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REVIEW

Biomonitoring of Benthic Diatoms as Indicators of Water Quality, Assessing the Present and Projecting the Future: A Review

Biomonitoreo de diatomeas bentónicas como indicadores de la calidad del agua, evaluación del presente y proyección del futuro: Una revisión

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ABSTRACT

This article delves into using benthic diatoms as bioindicators of water quality, focusing on their ability to detect eutrophication and pollution resulting from industrialization and urbanization. We systematically analyzed 1099 articles from databases such as Web of Science and Scopus using PRISMA methodology, evaluating the efficacy, role, utilities, limitations, and influence of environmental factors of diatoms. The results show variability in water quality monitoring methods, from multivariate analyses to formulas based on species abundance. We highlighted the need for adaptability and validation of specific indices such as IDP and DDI, principally due to limitations in their transregional applicability. In South America, only four countries have developed their methods for assessment using diatoms, while others still rely on international standards. This fact underlines the importance of implementing effective local policies to manage water resources. Finally, we concluded that diatoms are crucial biological indicators for monitoring aquatic ecosystems, although challenges such as complexity in taxonomic identification and lack of standardization condition their effectiveness. In addition, biogeographical and environmental factors play an essential role in the diversity of these species, being necessary for understanding and anticipating changes in aquatic environments.

Keywords: Environmental Biomarkers; Environmental Monitoring; Water Quality; Diatoms; Ecosystems.

RESUMEN

Este artículo profundiza en el uso de las diatomeas bentónicas como bioindicadores de la calidad del agua, enfocándose en su capacidad para detectar la eutrofización y la contaminación resultantes de la industrialización y urbanización. Utilizando la metodología PRISMA, se analizaron sistemáticamente 1099 artículos de bases de datos como Web of Science y Scopus, evaluando la eficacia, el papel, las utilidades, las limitaciones y la influencia de factores ambientales de las diatomeas. Los resultados muestran una variabilidad en los métodos de monitoreo de la calidad del agua, desde análisis multivariantes hasta fórmulas basadas en la abundancia de especies. Se destacó la necesidad de adaptabilidad y validación de índices específicos como el IDP y el DDI, especialmente debido a limitaciones en su aplicabilidad regional. En América del Sur, solo cuatro países han desarrollado métodos propios para la evaluación utilizando diatomeas, mientras que otros aún dependen de estándares internacionales. Esto subraya la importancia de implementar políticas locales efectivas para la gestión de los recursos hídricos. Finalmente, se concluye que las diatomeas son indicadores biológicos cruciales para el monitoreo de ecosistemas acuáticos, aunque su efectividad está condicionada por desafíos como la complejidad en la identificación taxonómica y la falta de estandarización. Además, los factores biogeográficos y ambientales juegan un papel esencial en la diversidad de estas especies, siendo clave para comprender y anticipar cambios en los ambientes acuáticos.

Palabras clave: Biomarcador Ambiental; Monitoreo Ambiental; Calidad del Agua; Diatomeas; Ecosistemas.

INTRODUCTION

Aquatic systems, which are essential in the circulation of materials and the transfer of energy, significantly influence natural ecosystems and social systems.(1) In fact, the steady increase in population and the growth of industrial and agricultural activities have caused a progressive deterioration in freshwater ecosystems, as noted by Luo et al.(2) To assess the health of these water bodies, their quality can be measured using physical, chemical, and biological indices, relying on the expertise of specialists and on governmental regulations, as highlighted by Zhao et al.(3) Since the 1970s, both the U.S. Environmental Protection Agency (EPA) and the European Union's Water Framework Directive (WFD) have extensively used fish, macroinvertebrates, and diatoms to ecologically monitor freshwater aquatic ecosystems.(4)

Numerous studies, such as those by Xue et al.(5), have found that diatom communities effectively respond to various types of pollution, making them reliable environmental indicators for assessing water quality. Based on this capability, some countries have developed their diatom indices, taking into account the community structures of these organisms and the ecological preferences of the species in specific regions.(6) Currently, there are several diatom-based indices capable of reflecting the level of organic pollution, eutrophication, or the presence of specific contaminants in bodies of water.(7)

Diatom classification systems, operating at the species level, play a crucial role in understanding the ecological health of aquatic ecosystems.(8) These classifications are meticulously organized into various strata, taking into account the specific ecological preferences of diatoms and their remarkable ability to withstand different degrees of pollution. (9) Diatoms, as unicellular microalgae and essential components of phytoplankton, act as sensitive indicators of environmental changes, particularly in bodies of water such as rivers, lakes, and oceans.(10) Their ability to adapt to varied environments, from pristine waters to those highly contaminated, enables scientists to effectively assess water quality and the presence of contaminants.(11) This classification not only highlights pollution-tolerant species but also identifies those sensitive to minimal environmental changes, providing a comprehensive view of the ecosystem's ecological dynamics. By studying these patterns and distributions, ecological health can be monitored and potential environmental impacts predicted, which is essential for the conservation of aquatic ecosystems and the sustainable management of water resources.

This study contributes to the understanding of biomonitoring of benthic diatoms as indicators of water quality by providing a comprehensive and detailed perspective on key issues such as the fundamental role of biological indicators in biomonitoring, the usefulness and limitations of diatom-based indices, and the influence of biogeographical and environmental factors on these species. This study focuses on analyzing the effectiveness of benthic diatoms as bioindicators of water quality, providing insight into their role in biomonitoring. It systematically examines their utility and limitations, as well as the influence of biogeographic and environmental factors on their performance.

