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Phytoplankton in lake water quality assessment: a review of scientific literature based on bibliometric and network techniques

Fitoplâncton na avaliação da qualidade da água de lagos: uma revisão da literatura científica baseada em técnicas bibliométricas e de rede

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Abstract: Aim: This study aims to analyze the scientific literature on phytoplankton in assessing lake water quality, based on bibliometric and network techniques. **Methods:** PRISMA criteria were adopted to produce reliable results. The Scopus and Web of Science databases were consulted to retrieve the documents to be studied. The number of publications, citations and bibliographic coupling were techniques used to identify relevant journals, countries, authors, and articles. The conceptual evolution was analyzed by keywords co-occurrence and thematic mapping. **Results:** Based on 2429 documents selected from the 1973-2023 annual period, the main results indicated 519 journals, 6450 authors, 54907 references, and 4844 keyword authors, among others. The annual growth index was 10.27%, reflecting the upward trend at the time. Erick Jeppesen resulted as the top influential author, China leaded in publications and collaborations with The United States of America. Hydrobiologia was the top journal. Top influential articles content theme related to cyanobacterial blooms. According to the results of the analysis of the conceptual framework, phytoplankton, water quality, eutrophication, and cyanobacteria were the most relevant themes. Furthermore, the trending topics were mainly climate change and degradation. **Conclusions:** This comprehensive analysis allowed us to interpret the development of research related to the subject of assessing lake water quality.

Keywords: bibliometric analysis; eutrophication; lake ecosystem; network techniques; phytoplankton; water quality.

Resumo: Objetivo: Este estudo teve como objetivo a análise da literatura científica sobre o fitoplâncton na avaliação da qualidade da água de lagos, baseada em técnicas bibliométricas e de rede. **Métodos:** Critérios PRISMA foram adotados para produzir resultados confiáveis. As bases de dados *Scopus* e *Web of Science* foram consultadas para recuperação dos documentos a serem estudados. O número de publicações, citações e acoplamento bibliográfico foram técnicas utilizadas para identificar periódicos, países, autores e artigos relevantes. A evolução conceitual foi analisada por meio de coocorrência de palavras-chave e mapeamento temático. **Resultados:** Com base em 2429 documentos selecionados do período anual 1973-2023, os principais resultados indicaram 519 periódicos, 6450 autores, 54907 referências e 4844 autores de palavras-chave, entre outros. O índice de crescimento anual foi de 10.27%, refletindo a tendência ascendente da época. Erick Jeppesen foi apontado como o autor mais influente, a China liderou em publicações e colaborações com os Estados Unidos. Hydrobiologia foi o principal periódico. O tema de conteúdo dos artigos mais influentes foi relacionado à proliferação de cianobactérias. De acordo com os resultados da análise da estrutura conceitual, o fitoplâncton, a qualidade da água, a eutrofização e as cianobactérias foram os temas mais relevantes. Além disso, os tópicos em alta foram principalmente as alterações climáticas e a degradação. **Conclusões:** Esta análise abrangente permitiu interpretar o desenvolvimento de pesquisas relacionadas ao tema do estudo.

Palavras-chave: análise bibliométrica; eutrofização; ecossistema lacustre; técnicas de rede; fitoplâncton; qualidade da água.

1. Introduction

Lakes are important landscape units where eutrophication is the most common degradation factor (Smith, 2003; Paerl, 2018; Vinçon-Leite & Casenave, 2019). The process is associated with anthropic pressures where agricultural waste and runoff, industrial and/or domestic/urban sewage, and others that mainly modify water quality (Lin et al., 2021), reduce the natural ability to maintain a good state of health, with negative effects on the food web (Florescu et al., 2022), cause high phytoplankton proliferation (Huisman et al., 2018) with the disappearance of submerged plants (Chao et al., 2022) and the death of wildlife from anoxia (Kragh et al., 2020).

