitoring compared with conventional observation methods (Muhammed *et al*., 2024). This technological convergence represents an important shift toward autonomous environmental monitoring frameworks capable of supporting timely management decisions.

The thematic evolution also demonstrates increasing attention toward ecosystem-based applications, particularly through the emergence of mangrove as a distinct research theme linked to earlier studies on conservation (Figure 10). This transition suggests that technological innovations are being applied not only to HAB prediction but also to broader ecosystem monitoring and coastal resource management. Mangrove ecosystems play critical ecological roles in maintaining coastal water quality, supporting biodiversity, and enhancing ecosystem resilience, making them increasingly relevant within integrated environmental monitoring frameworks (Roy *et al*., 2026). The continued prominence of water quality likewise emphasizes that technological developments remain closely aligned with fundamental environmental indicators used to assess HAB dynamics and aquatic ecosystem health.

The observed thematic transitions indicate that technology-driven HAB research is undergoing a process of increasing interdisciplinary integration. Rather than evolving through isolated technological advancements, the field appears to combine environmental science, artificial intelligence, remote sensing, Internet of Things technologies, and ecological management into increasingly comprehensive monitoring systems. This convergence is consistent with the broader digital transformation occurring within environmental research, where multiple data sources, intelligent algorithms, and automated sensing technologies are integrated to improve environmental prediction, decision support, and resource management (Tiggeloven *et al*., 2025).

The thematic evolution shown in Figure 10 also suggests that future research is likely to emphasize the integration of multiple technological platforms rather than the advancement of individual technologies in isolation. The continued linkage among remote sensing, machine learning, artificial intelligence, IoT, and ecosystem-based monitoring reflects an emerging research direction toward intelligent environmental monitoring systems capable of combining satellite observations, in situ sensor networks, predictive analytics, and ecological information within unified decision-support frameworks. Expanding these integrated approaches may improve the accuracy, scalability, and operational applicability of HAB monitoring and prediction across diverse aquatic environments in Southeast Asia (Carvajal Romero, Rojas Ángel and Gaitan-Angulo, 2026).

Conclusion

This study systematically examined the research landscape of technology-driven solutions for harmful algal bloom (HAB) monitoring and prediction in Southeast Asia through a comprehensive bibliometric analysis of publications indexed in the Scopus database. Using Bibliometrix and VOSviewer, the study analyzed research productivity, citation performance, influential scientific contributors, international collaboration patterns, and the evolution of research themes and emerging technologies. Collectively, these analyses provide a quantitative overview of the development, current status, and future trajectory of technology-driven HAB research within the region.

The findings reveal that scientific production has increased substantially over the past three decades, with accelerated growth occurring after 2015, reflecting the expanding application of digital technologies in aquatic environmental monitoring. The citation analysis and logistic growth model indicate that the research field is currently undergoing a period of rapid scientific expansion and is approaching a critical stage in its developmental life cycle. Although publication productivity continues to increase, the bibliometric evidence suggests that future advances will depend not only on sustained scientific output but also on the continued development of innovative technologies and interdisciplinary research. The study further identified a relatively concentrated group of influential publication sources, authors, research institutions, and countries that have significantly contributed to advancing knowledge in this domain. Universities in Singapore, Malaysia, and Indonesia emerged as major centers of scientific production, while extensive collaboration among Southeast Asian countries and international research partners demonstrates the increasingly global nature of technology-driven HAB research. These collaborative networks facilitate knowledge exchange, technological innovation, and the integration of multidisciplinary expertise necessary to address increasingly complex environmental challenges.

The thematic evolution analysis demonstrates a clear transition from conventional environmental monitoring approaches toward intelligent, technology-enabled systems. While remote sensing, water quality assessment, and conservation remain fundamental research themes, recent years have witnessed the increasing prominence of artificial intelligence, machine learning, deep learning, Internet of Things (IoT), and other advanced digital technologies. These emerging research directions indicate a growing emphasis on real-time monitoring, predictive analytics, autonomous sensing, and data-driven decision support for aquatic ecosystem management. This study contributes to the existing body of knowledge by providing one of the first bibliometric assessments specifically focused on technology-driven HAB monitoring and prediction research within Southeast Asia. By identifying influential contributors, collaboration structures, and evolving research themes, the findings establish a valuable knowledge base for researchers, research institutions, policymakers, and funding agencies seeking to strengthen scientific collaboration and prioritize future investments in intelligent environmental monitoring technologies.

Nevertheless, several limitations should be acknowledged. The analysis was based exclusively on publications indexed in the Scopus database and was limited to English-language documents, which may have excluded relevant studies published in other databases or languages. In addition, bibliometric indicators primarily evaluate publication and citation characteristics and do not directly assess the technical performance, implementation, or operational effectiveness of individual monitoring technologies. Future investigations should expand bibliometric analyses by incorporating additional databases such as Web of Science and Dimensions, exploring author-, institution-, and funding-level collaboration in greater detail, and integrating bibliometric approaches with systematic literature reviews or scientometric analyses. Further research may also examine the practical adoption and performance of emerging technologies including explainable artificial intelligence, digital twins, autonomous monitoring platforms, edge computing, and integrated Internet of Things (IoT) ecosystems to support more accurate, adaptive, and sustainable HAB monitoring and prediction systems across Southeast Asia.

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Conflict of Interest

The author declares that there are no competing financial interests, personal relationships, or other conflicts of interest that could have influenced the conduct, interpretation, or publication of this research.

Data Availability Statement

The bibliometric dataset analyzed during the current study was retrieved from the Scopus database. The processed dataset and supporting materials are available from the corresponding author upon reasonable request, subject to the data usage policies and licensing terms of Scopus.

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