METHODS

The Preferred Reporting for Systematic Reviews and Meta-Analyses (PRISMA) methodology was applied in the preparation of this article. This methodology is characterized by its systematic and explicit approach to the identification, selection, and critical evaluation of relevant research. In addition, it facilitates the collection and analysis of data from the studies included in the review.(12) This method allowed efficient identification and analysis of studies related to the critical importance of biological indicators in biomonitoring. The advantages and challenges of diatom-based indices were also explored and the impact of biogeographic and environmental factors on these species was assessed. The bibliographic exploration started in the Web of Science Core Collection databases of Clarivate Analytics and Scopus. For the first section of the search, synonyms related to biological indicators of water was adopted. The second part focused on the use of synonyms for diatom index. These terms were organized using Boolean operators. The search strategy employed to select articles relevant to this study was:

("Aquatic biomarkers" OR "Biological markers of water quality" OR "Aquatic ecological indicators" OR "Biomarkers of aquatic ecosystems" "Water health indicators" "Biological parameters of water" OR "Biological signals of water quality" OR "Biological indicators Aquatic biotic indicators") AND ("Diatom Index" OR "Diatom Score" OR "Diatom Biodiversity Index" OR "Diatom Biotic Index" OR "Diatom Assessment" OR "Diatom Measurement" OR "Diatom Diversity Index" OR "Diatom-Based Quality Index").

Search terms were specifically applied to the titles, abstracts, and keywords of the articles, all peerreviewed. In addition, no restriction was placed on the year of publication.

The review for this study was initiated in August 2021 and updated in October 2022. The initial search with the selected keywords resulted in hundreds of articles. These were analyzed in detail using the previously mentioned criteria, yielding the following results:

In the Web of Science Core Collection of Clarivate Analytics: 421 articles were identified.

In Scopus: 678 articles were found.

The search process and the results of this review are detailed in the PRISMA flowchart presented in figure 1.

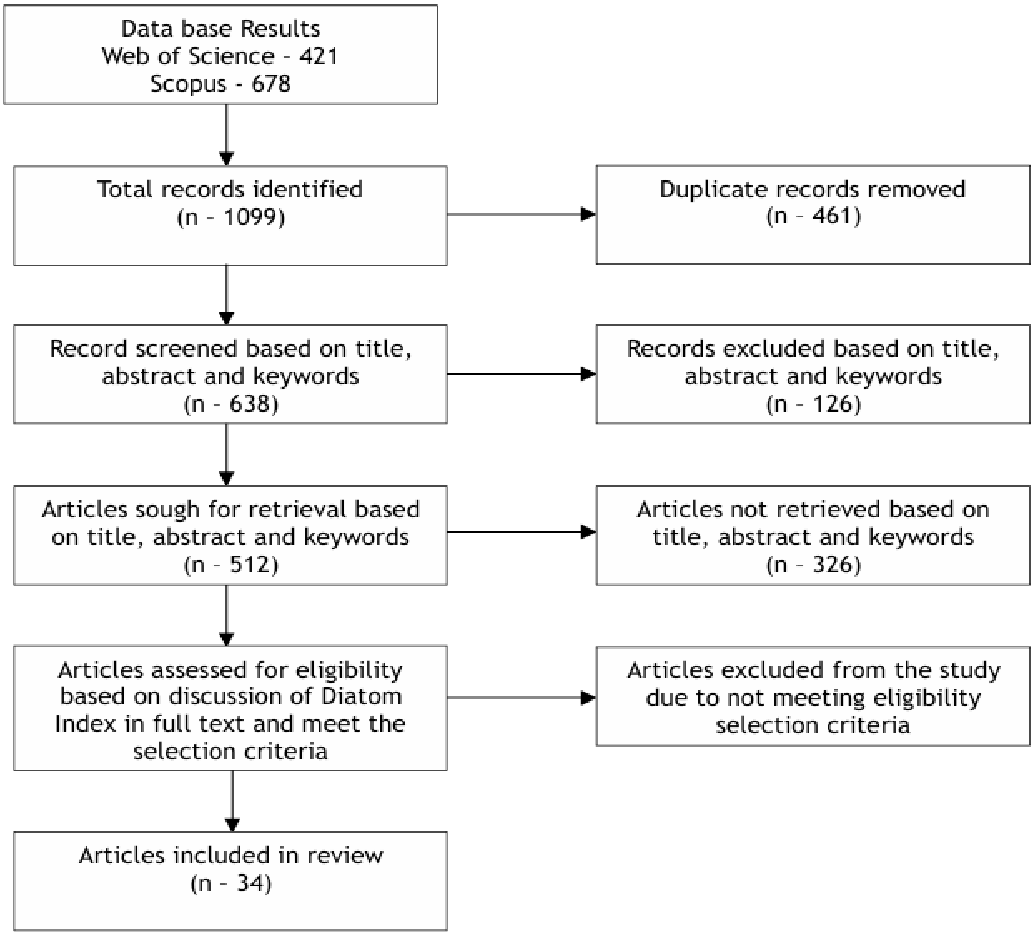

Figure 1. Systematic literature review flowchart using PRISMA

RESULTS

The following section provides a comprehensive analysis of the findings from the systematic literature review. This part focuses on the fundamental relevance of biological indicators for environmental monitoring. In addition, both the advantages and challenges associated with diatom-based indices are examined, along with an assessment of how biogeographic and environmental factors affect these species, all based on the study data collection and analysis. Thirty-four articles that met the previously defined inclusion criteria were investigated.

