Bibliometric insights and content analysis of diatom paleolimnology in lakes: Global perspectives and Indonesian contributions over the last decade

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Abstract. This study evaluates global scientific publications on diatom-based lake paleolimnology from 2014 to 2024, with a focus on Indonesia's contributions, using bibliometric and content analysis of Scopus data. A total of 378 publications were identified, with relatively stable annual output. The Journal of Paleolimnology is the leading publication outlet, and Agricultural and Biological Sciences is the most studied subject area. Canada, the United States, and China dominate in publication volume, with Canadian authors being the most influential. Indonesia's research remains limited to a few lakes (Towuti, Rawapening, and Warna), indicating challenges but also potential for expansion. Keyword analysis revealed seven clusters centered on paleolimnology and diatoms. Underexplored research areas include microenvironment, miocene, modern analogs, modern sediments, nutrient limitation, siliceous components, and Patagonian palaeoenvironments. These themes suggest promising directions such as investigating Miocene microhabitats, improving ecological reconstructions through modern analog comparisons, and studying nutrient dynamics and silica availability, which are crucial for diatom growth and lake productivity. The study's findings aim to inform and enhance paleolimnology research in Indonesia and foster greater international collaboration.

1 Introduction

Paleolimnology is a branch of science that studies the past environmental conditions of aquatic bodies, especially lakes, through the analysis of sediment records [1]. Among the

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various biological indicators used in paleolimnological studies, diatoms occupy an important position due to their ecological sensitivity to physical, chemical, and biological changes in aquatic ecosystems [2]. Diatoms have silica shells that can be well preserved in sediments for a long time, allowing them to serve as natural archives of environmental dynamics that occurred throughout the past [3]. Diatom-based paleolimnological studies can be an effective method for reconstructing the history of climate, eutrophication, land use changes, and other anthropogenic impacts on lake ecosystems [4].

Issues related to climate change and water quality degradation have become global concerns. While paleolimnology has significantly developed over the past decade, research contributions from developing countries, including Indonesia, remain limited compared to those from countries with better research infrastructure and international collaboration networks. This study aims to bridge this gap by analyzing global research trends in diatom-based paleolimnology and examining Indonesia's role and contributions to this field. In Indonesia, paleolimnology has great potential to enhance the understanding of lake ecosystem dynamics, particularly in relation to the 15 priority national lakes designated by the government for conservation and management. These lakes are vital for biodiversity, water resources, and local communities, making it crucial to incorporate paleolimnological data into management policies. However, the use of paleolimnology in lake management in Indonesia has not been fully optimized. Paleolimnological research findings can inform lake management strategies, particularly in addressing increasing pressures from climate change and human activity.

In order to better understand the development of diatom-based paleolimnology, it is necessary to use systematic methods that can measure the quantity and quality of scientific publications. A systematic literature review, along with bibliometric and content analysis, is employed to map the scientific development of lake paleolimnology. This approach allows for the analysis of global publication trends, the most productive journals, key subject areas, leading authors, influential countries, and the most cited articles. Specifically, this study will compare Indonesia's research output with global trends, identifying opportunities to strengthen Indonesia's scientific contributions to this field. The results are expected to guide the future direction of paleolimnology research in Indonesia and foster greater integration with the global scientific community.

This study will address the following research questions:

R1. What are the trends in global scientific publications on paleolimnology based on diatoms over the last decade?
R2. What are the most productive journals and the most common subject areas globally and in Indonesia?
R3. What are the main keywords in global research over the last decade?
R4. What are the most influential countries in global research in terms of publication volume and citation counts?
R5. What are the most influential articles globally based on citation counts, and how do articles from Indonesia compare in terms of citation impact?

2 Method

In this study, bibliometric and content analysis methods were employed to identify publication patterns, author productivity, and the distribution of international collaborations in the field of lake paleolimnology using diatoms. The research process and procedures followed in this study were based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). Using PRISMA, readers can evaluate the relevance of the methodology [5]. The PRISMA approach in this study consisted of three main steps:

identification, screening, and final determination. The details of this process are further outlined in **Figure 1**.