Phytoplankton play an essential role in introducing energy into aquatic ecosystems (Florescu et al., 2022). Their growth is related to the cycles of nutrients such as phosphorous and nitrogen (Abell et al., 2010). The role of the phytoplankton in lakes as a sensitive ecological indicator of water quality is widely recognized (e.g., Yang et al., 2012; Thackeray et al., 2013), highlighting in many studies that analyze the biomass, composition, and species diversity in assessing water quality (e.g., Dembowska et al., 2015; Alcocer et al., 2022). A preliminary review on the global perspective shows the increase of research on the topic (Liu et al., 2017).

Water quality assessment methods based on bioindicators are being developed (e.g., Dufrêne & Legendre, 1997; Birk et al., 2012; Lobo et al., 2016). Among them, those concerning phytoplankton (Kolada et al., 2016; Yusuf, 2020) constitute an alternative to traditional methods, such as direct measurements of physical and chemical parameters (Shrestha & Kazama, 2007), or indirect with the application of technology such as the use of remote sensing (Dörnhöfer et al., 2018), wich is used by the scientific community for its ability to measure transparency, temperature, water level, chlorophyll, phytoplankton and cyanobacteria on spatial scale (Amorim & Moura, 2021).

Academic knowledge is expanding globally at an accelerated pace (Mahi et al., 2021). Thus, the bibliometric method is a technique highly accepted by the scientific community to analyze the quality, productivity, and evolution of different areas of knowledge (Rodríguez-Bolívar et al., 2018). The purpose of applying this method is to show researchers valuable information about research progress and future trends (Linnenluecke et al., 2019). Mapping the scientific literature is necessary to know the natural development of science, which is highly organized and observable in citation patterns among scientists and journals (Adler & Sarstedt, 2021). Thus, qualitative and quantitative aspects of publications indexed by databases are important components in the bibliometrics method to determine collaborations between countries or institutions, co-authorship, co-occurring categories, and keywords (Liu et al., 2019).

In this context, this research aimed to analyze the scientific literature about the current state of intellectual structure and emerging trends on the phytoplankton in lake water quality assessment (PLWQA), through the bibliometric method. Currently, there are different methodologies to assess water quality (Uddin et al., 2021), but this article focuses on: What is known about the use of the phytoplankton in the evaluation of water quality in lakes? A question that can be resolved with the development of the following premises: How behaves the productivity of scientific literature? What are the most influential articles? How is the citation flow between articles? And what are the main themes and their conceptual evolution?

2. Material and Methods

2.1. Research strategy

Bibliometric analysis is used to collect information about a specific area of research (Secinaro et al., 2021). The method is reproducible and minimizes intrinsic subjectivity (Corsini et al., 2019), systematizes information acquired in databases and converts it into understandable information related to the knowledge of a study area (Mahi et al., 2021). Bibliometric analysis is characterized by the analysis of performance and science mapping, the first, related to the productivity of research constituents, and the second, on the relationships between research constituents (Donthu et al., 2021), aspects developed in this article. Finally, we follow the PRISMA protocols to work in a standardized process (Maier, 2022). Figure 1 shows the selection process of articles for this research.

2.2. Inclusion criteria

Three aspects were considered to decide which studies to include in this review: limits (databases), strings (search terms), period and search criteria (Dada, 2018). First, the dataset was obtained from Scopus and Science Citation Index Expanded on the Web of Science Core Collection databases. These platforms provide scientific literature with acceptable quantity and high quality (Md Khudzari et al., 2018). Second, the following search terms were used: 'Phytoplankton', 'water quality', 'lake', 'river', 'reservoir' were used. 'OR', 'AND' and 'AND NOT' were Boolean operators used to relate terms. Thus, in Scopus database the string: "water quality" AND lake* AND phytoplankton AND NOT (river* or reservoir*") was used. Whereas in WOS database it was the string: (TS = (water quality) AND TS = (lake*) AND TS = (phytoplankton) NOT TS = (river* or reservoir) AND (DT = (article and review) AND (LA = (English)) were used. Some terms have quotation marks (") or asterisk (*) for efficient searching. Third, considered period was 1973 to 2023, to have a complete view of the development of the studied topic. Fourth, regarding the search criteria: "topic" was used in WOS and "article title, abstract and keywords" was used in Scopus (Wang et al., 2021). The information was retrieved on April 18, 2024. In addition, original records were extracted, including the publication type, title, keywords, abstract, author information, year, institution, volume, cited references, among others.