Water quality monitoring through biological indicators

Biomonitoring is the use of biological variables to study the environment.[13] The main task of biomonitoring is to find ideal indicators (or biomarkers) whose presence, abundance and/or behavior reflect the effects of stressors on the biota. Indicators can be used to organize biomonitoring at multiple levels, from suborganisms to populations, communities and even ecosystems.[14] The use of biological indicators such as diatoms is commonly used to capture the response of species and communities to environmental conditions such as eutrophication, acidification and organic pollution[15] or even specific stressors;[16] macroinvertebrates due to their characteristics are considered as good bioindicators because of their wide distribution, limited mobility, abundance, respond rapidly and with high sensitivity to environmental changes and stressors, as well as ease of detection, quantification and standardization;[17] Fish are suitable for a variety of methods that determine toxic effects by determining the accumulation of substances in tissues. In addition, due to their complex habitat requirements, ichthyofauna is a critical indicator of the ecological integrity of aquatic systems at various scales.[18]

Biomonitoring activities are now considered a branch of applied ecology that brings together ecological, scientific and economic interests that allow to move towards integrated water resources management.[19,20] The number of biomonitoring and assessment studies based on biological indicators has increased considerably in the last 20 years.[21] However, the demand for natural resources and consequently the degradation of ecosystems have accelerated significantly.[22] Therefore, it is important to develop cost-effective and time-saving biomonitoring and assessment strategies to evaluate ecosystem health.

Ambiguous guidelines and questionable assumptions about the effectiveness of taxonomic indicators in reflecting other ecosystem trends, together with difficulties in distinguishing between human impacts and natural changes, have led to intense debate around these indicators. In addition, the process of taxonomic identification frequently suffers from a lack of validation or a well-defined rating system.[23] Also, it is noted that the classification of diatoms at the species level can vary significantly among taxonomists, influenced by their level of expertise and the availability and updating of taxonomic keys.[24] To improve the effectiveness of taxonomic indicators in the study of ecosystems, it is imperative to address these issues by clarifying guidelines, standardizing methods, and continuously updating taxonomic keys, thus ensuring greater accuracy and reliability in ecological research.

Diatom Indices for Water Quality Assessment

Due to their advantages, diatoms are frequently used in water quality studies, because of which different methods for the development of indices have been generated. Some are based on the saprobic system that specifies that eutrophication and pollution are not the same all over the world, there must be differences in the saprobic evaluation of the same species in different regions.[25] Others on autoecological knowledge[26] which provide the basis for the development of diatom indices, which are based on their sensitivity to environmental stressors and their ecological breadth.[27] And others on community structure which is closely related to the nature of species abundance distributions.[28]

Biological indices provide objectivity and quantification, making it easier to communicate results to non-technical audiences. However, valid interpretation of index scores is generally not straightforward.[29] The drawback of these indicators, if considered as such, is that they provide an assessment of water quality that is sometimes not very meaningful. Although they are synthetic and easy to use, determining water quality as good, bad or even "average" can leave the user confused.[30] According to Stevenson et al.[31] two fundamental questions need to be answered in ecological assessments: Is there a problem and What is the cause of the problem? Understanding the meaning of these questions and how they will be posed and answered by government agencies or other scientists is important in determining how diatoms can serve as readily available tools in water quality assessment.

Several diatom-based aquatic ecosystem health assessment indices have been developed, most of which are general pollution indices, especially indicative of eutrophication and organic pollution.[20] Based on statistical methods, various diatom indices, by summarizing and quantifying the information provided by diatom assemblages, have been gradually established and implemented to assess water quality and ecological system status worldwide.[5] For this reason, an exhaustive analysis has been carried out of the different diatom indices developed globally, which are detailed in table 1.

Table 1. Comparative analysis of diatom indices used worldwide

Index name	Area / Region of application	Type of index	Sampling and sample size	Taxonomic level	Index calculation and final valuation	Main references
Diatom- based TP and TN interference indices	New Jersey/ United States	Trophic state	45 sites in 3 ecoregions with a total of 101 samples	Species	Inferred TP and TN values on a standardize d scale ranging from 0 to 100, where higher index scores indicate higher levels of nutrient enrichment.	[32]
Eutrophication/ diatom- based pollution index (EPI- D)	Marche/Italy	Trophic state	13 monitoring stations along the 88 kilometers of the Potenza River	Species	Species sensitivity is a composite index ranging from 0 to 4, while reliability scores range from 1 to 5.	[42]
Trophic Diatom Index (TDI)	Durham / England	Trophic state	70 sites that were free of significant contamination and 10 sites with high nutrient contamination	Species	The TDI value can range from 1 (very low nutrient concentrations) to 5 (very high nutrient concentrations).	[34]

Quality Index (TWQI)	Botucatu / Brazil	Trophic state	collected at 8 stations on the Pardo River and 20 stations on the Grande River.		range from 1 to 4 where values between 1,0-1,5 indicate oligotrophic conditions, 1,5-2,5 indicate β- mesotrophic conditions, 2,5-3,5 indicate α- mesotrophic conditions, and 3,5-4,0 indicate eutrophic conditions.	(43)
Pampean Diatom Index (IDP)	Pampas plains / Argentina	Organic contamination / Trophic state	A total of 164 samples of epipeelid diatoms were collected during 1995-1999 from Pampean rivers and streams.	Species	The classes are classified as 0, I, II, III and IV with the highest values representing the most contamination.	(36)
Generic index (GI)	Taiwan, specifically in the Keelung River.	Organic contamination	A total of 161 samples from 10 monitoring stations	Genre	GI values range from 1 to 5 where values between 1,0-1,5 indicate an oligosaprobic level, 1,5-3,5 indicate βmesosaprobic conditions, 3,5-5 indicate αmesosaprobic conditions	(37)
Diatom Assemblage Index (DAIpo)	Japan	Organic contamination	A total of 452 taxa from 472 samples collected.	No mention of taxonomic level	The index has values ranging from 0 to 100; the higher the index value, the greater the number of saprophytic species.	(38)
Diatom Index Artois Picardie IDAP	France, specifically the Artois Picardie basin	Organic contamination / Trophic state	A total of 45 genera and 91 species out of 480 samples collected	Species	The IDAP classifies water quality into five categories: zero pollution or low eutrophication (IDAP ≤ 16), moderate eutrophication (13,5 < IDAP < 16), moderate pollution or heavy eutrophication (11 < IDAP < 13,5), high pollution (7< IDAP <11), and very heavy pollution (IDAP < 7).	(40)
Trophic diatom index for lakes (TDIL)	Shallow lakes in Hungary	Trophic state		Species	The value of the index varies between 0 and 5 ecological values are classified: 4-5 Excellent 3 < 4 Good 2 < 3 Medium 1<2 Tolerable 0 < 1 Bad	(44)
Specific index for lakes (EPI- L)	64 Lakes of Italy	Trophic state	A total of 108 diatom samples were collected from 64 lakes in Italy.	Genre	The value of the index varies between 0 and 10 ecological values are classified: 10-9 Excellent >7 and <9 Good >5 and <7 Medium >3 and <5 Tolerable < 3 Bad	(41)
Douro Diatom Index (DDI)	Northeastern Spain	Organic contamination / Trophic state	355 samples of epilithic diatoms in the watercourses of the Duero River basin.	Species	The DDI values are: High 10,00 Good 8,50-9,99 Acceptable 7,50-8,49 Poor 6,00-7,49 Bad < 6,00	(27)