2.1 Data Collection, Filtering, and Cleaning

This study used the Scopus database to analyze global publication trends and Indonesia's contribution to diatom-based lake paleolimnology from 2014 to 2024, with data extracted using a search string focused on relevant keywords and filtered by year, document type, and language. Scopus, known for its rigorous content selection and quality assurance processes, was chosen for its broad global coverage and reliability [6]. However, its exclusion of non-English publications introduces potential bias, as it may overlook significant studies from regions or languages not represented in the database. To enhance the objectivity of the content analysis, inter-coder reliability checks were conducted, ensuring consistency in categorization, while data cleaning was done using OpenRefine to correct errors, eliminated duplicates, and resolve inconsistencies in author keywords, improving the data's accuracy and reliability [7].

2.2 Data Analysis

Data analysis was conducted using bibliometrics and content analysis. Bibliometric analysis, a common method for understanding the development of a scientific field and identifying trends, was applied to map the progress of diatom-based lake paleolimnology over the past decade. It involved analyzing document counts, H-Index, and citation distribution to assess the productivity and scientific impact of authors and countries [8]. Content analysis, a method for systematically examining information both quantitatively and qualitatively, was used to identify keywords in global publications and highlight the most influential articles globally and in Indonesia [9]. This analysis offers insights into future research directions, highlighting gaps that could drive scientific advancement, particularly in Indonesia, which holds significant potential for research on tropical lake ecosystems and ancient lakes.

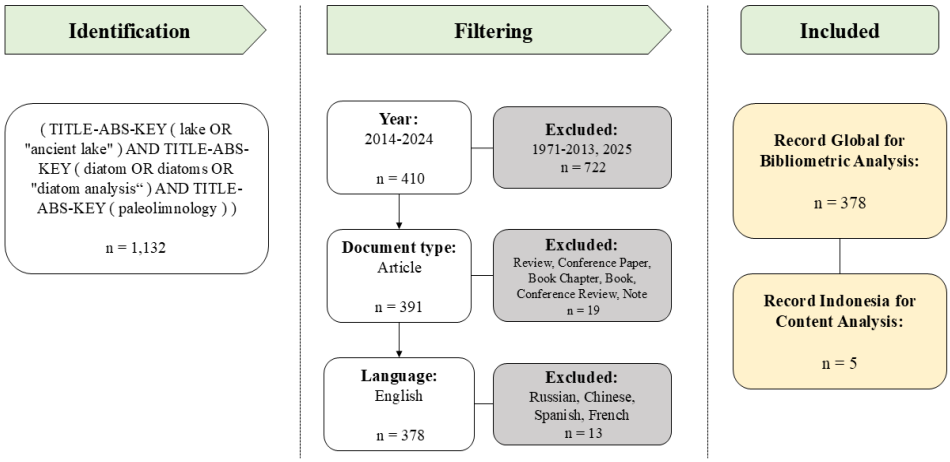

Fig. 1. PRISMA

3 Result

R1. What are the trends in global scientific publications on paleolimnology based on diatoms over the last decade?

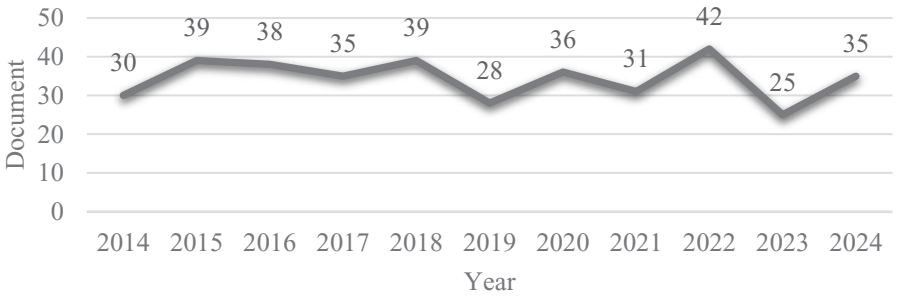

Fig. 2. Publication Trends Over a Decade (2014-2024) in Diatom-based Paleolimnology Research on Lakes or Ancient Lakes