2.3. Exclusion criteria

In the process of selecting scientific literature, the considered parameters were: type of article, language and duplicated documents were the parameters considered (Vrontis & Christofi, 2021). First, regarding the good practices used in the reviews, the search prioritized peer-reviewed articles (Ho & Ranasinghe, 2022), which contained

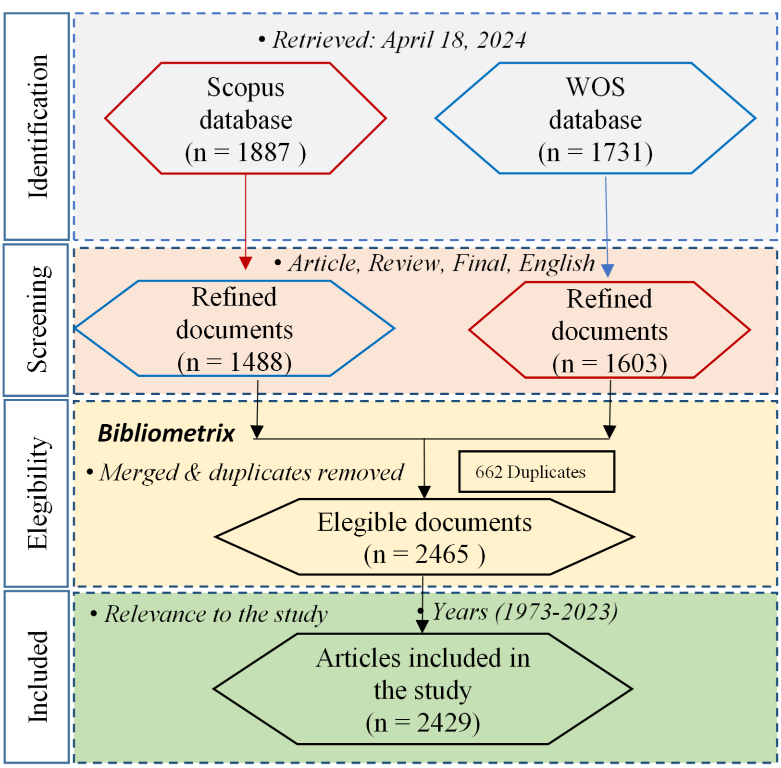

Figure 1. PRISMA document selection flowchart. Stages of the article selection process (labels in the left vertical margin), and quantitative flow of selected articles according to the stage of the selection process and exclusion criteria (labels in the right vertical margin).

complete scientific information (methods, results, discussions, and conclusions). Therefore, book chapters, conference paper, conference review, editorial letter, errata, note and data article were excluded (Vrontis & Christofi, 2021). Second, only articles published in "English" (Niu et al., 2021) was selected, as it is the most representative language in scientific journals and the scientific community around the world (Nguyen et al., 2018). Articles in another language were excluded. Third, duplicated articles were removed for correct quantification of the results (Vrontis & Christofi, 2021). Fourth, inappropriate publications (not related to the study topic) were excluded. Finally, records without access to the full text were excluded as they did not allow content evaluation (Moher et al., 2009).

2.4. Data analysis

The bibliometric indicators used were: (1) number of publications to identify the main authors, countries, journals (Adegoriola et al., 2021), complementary in journals was consulted Scimago Journal Rank to compare h index, (2) citation analysis (top cited and referenced articles) was used to analyze bibliometric information, as it is considered an indicator of scientific quality (Frandsen & Rousseau, 2005), impact and influence (Ellegaard & Wallin, 2015); total citation (TC) were considered in the analysis (Agbo et al., 2021), (3) bibliographic coupling, an important science mapping techniques (Zupic & Čater, 2015); (4) keywords analysis, to identify the central fields in the study area (Zupic & Čater, 2015) and their subfield links (Feng et al., 2017); and (5) Trend thematic of keywords was explored to know the conceptual tendencies (Della Corte et al., 2019). The analysis is based on the number of articles where the keywords occur together. In the process, a thesaurus file was used to merge similar keywords (e.g., "algal bloom" and "bloom"). The clustering technique was used to create a bibliometric network where the weight of a node reveals the occurrences of the corresponding keyword (Waltman et al., 2010).