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Water quality is essentially monitored by diatoms in a variety of global contexts, with each index designed for specific geographic conditions. These indices, while pursuing analogous objectives, differ in their methodological approach, ranging from multivariate analyses to simple formulas based on diatom species or genus abundance. The transferability of an index to another geographical context is a crucial issue, and many admit methodological limitations that must be considered in its application. Although some indices, such as the IDP and DDI, have demonstrated correlations with other indices, suggesting their versatility, adaptability and validation according to the specific environment is vital to ensure their accuracy and efficacy in various scenarios. In essence, the proper selection of the index according to the context and goals is crucial for efficient water quality monitoring.

In South America only 4 countries have successfully developed their own assessment methods using diatoms as biological indicators with focus mainly on trophic status and organic pollution. The rest of the countries in the region use methods developed in countries such as the European Union and North America. This is mainly due to the lack of interest in the care of aquatic ecosystems that exists in the governments by not generating adequate policies for the management of the water resources.

Biogeographic characterization of diatoms

Because diatoms contribute to ecosystem structure and function as one of the important components at the base of the food chain in freshwater ecosystems (lakes, rivers, ponds), it is timely to assess patterns of biogeographic diversity in their communities.(45) Biogeographic patterns in diatoms are still poorly developed and largely untested, in part due to the challenge of disentangling the many direct and indirect connections between ecological processes operating at different spatial and temporal scales.(46,47)

Geographic diversity, together with diverse physiographic regions and geological substrates produce remarkable climatic and limnological variability that can be used to examine the factors structuring species composition and diversity of diatom assemblages.(45) At a broad geographic scale, factors related to historical factors, climate, landscape , aquatic connectivity, and topography are determinants of diatom distributions and may be even stronger drivers than local environmental variables.(48,49) Due to these characteristics species-specific distribution modeling emerges as an important new tool to explain and predict responses of microorganisms to large-scale environmental gradients, as these factors often override local environmental conditions in explaining species abundance and composition.

Metacommunity ecology is a recently emerging subdiscipline of ecology, where dispersal among sites is considered key to understanding biotic assemblages.(50,51) Metacommunity theory also predicts that species sorting, i.e., the filtering of species by local biotic and abiotic factors is more pronounced when dispersal rates are intermediate. Such intermediate dispersal allows species to track variation in environmental conditions among sites within a region, resulting in a relatively good match between environmental conditions and community structure.(52) Dispersion can constrain or homogenize local communities, the effects of which may not be easily distinguishable, because both can induce spatial structuring in biological data.(48) Watershed identity and its associated biogeographic and climatic aspects will show the strongest effect on variation in community structure. This is because biogeographic factors, including regional variation in climate, should be more important over large spatial extents.(53)

South American lakes and streams are effective systems for examining patterns of diatom biogeography and biodiversity for several reasons. First, they are well-defined ecosystems, many of which have persisted over long geological time scales. They are also found in a topographically diverse landscape characterized by remarkable spatial variability in climate.(54) In addition, they are characterized by a large number of topographically closed watersheds, which form hydrological networks in which biological communities remain directly and indirectly related.(55) In South America, climatic and regional factors that vary with latitude had the strongest relationships with large-scale diversity patterns,(56) indicating a significant increase in diatom species richness as a function of distinctive spatiotemporal and climatological features that exist between ecosystems rather than the characteristics of the physicochemical parameters governing the systems.

Latitudinal Gradients in Diatom Richness

The tendency of biological diversity to concentrate in the tropics, also known as the Latitudinal Diversity Gradient (LDG), is undoubtedly the best-studied and most well-known pattern in ecology.(57) Understanding the factors driving these gradients is one of the major challenges in ecological and biogeographical research.(58) Many ecological and evolutionary hypotheses have been proposed to explain the LDG. Among the evolutionary hypotheses, "Out of the Tropics" (OTT) has received considerable attention as it posits that the tropics are both a cradle and a source of biodiversity for extratropical regions.(59) It's important to recognize that, in general, studies of latitude have focused on species richness and overlooked community evenness, which is an important aspect as it measures how similar species are in abundance and allows for a full appreciation of the consequences of human impacts on aquatic ecosystems that cause extinction and/or changes in abundance

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distribution.[60]

For a long time, it has been believed that microbial organisms have an unlimited dispersal capacity,[61] making them ubiquitous and exhibiting weak or absent latitudinal diversity gradients. However, Vyverman et al.,[62] using a global dataset of freshwater diatoms, demonstrated that latitudinal gradients in the richness of local and regional genera are present and highly asymmetric between hemispheres. Latitudinal gradients can be stronger or weaker depending on the prevailing hydrographic and climatic conditions at a macroscale.[63] Therefore, these conditions should be considered as potential sources of divergence among different studies on the latitudinal diversity gradients (LDG) of diatoms.