The annual publication trend in paleolimnology using diatoms as biological indicators shows considerable variation (**Figure 2**), with a total of 378 global publications recorded from 2014 to 2024. Annual publications ranged from 25 to 42, with fluctuations indicating challenges in the field. A rise in publications occurred from 2015 to 2018, followed by a decline in 2019, and additional decreases in 2021 and 2023. The highest number of publications over the past decade occurred in 2022, with 42 publications, marking the peak for the period. The decline in publications may be attributed to the lengthy and complex nature of paleolimnology research, which involves sediment core collection, laboratory preparation, analysis, and stratigraphic interpretation. Additionally, the increasing competition for publication in top-tier journals has led some studies to be published locally or nationally. These fluctuations reflect not only the interest in paleolimnology but also the need for enhanced human resource capacity, sustainable funding, and interdisciplinary collaboration to improve understanding of past lake environments.

R2. What are the most productive journals and the most common subject areas globally and in Indonesia?

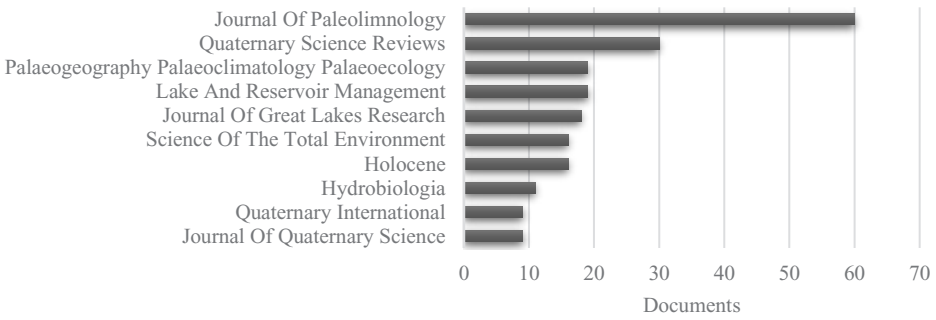

Fig. 3. Most Productive Journal in Diatom-based Paleolimnology Research on Lakes or Ancient Lakes

Figure 3 shows the names of the journals that published the most articles related to lake paleolimnology or ancient lakes based on diatoms. The *Journal of Paleolimnology*, which has become the main reference for authors to publish their work, is proven by having the largest number of publications, with 60 articles. The presence of the word "paleolimnology" in the journal's name boosts the author's confidence that their research on the study of the past of lakes is appropriate and worthy of publication in the journal. Key factors influencing authors choice of journal include the belief that their article fits within the journal's scope, the journal's reputation, the quality of reviewer feedback, and the reliability of the reviewers. The other top four journals, namely *Quaternary Science Reviews*, *Palaeogeography, Palaeoclimatology, Palaeoecology*, *Lake and Reservoir Management*, and *Journal of Great Lakes Research*, each publish fewer articles, with the number of publications being no more than half of those in the *Journal of Paleolimnology*. The number of articles published in these journals may be influenced by factors. Some factors that can influence the number of journal submission are: the journal's impact factor, its scope and focus, peer review reputation, and the level of competition for publication.

Table 1. Common Subject Areas

Subject Area	Document(s)		Subject Area	Document(s)	
	Global	Indonesia		Global	Indonesia
Agricultural and Biological Sciences	258	4	Pharmacology, Toxicology and Pharmaceutics	4	-
Earth and Planetary Sciences	209	2	Chemistry	3	-
Environmental Science	199	3	Immunology and Microbiology	2	-
Arts and Humanities	64	-	Multidisciplinary	2	-
Social Sciences	40	-	Engineering	1	-
Biochemistry, Genetics and Molecular Biology	12	1	Medicine	1	-
Decision Sciences	6	-			