Coupling analysis is a powerful technique to recognize research flows (Khan et al., 2022). Thus, based on results obtained from Bibliometrix Package in R (Aria & Cuccurullo, 2017), two clusters were identified in PLWQA, where each cluster (differenced by colors) corresponded to a spatial group. This analysis was applied to the fifty most relevant articles (according of the citation score). Two main groups were identified with coupling analysis, the red and blue cluster.

2.5. Tools

R-Tool Bibliometrix package is a powerful tool for performing comprehensive science mapping analysis, highlighting that the scientific community has embraced the processing and analysis of scientific information using Bibliometrix (Aria & Cuccurullo, 2017). First, this tool was used to convert data recovered in "bib" format of Scopus and Web of Science (WOS) scientific data bases to "csv" standard format for working in R-Tool Bibliometrix; second, to determine: (1) a summarize of bibliometric information, (2) the annual production of articles, (3) three fields plot with relationship of top 10 authors, countries and journals (h-index for each journal was included consulting Scimago database), according to publication number, (4) top cited articles, according to number citations, (5) a bibliographic coupling, i.e. a network technique considering 50 top articles were considered according to citation numbers, (6) a co-keyword analysis, i.e., a network technique constructed with 50 author keywords with more co-occurrences, and (7) a trend topic, i.e., a co-keyword analysis considering the period 2019-2023, with a minimum of 3 co-occurrences and 8 author keywords per year.

Complementary, the bibliographic information was recovered in (1) "ris" format for to use in Mendeley reference manager thus to locate and cite articles, and (2) "txt" format for internal analysis with Histcite software to consult articles, this ultimate is a versatile and powerful tool used to quantify scientific literature metrics (Liu & Avello, 2021).

Coupling analysis, a powerful technique for recognizing research flows (Khan et al., 2022), was performed with the Bibliometrix package in R (using the strength of association method), and was configured to display all fifty most relevant articles according to the association score.

The analyzes the co-occurrence of authors' keywords, based on data obtained from Scopus and WOS, were represented graphically and show nodes associated with the frequency of each keyword and colors that provide a preview of keyword matches (Kumar et al., 2021).

3. Results

3.1. Bibliometric indicators

The global analysis of documents written in the PLWQA (Table 1), based on 2429 scientific documents (sample), allowed the identification of

519 journals, 6450 authors, 7983 keywords plus, 4844 author keywords, and 54907 references. The average citations per document was 32 and 4 co-authors per document.

3.2. Publications and trend on PLWQA

Annual productivity represented in number of publications (NP) in PLWQA increased dramatically over time (Figure 2). In the period from 1973 to 2007, the NP did not exceed fifty, but the dynamic experienced a progressive increase since 2007 (NP > 50), showed an intensification in 2015 (NP ≥ 100) and reached a peak in 2022 (NP > 1505). The average annual growth rate during the period 1973-2023 was 10.27%.

Table 1. Summary of bibliometric indicators of publication in PLWQA.

Description	Results
Documents	2429
Sources (Journals)	519
Keywords Plus (ID)	7983
Author Keywords (DE)	4844
Years	1973-2023
Average citations per documents	32
Authors	6450
Average years from publication	13
Authors per Document	4
Average citations per year per doc	3
References	54907
Average co-Authors per document	4

Source: Bibliometrix Package in R (Aria & Cuccurullo, 2017).