The study conducted by Passy[64] revealed that the LDG (Latitudinal Diversity Gradient) of diatoms was not neutral, but driven by characteristics of streams and watersheds linked to resource supply, showing quadratic latitudinal gradients. It is evident that freshwater diatoms do not show a clear linear LDG observed for most of the studied taxa, but the patterns have been context-dependent and related to nutrient supply.[65] Altitudinal gradients provide excellent opportunities to study the relationships between species distribution and climatic variables.[66] Collectively, temperature and moisture can limit species richness at both ends of the gradient,[67] making altitudinal gradients a very useful natural laboratory for examining potential effects of climate changes on biodiversity patterns.[60] Therefore, it is suggested that modern diatom diversity gradients are shaped by environmental dynamics.

Variables ambientales que influyentes en la riqueza de diatomeas

Because of their response to environmental perturbations through changes in their structure and community dynamics, diatoms are of great interest as bioindicators.[68] The question of key environmental drivers of diatom community composition in lakes and streams has been extensively addressed in the diatom ecology literature in recent years.[65] Patterns of diatom richness are not clearly explained by individual or collective effects of independent variables. As explained by Liu et al.,[69] where chemical environmental variables explained 12,5 % of the species richness switching. The study by Díaz & River[70] establishes that the structure of diatom communities in the rivers studied is mainly determined by physical (32,3 %), chemical (56,4 %) and hydrological (11,3 %) variables. These significant changes in environmental variables can be influenced directly by natural factors, but mainly by anthropogenic factors.

Recent findings in freshwaters underscore the importance of simultaneously studying historical processes, drainage basin characteristics, and local environmental conditions to understand variation in species richness.[71] On a global scale, changes in climate, geology, topography, land use, ion concentrations, and trophic status are the main environmental drivers of diatom distribution in streams and rivers.[72] It is important to consider that geomorphological and hydrological features vary at different spatial and temporal scales to form environmental gradients, along which different types of diatom communities are found,[73] so species turnover is mainly driven by different environmental factors that are thrown out of balance by human activities along rivers, streams, and estuaries.

Environmental standards are complicated to relate to diatom abundance or richness, but there are environmental variables such as temperature that is an important factor in the physical environment of water bodies and gradually has a controlling effect on phytoplankton activities and their distribution. Environmental standards are complicated to relate to the abundance or richness of diatoms, but environmental variables such as temperature is an important factor in the physical environment of water bodies and gradually has a controlling effect on the activities of phytoplankton and their distribution[74,75,76,77] and also influences species seasonality.[78] Variations in water temperature strongly affect the composition and growth of the phytoplankton community.[79] high turbidity levels reduce light penetration and thus limit phytoplankton growth.[80] Other important factors such as altitude and conductivity are explained in,[81] nitrites and silicates[82] nitrates and total phosphorus[83] and pH[84] in conclusion, diatom research should focus on ecosystem processes and functional characteristics of the assemblages where the fundamental approach would be to link the evaluation of water quality with environmental variables, structure and function of ecosystems, i.e. it should be of an integral nature.

CONCLUSIONS

Diatoms are essential biological indicators in monitoring aquatic ecosystems. These organisms are valuable because of their ability to accurately reflect the effects of environmental stressors such as eutrophication, acidification and organic pollution. The effectiveness of these bioindicators is due to characteristics such as their specific distribution, limited mobility, rapid response to environmental changes, and ease of quantification. However, challenges in taxonomic identification and lack of standardization of methods highlight the need for improved guidelines and updated taxonomic keys to enhance the accuracy and reliability of ecological studies.

Diatom-based indices are valuable tools for assessing water quality and the health of aquatic ecosystems. These indices, which range from multivariate analyses to the assessment of species or genus abundance, have proven to be effective. However, their applicability may be restricted to specific geographic contexts, and transferring these indices to new contexts requires careful adaptation and validation. In addition, interpreting scores from these indices can be complex, highlighting the importance of communicating the results effectively to non-specialist audiences.

Diatom diversity and distribution are significantly influenced by a variety of biogeographic and environmental factors. Elements such as climate, topography, aquatic connectivity, and limnological variability play a crucial role in determining the biogeographic patterns of these species. Understanding these patterns is essential for interpreting the structure and function of aquatic ecosystems and for predicting diatom responses to large-scale environmental changes. Variability in geomorphological and hydrological features creates environmental gradients that affect the diversity and composition of diatom communities, underscoring the importance of integrating ecological and biogeographical approaches to diatom research.

REFERENCES

1. Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, et al. Global threats to human water security and river biodiversity. Nature. 2010;467(7315):555-61.

2. Luo Z, Zuo Q, Shao Q. A new framework for assessing river ecosystem health with consideration of human service demand. Sci Total Environ. 2018;640-641(March 2021):442-53.

3. Zhao YW, Zhou LQ, Dong BQ, Dai C. Health assessment for urban rivers based on the pressure, state and response framework—A case study of the Shiwuli River. Ecol Indic. 2019;99(April 2018):324-31.

4. Tan X, Ma P, Bunn SE, Zhang Q. Development of a benthic diatom index of biotic integrity (BD-IBI) for ecosystem health assessment of human dominant subtropical rivers, China. J Environ Manage [Internet]. 2015;151:286-94. Available from: http://dx.doi.org/10.1016/j.jenvman.2014.12.048

5. Xue H, Zheng B, Meng F, Wang Y, Zhang L, Cheng P. Assessment of aquatic ecosystem health of the wutong river based on benthic diatoms. Water (Switzerland). 2019;11(4).

6. Yu P, You Q, Pang W, Cao Y, Bi Y, Wang Q. Development of a periphytic diatom-based comprehensive diatom index for assessing the trophic status of lakes in the lower reaches of the yangtze river, China. Water (Switzerland). 2021;13(24).

7. Bassi MA, Lopez MA, Confalone L, Gaudio RM, Lombardo L, Lauritano D. Enhanced Reader.pdf. Vol. 388, Nature. 2020. p. 539-47.