Table 1 shows the fields or disciplinary focuses of the journal publications. The three subjects with the most documents (more than 100) are Agricultural and Biological Sciences; Earth and Planetary Sciences; and Environmental Science. Agricultural and Biological Sciences is the most important field related to the paleolimnology of lakes or ancient lakes based on diatoms. This field is highly relevant to paleolimnology because many studies discuss changes in ecosystems due to human activities, particularly agriculture, which affect water quality and biodiversity in lakes. In addition, diatoms, as biological indicators, which are the main focus of study, are certainly well-suited to this field. Earth and Planetary Sciences is the second leading field, as paleolimnology is closely related to Earth science (geology), where information about lake sediment layers, climate change, geological activity, and topographic conditions are widely studied. Meanwhile, Environmental Science is a broader field that discusses the environment, both aquatic and terrestrial. This field is relevant because paleolimnological studies aim to understand the environmental history of lakes in the past as a basis for present conservation and mitigation efforts.

R3. What are the main keywords in global research over the last decade?

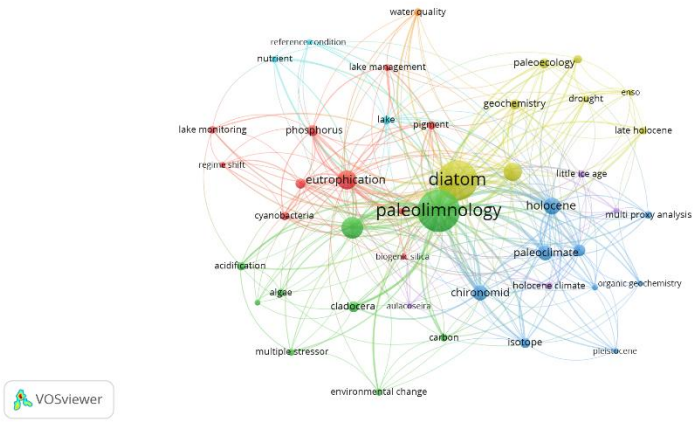

Fig. 4. Network Visualization Author Keyword with a Minimum Occurrence of 5 in Diatom-based Paleolimnology Research on Lakes or Ancient Lakes

Figure 4 highlights "Diatom" and "Paleolimnology" as the central focus of the reviewed studies. Diatoms are widely used as environmental indicators in paleolimnological research, while paleolimnology itself examines past environments using lake sediment data. Diatom indicators are key in predicting the trophic history of lakes. The image also presents seven keyword clusters, each representing related topics frequently appearing together in the research. The first, red cluster includes terms related to eutrophication, which impacts water quality and phytoplankton diversity, including diatoms. The second, green cluster focuses on paleolimnology, incorporating topics like climate change and acidification. The third, dark blue cluster is linked to geochemistry and isotopes used for analyzing lake conditions during the Holocene and Pleistocene. The fourth, yellow cluster examines diatom fossils in sediments to assess lake conditions in the Late Holocene. The fifth, purple cluster connects Aulacoseira diatoms to human impacts during the Holocene. The sixth, light blue cluster addresses lake nutrients as reference conditions, and the seventh, orange cluster covers general water quality issues.

R4. What are the most influential countries in global research in terms of publication volume and citation counts?

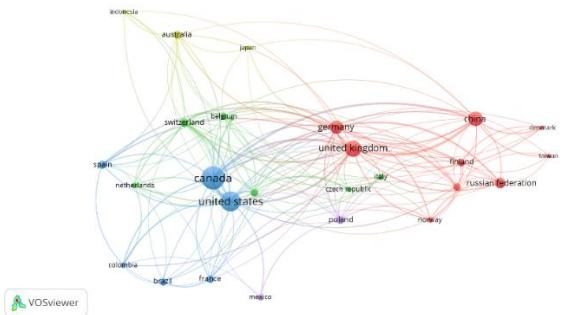

Fig. 5. Network Visualization of International Collaborations in Diatom-based Paleolimnology Research on Lakes or Ancient Lakes

Figure 5 shows the collaboration network between countries visualized using VOSviewer illustrates the close scientific relationships between countries as global research centers. Canada and the United States serve as the main network hubs, forming a large cluster with Western European countries such as the Netherlands, France, and Spain. The United Kingdom and Germany also appear to connect, strengthening the relationship between the American and Asia-Eastern Europe clusters. China and the Russian Federation are in a cluster with Finland, Norway, and Taiwan. Meanwhile, Australia, Japan, and Indonesia appear to be beginning to form a scientific network, although it is still limited. Overall, these two visualizations demonstrate that the development of diatom-based paleolimnology studies is heavily influenced by a country's capabilities, both in terms of finance and technology, as well as international collaborative networks. The dominance of influential countries in the production of publications and scientific collaborations highlights the importance of building research capacity in developing countries. This is intended to enable a more in-depth study of the potential of ancient lakes in tropical regions and to contribute to global understanding.