3.3. Relevant authors, countries and journals

Sankey diagrams (or three fields plot) are used to compare relationships in various networks, which generally represent associations, and their transition with quantitative details (Kumar et al., 2021). Thus, Figure 3 shows the relationship between the top 10 representative authors, countries and journals (based on NP and h index). Erick Jeppesen (191 publications), Yunlin Zhang (185 publications), and Yunmei Li (129 publications) were the most relevant authors. On the other hand, China (802 publications), USA (499 publications) and Canada (213 publications) represented the most productive countries. With respect to sources, Hydrobiologia (276 publications), Journal of Great Lakes Research (263 publications), and Science of the Total Environment (195 publications) were the journals with the highest NP on the topic of study. The h-index showed that Water Research (376), Science of the Total Environment (353) and Ecological Indicators (183) were the three journals with more scientific impact. According to results, E. Jeppesen, and Y. Zhang are researching from China and works primarily with the journal Water and secondarily with Science of the Total Environment**.** Thus, articles from China are hardly published in Science of the Total Environment, Water and Hydrobiologia. Meanwhile, USA, and Canada researchers favored the Journal of Great Lakes Research. The Water Research and Science of the Total Environment were the top journal according of the h-index, with values of 376 and 353, respectively.

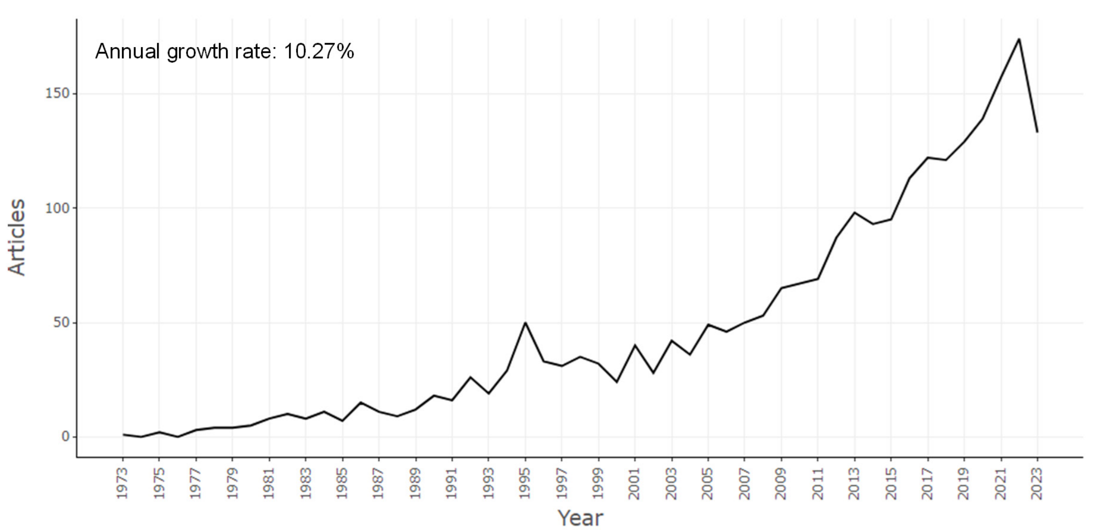

Figure 2. Annual productivity and publication trend from 1973-2023 (Source: Bibliometrix Package in R, Aria & Cuccurullo (2017).

3.4. Influential publications

The topics in the most influential articles (Table 2) were centered in cyanobacterial blooms, climate change, nutrients and control (Paerl & Paul, 2012; Paerl et al., 2016; Xu et al., 2015; Huisman et al., 2018), eutrophication (Smith & Schindler, 2009), sediments, phosphorus, nitrogen, and phytoplankton (Sondergaard et al., 2003; Xu et al., 2010; Wu et al., 2017; Ho et al., 2019).

The analysis of the most influential referenced articles (Table 3) had focus in alternative equilibria of lakes (Scheffer et al., 1993), trophic state index (Carlson, 1977), responses of lakes to nutrients (Jeppesen et al., 2005), algal blooms (Paerl & Huisman, 2008) and functional classification of freshwater phytoplankton (Reynolds et al., 2002).