8. Kalyoncu H, Şerbetci B. Applicability of Diatom-Based Water Quality Assessment Indices in Dari Stream , Isparta-. Int J Environ Earth Sci Eng. 2013;7(6):188-96.

9. Resende P, Azeiteiro U, Pereira MJ. Diatom ecological preferences in a shallow temperate estuary (Ria de Aveiro, Western Portugal). Hydrobiologia. 2005;544(1):77-88.

10. Flower RJ, Williams DM. Diatomites: Their formation, distribution and uses. Ref Modul Earth Syst Environ Sci. 2023;

11. Hubas C, Monti D, Mortillaro JM, Augagneur S, Carbon A, Duran R, et al. Chlordecone-contaminated epilithic biofilms show increased adsorption capacities. Sci Total Environ. 2022;825:153942.

12. Moher D, Liberati A, Tetzlaff J, Altman DG, Grp P. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement (Reprinted from Annals of Internal Medicine). Phys Ther. 2009;89(9):873-80.

13. Gerhardt A. Biomonitoring of polluted water : reviews on actual topics. Gerhardt A, editor. Uetikon, Zurich: Trans Tech; 2000. (Environmental research forum, v. 9).

14. Niemi GJ, McDonald ME. Application of ecological indicators. Annu Rev Ecol Evol Syst. 2004;35(Rapport 1992):89-111.

15. Passy SI, Bode RW. Diatom model affinity (DMA), a new index for water quality assessment. Hydrobiologia.

2004;524(1):241-52.

16. Vilmi A, Karjalainen SM, Hellsten S, Heino J. Bioassessment in a metacommunity context: Are diatom communities structured solely by species sorting? Ecol Indic [Internet]. 2016;62:86-94. Available from: http://dx.doi.org/10.1016/j.ecolind.2015.11.043

17. Hilty J, Merenlender A. Faunal indicator taxa selection for monitoring ecosystem health. Biol Conserv. 2000;92(2):185-97.

18. Trach Y, Chernyshev D, Biedunkova O, Moshynskyi V, Trach R, Statnyk I. Modeling of Water Quality in West Ukrainian Rivers Based on Fluctuating Asymmetry of the Fish Population. Water. 2022;1-20.

19. Stevenson J. Ecological assessments with algae: a review and synthesis. J Phycol. 2014;50(3):437-61.

20. Bere T. Challenges of diatom-based biological monitoring and assessment of streams in developing countries. Environ Sci Pollut Res. 2015;23(6):5477-86.

21. Charles DF, Kelly MG, Stevenson RJ, Poikane S, Theroux S, Zgrundo A, et al. Benthic algae assessments in the EU and the US: Striving for consistency in the face of great ecological diversity. Ecol Indic [Internet]. 2021;121(October 2020):107082. Available from: https://doi.org/10.1016/j.ecolind.2020.107082

22. Costa APT, Schneck F. Diatoms as indicators in running waters: trends of studies on biological assessment and monitoring. Environ Monit Assess [Internet]. 2022;194(10):695. Available from: https://pubmed.ncbi.nlm.nih.gov/35986195/

23. Maitland VC, Robinson CV, Porter TM, Hajibabaei M. Freshwater diatom biomonitoring through benthic kick-net metabarcoding. PLoS One. 2020;15(11 November):1-18.

24. Kahlert M, Ács É, Almeida SFP, Blanco S, Dreßler M, Ector L, et al. Quality assurance of diatom counts in Europe: towards harmonized datasets. Hydrobiologia. 2016;772(1):1-14.

25. Sládeček V. Diatoms as Indicators of Organic Pollution. Acta Hydrochim Hydrobiol. 1986;14(5):555-66.

26. Vanlandingham S. Evaluación comparativa de la calidad del agua en el río St. Joseph (Michigan e Indiana, EE. UU.) mediante tres métodos de análisis de algas. Hidrobiología. 1976;

27. Álvarez-Blanco I, Blanco S, Cejudo-Figueiras C, Bécares E. The Duero Diatom Index (DDI) for river water quality assessment in NW Spain: Design and validation. Environ Monit Assess. 2013;185(1):969-81.

28. Vam Dam H. On the use of measures of structure and diversity in applied diatom ecology. Hydrobiol Bull [Internet]. 1982;16(2):288. Available from: http://eprints.uanl.mx/5481/1/1020149995.PDF

29. Chessman BC, Townsend SA. Differing effects of catchment land use on water chemistry explain contrasting behaviour of a diatom index in tropical northern and temperate southern Australia. Ecol Indic. 2010;10(3):620-6.

30. Ab N. Débits minima, Débit biologiques, Débits objectifs d'étiage, Synthèse méthodologique et proposition d'harmonisation pour les cours d'eau de tête de bassin. L'eau en Mont Fiche action. 2010;1-61.

31. Stevenson RJ, Pan Y, Manoylov KM, Parker CA, Larsen DP, Herlihy AT. Development of diatom indicators of ecological conditions for streams of the western US. J North Am Benthol Soc. 2008;27(4):1000-16.

32. Ponader KC, Charles DF, Belton TJ. Diatom-based TP and TN inference models and indices for monitoring nutrient enrichment of New Jersey streams. Ecol Indic. 2007;7(1):79-93.