R5. What are the most influential articles globally based on citation counts, and how do articles from Indonesia compare in terms of citation impact?

Table 2. Top 5 Highly cited global articles

No.	Cites	Authors, Year	Title	Source Title/ Publisher	Research Location (Country)	Conclusion
1.	95	Bunting et al. (2016)	Increased variability and sudden ecosystem state change in Lake Winnipeg, Canada, caused by 20th century agriculture	Limnology and Oceanography/ Wiley Blackwell	Lake Winnipeg, Canada	Lake Winnipeg has reached an alternative stable state due to agricultural and socio-economic changes.
2.	51	Su et al. (2021)	Long-term empirical evidence, early warning signals and multiple drivers of regime shifts in a lake ecosystem	Journal of Ecology/ John Wiley and Sons Inc	Lake Taihu, China	Major ecosystem changes driven by river flow, climate warming, eutrophication, and fish addition make the lake difficult to restore.
3.	69	Thienport et al. (2016)	Multi-trophic level response to extreme metal contamination from gold mining in a subarctic lake	Proceedings of the Royal Society B: Biological Sciences/ Royal Society of London	Pocket Lake, Canada	Heavy metal contamination led to the loss of organisms and no recovery despite halting mining activities 20 years ago.
4.	79	Reavie et al. (2017)	Climate warming and changes in Cyclotella sensu lato in the Laurentian Great Lakes	Limnology and Oceanography/ Wiley Blackwell	Laurentian Great Lake, North America	Climate warming altered the diatom community, increasing Cyclotella species linked to water stratification and ice-free duration.
5.	58	Biskaborn et al. (2015)	Late Quaternary vegetation and lake system dynamics in north-eastern Siberia: Implications for seasonal climate variability	Quaternary Science Reviews/ Elsevier Ltd	Lakes of Eastern Siberia	Holocene climate changes caused shifts in diatom communities in lake ecosystems.

Most of the studies in **Table 2** discuss the impact of human activities on lake ecosystems. Intensive agriculture can increase ecosystem variability and its vulnerability to change. This topic reflects a global trend, where researchers are increasingly focusing on the long-term impacts of agriculture and mining on water quality and biodiversity in lake ecosystems. Another study contributes to understanding the effects of climate change on lake ecosystems and how early warning signals can be used to anticipate further changes before greater ecosystem damage occurs. Heavy metal contamination will be a significant problem in many parts of the world, and this study provides a better understanding of the long-term impacts of mining on water quality and aquatic biota. Global warming has significantly impacted the composition of phytoplankton, an essential component of the food chain in lake ecosystem. Additionally, the long-term effects of climate change on lake systems and vegetation in subarctic regions have been examined, with a focus on how temperature fluctuations affect water stratification and the distribution of biota species.

Global-scale studies are very important because they provide scientific evidence of the impact of human activities and climate change on lake ecosystems. Understanding how agriculture, mining, and climate warming affect biodiversity and water quality can help develop better management strategies to protect and restore affected ecosystems. Human activities such as farming and mining lead to environmental contamination that can harm ecosystem health in the long term. Prevention and reduction of impacts need to be carried out through more environmentally friendly policies and sustainable use of natural resources.