3.5. The bibliographic coupling analysis

This analysis displayed two important cluster (Figure 4). The blue cluster articles, developed knowledge on 'cyanobacteria' and 'harmful blooms' (Huisman et al., 2018), 'internal drivers' (Isles et al., 2015), 'cyanotoxins' and 'environmental drivers' (Chaffin et al., 2019), 'climate change' (Paerl & Paul, 2012), 'extreme events' and 'nutrient enrichment' (Richardson et al., 2019), 'prediction' for algae (Beal et al., 2023), 'nitrogen', 'cyanobacteria' and 'climate change' (Doubek et al.,

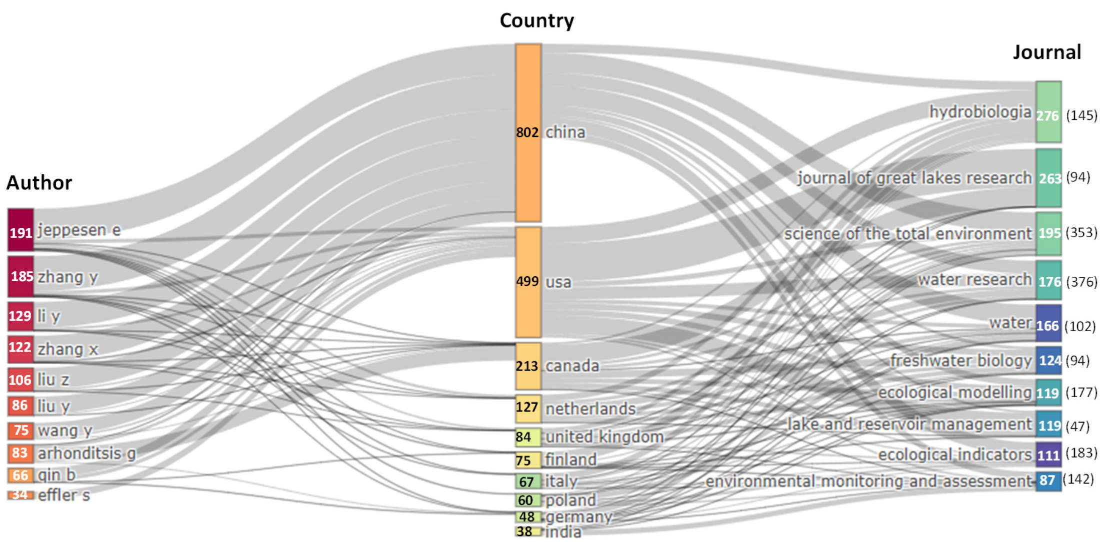

Figure 3. Sankey diagram of the top 10 authors, countries, journals and relationships. Numbers in the box indicate publications and parenthesis numbers indicate the h index for journals (Source: Bibliometrix Package in R, Aria & Cuccurullo (2017).

Table 2. The 10 most cited articles.

R	Article	Topic	TC	TCY
1	Huisman et al. (2018)	Cyanobacterial blooms	1480	211
2	Smith & Schindler (2009)	Eutrophication science	1363	85
3	Paerl & Paul (2012)	Climate change and expansion of harmful cyanobacteria	1139	88
4	Sondergaard et al. (2003)	Sediment and phosphorus in shallow lakes	1127	51
5	Xu et al. (2010)	Nitrogen, phosphorus & phytoplankton growth in eutrophic Lake	736	49
6	Ho et al. (2019)	Global increase of lake phytoplankton blooms since the 1980s	636	106
7	Jeppesen et al. (2009)	Climate change, runoff, phosphorus and lake ecological state	450	28
8	Paerl et al. (2016)	Cyanobacterial harmful algal blooms, climate and anthropogenic nutrients	406	45
9	Xu et al. (2015)	Nutrients, control harmful cyanobacterial blooms	344	34
10	Padisák et al. (2006)	Ecological status and phytoplankton assemblage index	321	17

Source: Bibliometrix Package in R (Aria & Cuccurullo, 2017). Notation in the table. R: ranking, TC: total citation, TCY: total citations per year.

Table 3. Top 10 referenced articles.