33. Dell'uomo A, Torrisi M. The Eutrophication/Pollution Index-Diatom based (EPI-D) and three new related indices for monitoring rivers: The case study of the river Potenza (the Marches, Italy). Plant Biosyst - An Int J Deal with all Asp Plant Biol [Internet]. 2011 Jun [cited 2023 Sep 29];145(2):331-41. Available from: https://www.tandfonline.com/doi/abs/10.1080/11263504.2011.569347

34. Kelly MG, Whitton BA. The Trophic Diatom Index: a new index for monitoring eutrophication in rivers. J Appl Phycol [Internet]. 1995;7(4):433–44. Available from: https://link.springer.com/article/10.1007/BF00003802

35. Lobo EA, Schuch M, Heinrich CG, da Costa A Ben, Düpont A, Wetzel CE, et al. Development of the Trophic Water Quality Index (TWQI) for subtropical temperate Brazilian lotic systems. Environ Monit Assess [Internet]. 2015;187(6):1–13. Available from: https://link.springer.com/article/10.1007/s10661-015-4586-3

36. Gómez N, Licursi M. The Pampean Diatom Index (IDP) for assessment of rivers and streams in The Pampean Diatom Index (IDP) for assessment of rivers and streams in Argentina. 2001;(June).

37. Wu JT. A generic index of diatom assemblages as bioindicator of pollution in the Keelung River of Taiwan. Hydrobiologia [Internet]. 1999;397(0):79–87. Available from: https://link.springer.com/article/10.1023/A:1003694414751

38. Watanabe T, Asai K, Houki A. Numerical estimation to organic pollution of flowing water by using the epilithic diatom assemblage ----- diatom assemblage index (DAIpo) ----. Sci Total Environ. 1986 Nov 1;55(C):209–18.

39. Zelinka M, Marvan P. Zur Präzisierung der biologischen Klassifikation der Reinheit fliessender Gewässer. Archiv für Hydrobiologie; 1961.

40. Prygiel J, Leveque L, Iserentant R. Un nouvel Indice Diatomique Pratique pour l'évaluation de la qualité des eaux en réseau de surveillance. Rev des Sci l'eau / J Water Sci [Internet]. 1996 [cited 2023 Oct 6];9(1):97–113. Available from: https://id.erudit.org/iderudit/705244ar

41. Marchetto A, Sforzi T. Using benthic diatoms for estimating lake ecological quality: Comparing different taxonomic resolution. Adv Oceanogr Limnol [Internet]. 2018 Jul 10 [cited 2023 Oct 9];9(1):1–9. Available from: https://www.pagepressjournals.org/index.php/aiol/article/view/7389

42. Dell'uomo A, Torrisi M. The Eutrophication/Pollution Index-Diatom based (EPI-D) and three new related indices for monitoring rivers: The case study of the river Potenza (the Marches, Italy). Plant Biosyst - An Int J Deal with all Asp Plant Biol [Internet]. 2011;145(2):331–41. Available from: https://www.tandfonline.com/doi/abs/10.1080/11263504.2011.569347

43. Lobo EA, Schuch M, Heinrich CG, da Costa A Ben, Düpont A, Wetzel CE, et al. Development of the Trophic Water Quality Index (TWQI) for subtropical temperate Brazilian lotic systems. Environ Monit Assess. 2015;187(6).

44. Stenger-Kovács C, Buczkó K, Hajnal É, Padisák J. Epiphytic, littoral diatoms as bioindicators of shallow lake trophic status: Trophic Diatom Index for Lakes (TDIL) developed in Hungary. Hydrobiologia. 2007;589(1):141–54.

45. Nascimento J, Sousa C, Morales MJ, Arminini A, Arroyo-Pérez, Yohana W, et al. Tropical and Subtropical South America: A Study of Community Turnover Across Environmental Gradients. Rull V, Carnaval A, editors. Barcelona: Springer Nature Switzerland AG.; 2020. 71–83 p.

46. Antonelli A, Nylander JAA, Persson C, Sanmartín I. Tracing the impact of the Andean uplift on Neotropical plant evolution. Proc Natl Acad Sci U S A. 2009;106(24):9749–54.

47. Luebert F, Weigend M. Phylogenetic insights into Andean plant diversification. Front Ecol Evol. 2014;2(JUN).

48. Heino J, Soininen J, Alahuhta J, Lappalainen J, Virtanen R. Metacommunity ecology meets biogeography: effects of geographical region, spatial dynamics and environmental filtering on community structure in aquatic organisms. Oecologia. 2017;183(1):121–37.

49. Pajunen V, Luoto M, Soininen J. Climate is an important driver for stream diatom distributions. Glob Ecol Biogeogr. 2016;25(2):198–206.

50. Jocque M, Field R, Brendonck L, De Meester L. Climatic control of dispersal-ecological specialization

trade-offs: A metacommunity process at the heart of the latitudinal diversity gradient? Glob Ecol Biogeogr. 2010;19(2):244–52.

51. Baselga A. Partitioning the turnover and nestedness components of beta diversity. Glob Ecol Biogeogr. 2010;19(1):134–43.

52. Leibold MA, Holyoak M, Mouquet N, Amarasekare P, Chase JM, Hoopes MF, et al. The metacommunity concept: A framework for multi-scale community ecology. Ecol Lett. 2004;7(7):601–13.

53. Viana DS, Figuerola J, Schwenk K, Manca M, Hobæk A, Mjelde M, et al. Assembly mechanisms determining high species turnover in aquatic communities over regional and continental scales. Ecography (Cop). 2016;39(3):281–8.

54. Baker PA, Fritz SC. Nature and causes of Quaternary climate variation of tropical South America. Quat Sci Rev. 2015;124:31–47.

55. Särkinen T, Pennington RT, Lavin M, Simon MF, Hughes CE. Evolutionary islands in the Andes: Persistence and isolation explain high endemism in Andean dry tropical forests. J Biogeogr. 2012;39(5):884–900.

56. Benito X, Fritz SC, Steinitz-Kannan M, Tapia PM, Kelly MA, Lowell T V. Geo-climatic factors drive diatom community distribution in tropical South American freshwaters. J Ecol. 2018;106(4):1660–72.

57. Hawkins B. Ecology 's oldest pattern ? Trends Ecol Evol. 2001;16(8):5347.

58. Taxböck L, Karger DN, Kessler M, Spitale D, Cantonati M. Diatom species richness in Swiss springs increases with habitat complexity and elevation. Water (Switzerland). 2020;12(2):1–15.