Table 3. Content Analysis for Research Articles in Indonesia

No.	Cites	Authors, Year	Title	Research location	Methods	Key findings
1.	25	Russel et al. (2020)	The late quaternary tectonic, biogeochemical, and environmental evolution of ferruginous Lake Towuti, Indonesia	Lake Towuti, South Sulawesi	Sediment cores, lithostratigraphy, mineralogy, geochemistry, and geochronology.	Lake Towuti's formation and evolution are influenced by tectonics, climate change, and volcanic activity, with endemic fauna evolution.
2.	23	Soeprobowati et al. (2018)	Diatom assemblage in the 24 cm upper sediment associated with human activities in Lake Warna Dieng Plateau Indonesia	Lake Warna, Central Java	Sediment cores, diatom analysis, 210Pb dating.	Eutrophication linked to human activities is reflected by diatom changes, particularly *Sellaphora seminulum* Grunow.
3.	15	Soeprobowati et al. (2016)	The minimum number of valves for diatoms identification in Rawapening Lake, Central Java	Lake Rawapening, Central Java	Diatom analysis on 314 samples.	A minimum of 300 diatom valves ensures stable representation in paleolimnology analysis.
4.	3	Ageli et al. (2022)	Benthic-Pelagic state changes in the primary trophic level of an ancient tropical lake	Lake Towuti (Maili Lake System), South Sulawesi	Sediment cores, non-metric multidimensional analysis.	Shift from planktonic to benthic diatom communities driven by nutrient cycles and water mixing.
5.	0	Prasetyo et al. (2024)	Vertical Distribution of Diatoms Analysis to Determine the Condition of Rawapening Lake in the Past through Cluster Analysis with the Bray-Curtis Model	Lake Rawapening, Central Java	Sediment core, Bray-Curtis cluster model.	Increased pH and hypereutrophic conditions in Rawapening Lake due to human activities and organic matter accumulation.

Of the 378 global publications, only 5 (1.32%) are from Indonesia (**Table 3**). These publications are spread across the years, with one article each in 2016, 2018, 2020, 2022, and 2024, reflecting Indonesia's limited involvement in lake paleolimnology research using diatoms. Contributing factors include limited diatom laboratories, funding, and lack of international collaboration. The five Indonesian publications focus on three lakes: Lake Warna, Lake Rawapening, and Lake Towuti, each differing in geology and ecology. The most cited publication (25 citations) is by Russel et al. (2020), based on research at Lake Towuti, Sulawesi. Towuti, one of Indonesia's oldest lakes, was studied for its evolution and ecosystem changes over one million years, offering insights into climate dynamics in Indonesia's past.

The second most cited article (23 citations) is by Soeprobowati et al. (2018), based on research at Danau Warna, Central Java. This lake represents a tropical volcanic lake ecosystem in the highlands. Although the size of the lake is relatively small, its sensitivity to land use changes is clearly illustrated through alterations in the diatom community. This condition is highly relevant, as it is observed in many other lakes across Indonesia, where human activities significantly impact the lake ecosystem. The research in Danau Warna also highlights the important role of paleolimnology studies in small lakes in tropical areas vulnerable to change. Soeprobowati also published in 2016 on Lake Rawapening, focusing on the recommended number of valves for paleolimnological research using diatom fossils. The study explains that the minimum number of valves to be identified is 300 to obtain stable and accurate data. Prior to this, there was no clear guideline regarding the number of valves necessary to provide representative results in paleolimnological studies, making this study a valuable methodological reference for future research.

Contributions to paleolimnological studies in Indonesia were also made by Ageli et al. (2022). Their research examined changes in trophic status and the dominance of planktonic to benthic primary producers. In oligotrophic waters, planktonic primary producers or phytoplankton dominate the ecosystem. However, as nutrient levels increase and trophic status shifts toward eutrophic or hypereutrophic conditions, benthic organisms become more dominant, as they are better able to survive in nutrient-rich environments. Understanding the shift in the dominance of primary producers is crucial for reconstructing the history of trophic status in lake and can serve as a model for climate and environmental changes in other lakes in Indonesia and globally. The most recent paleolimnology article in Indonesia was written by Prasetyo et al. (2024). This article contributes to paleolimnology by using diatoms as indicators to evaluate changes in the ecosystem of Lake Rawapening.

Scopus data shows that paleolimnology research in Indonesia has thus far focused on three lakes: Lake Rawapening, Lake Warna, and Lake Towuti, but there is potential for further exploration. Researchers can investigate other Indonesian lakes, including those in Kalimantan, Sumatera, Papua, and Nusa Tenggara, as well as ancient lakes that have transformed into terrestrial ecosystems. There lakes offer valuable environmental archives that are critical for conservation and mitigation efforts, providing essential data for studying long-term environmental trends in dynamic ecosystem. Furthermore, paleolimnology studies could benefit from other data sources, such as pollen, isotopes, and environmental DNA, and deeper analysis of diatom data correlated with parameters like pH, nutrients, and alkalinity.

4 Discussion

Based on bibliometric analysis, global diatom-based paleolimnological research on lakes remains predominantly conducted by developed countries. However, Indonesia possesses numerous unique tropical lakes that have been understudied, indicating a significant potential to contribute meaningfully to this field. The majority of existing studies continue to focus on the impacts of anthropogenic activities on lake ecosystems, such as nutrient pollution (eutrophication) and climate change [10]. Nevertheless, research methods that integrate

multiple types of indicators (such as diatoms in conjunction with environmental DNA, foraminifera, or stable isotopes) are still rarely employed. These integrative approaches can offer a more comprehensive and in-depth understanding of environmental changes. Indonesia holds considerable potential to develop and apply such methodologies in the study of its complex tropical lake systems.

The relatively low number of publications originating from Indonesia also reflects the limited research infrastructure, scarcity of specialized researchers, limited funding, and insufficient international collaboration [11] Paleolimnological studies could play a crucial role in informing governmental policies for more effective lake management [12]. In Indonesia, there are 15 priority lakes requiring urgent intervention, and the environmental history data derived from paleolimnological investigations could greatly enhance the effectiveness of these interventions [13]. Tropical lakes possess distinct characteristics compared to lakes in temperate climates [14]. Nutrient cycling, sedimentation rates, and hydrological circulation patterns differ significantly between tropical and subtropical or temperate regions [15]. Therefore, research methodologies developed in temperate zones cannot be directly applied in Indonesia without appropriate adaptation. With its rich natural resources and the abundance of both modern and ancient lakes, Indonesia has the potential to take a leading role in developing paleolimnological methods tailored to tropical environments.

5 Author's perspective on future research directions

Several keywords with low occurrences and total link strength include *microenvironment*, *Miocene*, *modern analog*, *modern sediment*, *nutrient limitation*, *siliceous component*, and *Patagonian palaeoenvironments*. This indicates that these topics are still relatively underexplored research areas. The keywords *microenvironment* and *Miocene* offer opportunities for further research on microhabitat conditions related to the ecosystem and climate changes that occurred during the Miocene period using diatom analysis. The keywords *modern analog* and *modern sediments* suggest potential in paleolimnological research through approaches that compare diatom communities in modern sediments with current environmental data to improve the accuracy of past ecological reconstructions. *Nutrient limitation* can be a relevant topic for continued research on lake water productivity and water quality management, as nutrient availability plays a key role in the growth of organisms such as phytoplankton, including diatoms. In addition, the *siliceous component* also holds potential for further study in lake ecosystems, as silica availability is a critical factor influencing diatom growth.

6 Conclusion

A bibliometric and content analysis of diatom-based lake paleolimnology research over the past decade shows a stable global trend, but Indonesia's contribution is minimal, with only 5 publications (1.32%) out of 378 global documents. *The Journal of Paleolimnology* is the most productive journal in this field, publishing 60 articles. The most widely studied fields are Agricultural Sciences and Biology, as diatom studies used as indicators are more closely related to biology. Visualization of the author keyword network reveals seven interconnected clusters, with "paleolimnology" and "diatoms" are the main terms. Developed countries, particularly Canada, the U.S., and China, dominate the field, with Canadian authors being the most influential. In Indonesia, diatom-based paleolimnology research is limited to Lake Towuti, Lake Rawapening, and Lake Warna, posing a challenge for further research. However, Indonesia has vast opportunities for expanding research in both study parameters

and locations. The result of this study are expected to provide insights to strengthen paleolimnology research in lakes and ancient lakes in Indonesia and to increase international cooperation with developed countries.

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