59. Raja NB, Kiessling W. Out of the extratropics: The evolution of the latitudinal diversity gradient of Cenozoic marine plankton. Proc R Soc B Biol Sci. 2021;288(1950).

60. Wang J, Meier S, Soininen J, Casamayor EO, Pan F, Tang X, et al. Regional and global elevational patterns of microbial species richness and evenness. Ecography (Cop). 2017;40(3):393–402.

61. Cavicchioli R, Bakken L, Baylis M, Foreman C, Karl D, Koskella B, et al. Scientists' warning to humanity: microorganisms and climate change. Nat Rev Microbiol. 2019;17:569–86.

62. Vyverman W, Verleyen E, Sabbe K, Vanhoutte K, Sterken M, Hodgson DA, et al. Historical processes constrain patterns in global diatom diversity. Ecology. 2007;88(8):1924–31.

63. Olguín HF, Alder VA, Puig A, Boltovskoy D. Latitudinal diversity patterns of diatoms in the Southwestern Atlantic and Antarctic waters. J Plankton Res. 2015;37(4):659–65.

64. Passy SI. A distinct latitudinal gradient of diatom diversity is linked to resource supply. Ecology. 2010;91(1):36–41.

65. Soininen J, Teittinen A. Fifteen important questions in the spatial ecology of diatoms. Freshw Biol. 2019;64(11):2071–83.

66. Gremmen NJM, Van De Vijver B, Frenot Y, Lebouvier M. Distribution of moss-inhabiting diatoms along an altitudinal gradient at sub-Antarctic Îles Kerguelen. Antarct Sci. 2007;19(1):17–24.

67. Kluge J, Kessler M, Dunn RR. What drives elevational patterns of diversity? A test of geometric constraints, climate and species pool effects for pteridophytes on an elevational gradient in Costa Rica. Glob Ecol Biogeogr. 2006;15(4):358–71.

68. Hering D, Johnson RK, Kramm S, Schmutz S, Szoszkiewicz K, Verdonschot PFM. Assessment of European streams with diatoms, macrophytes, macroinvertebrates and fish: A comparative metric-based analysis of organism response to stress. Freshw Biol. 2006;51(9):1757–85.

69. Liu Y, Fu J, Cheng D, Lin Q, Su P, Wang X, et al. The spatial pattern of periphytic algae communities

and its corresponding mechanism to environmental variables in the Weihe River Basin, China. Hydrol Res. 2020;51(5):1036-47.

70. Díaz C, Rivera C. Diatomeas De Pequeños Ríos Andinos Y Su Utilización Como Indicadoras De Condiciones Ambientales. Caldasia. 2004;26(2).

71. Zhang J, Guo L, Huang T, Zhang D, Deng Z, Liu L, et al. Hydro-environmental response to the inter-basin water resource development in the middle and lower Han River, China. Hydrol Res. 2021;00(0):1-14.

72. Soininen J. Environmental and spatial control of freshwater diatoms—a review. Diatom Res. 2007;22(2):473-90.

73. Vélez-Agudelo C, Espinosa M, Fayó R, Isla F. Modern diatoms from a temperate river in South America: the Colorado River (North Patagonia, Argentina). Diatom Res. 2017;32(2):133-52.

74. Liu C, Liu L, Shen H. Seasonal variations of phytoplankton community structure in relation to physico-chemical factors in Lake Baiyangdian, China. Procedia Environ Sci. 2010;2:1622-31.

75. Abdelmongy A, El-Moselhy K. Seasonal Variations of the Physical and Chemical Properties of Seawater at the Northern Red Sea, Egypt. Open J Ocean Coast Sci. 2015;2(1):1-17.

76. Sabater-Liesa L, Ginebreda A, Barceló D. Shifts of environmental and phytoplankton variables in a regulated river: A spatial-driven analysis. Sci Total Environ. 2018;642:968-78.

77. Yang M, Xia J, Cai W, Zhou Z, Yang L, Zhu X, et al. Seasonal and spatial distributions of morpho-functional phytoplankton groups and the role of environmental factors in a subtropical river-type reservoir. Water Sci Technol. 2020;82(11):2316-30.

78. Rivera J, Pinilla G, Rangel O. Assemblage of aquatic macroinvertebrates and its relationship whit physical and chemical variables in the wetland Jaboque-Colombia. Caldasia. 2013;35(2):389-408.

79. Deyab M, El-Adl M, Ward F, Omar E. Trophic status, phytoplankton diversity, and water quality at Kafr El-Shinawy drinking-water treatment plant, Damietta. Aqua Water Infrastructure, Ecosyst Soc. 2021;70(3):342-60.

80. Deyab M, Ahmed SA, Ward F. Seasonal patterns in phytoplankton growth, composition, and predominance in relation to water quality at Northwest El-Manzala Lake, Egypt. Water Sci Technol Water Supply. 2020;20(8):3341-57.

81. Cantonati M, Gerecke R, Bertuzzi E. Springs of the Alps - Sensitive ecosystems to environmental change: From biodiversity assessments to long-term studies. Vol. 562, Hydrobiologia. 2006. 59-96 p.

82. Salcedo M, Catañeda M, Langos F, Sosa C, Landeros C, Itzel G. Influence of physicochemical parameters on phytoplankton distribution in the lagoon system of Mandinga, Mexico. Rev bio ciencias. 2019;6:1-25.

83. Cantonati M, Spitale D. The role of environmental variables in structuring epiphytic and epilithic diatom assemblages in springs and streams of the Dolomiti Bellunesi National Park (south-eastern Alps). Fundam Appl Limnol. 2009;174(2):117-33.

84. Bellinger B, Sigee D. Freshwater Algae: Identification and Use As Bioindicators. J Phycol. 2010;47(2):436-8.

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