R	Cited reference	Topic	Rec
1	Scheffer et al. (1993)	Alternative equilibria in shallow lakes	141
2	Carlson (1977)	A trophic state index for lakes	125
3	Jeppesen et al. (2005)	Lake responses to reduced nutrient loading	103
4	Paerl & Huisman (2008)	Blooms Like It Hot	96
5	Reynolds et al. (2002)	Functional classification of the freshwater phytoplankton	77
6	Schindler (1977)	Evolution of Phosphorus Limitation in Lakes	73
7	O'Neil et al. (2012)	Harmful cyanobacteria blooms, eutrophication & climate change	59
8	Schindler et al. (2008)	Eutrophication, reducing nitrogen & lakes	59
9	Conley et al. (2009)	Controlling Eutrophication: Nitrogen and Phosphorus	57
10	Kosten et al. (2012)	Warmer climates boost cyanobacterial dominance in shallow lakes	51

Source: Bibliometrix Package in R (Aria & Cuccurullo, 2017). Notation in the table. R: ranking, Rec: recordings into analyzed database.

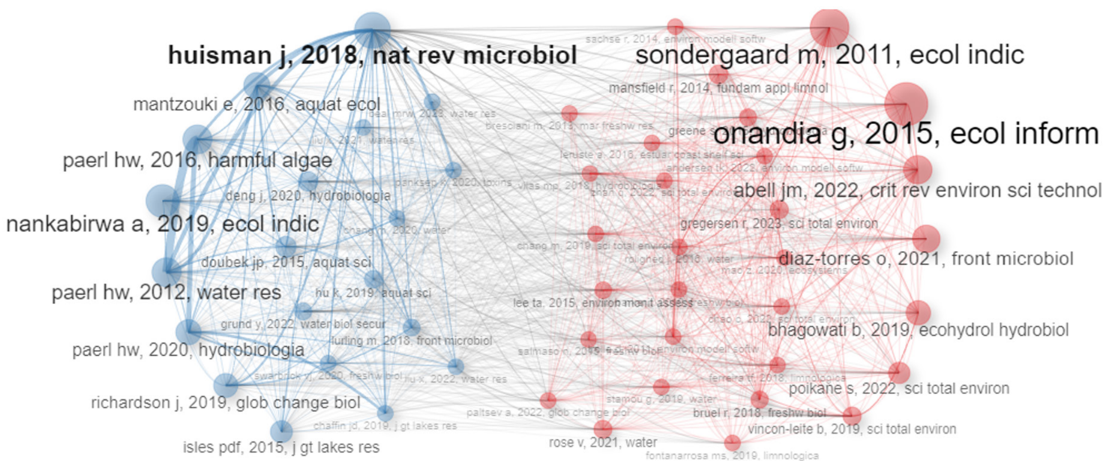

Figure 4. Bibliographic coupling with association strength method (Source: Bibliometrix Package in R, Aria & Cuccurullo (2017). The nodes represent the bibliography and their size varies according to the number of times it is cited in the data, and the colored clusters show the association or affinity according to the study of the subtopic.

2015; Deng et al., 2020), 'phosphorus' and 'phytoplankton' (Grund et al., 2022), 'control' and 'management' (Mantzouki et al., 2016), and 'mitigation' (Paerl et al., 2016).

The red cluster articles had important progress referred to 'biogeochemical models' and 'eutrophication' (Onandia et al., 2015), 'dynamic model' and 'lake eutrophication' (Bhagowati & Ahamad, 2019), 'ecological classification of lakes', 'chlorophyll' and 'cyanobacteria' (Søndergaard et al., 2011), 'ecological change' (Gregersen et al., 2023), 'ecological water quality' (Stamou et al., 2019), 'functional classifications in phytoplankton community' (Salmaso et al., 2015), 'alternative stable state' (Bruel et al., 2018), 'restoration' (Abell et al., 2022), 'rainy' and 'phytoplankton community' (Díaz-Torres et al., 2021), 'eutrophication management' (Poikane et al., 2022), 'water quality model' and 'submerged macrophytes' (Sachse et al., 2014), 'driver', 'changes'. 'phytoplankton community' and 'urban lake' (Mansfield et al., 2014).

3.6. Conceptual development

Figure 5 analyzes the conceptual development where four groups were identified.

3.6.1. Red cluster

In this group, the four top author keywords were 'phytoplankton', 'water quality', 'eutrophication' and 'cyanobacteria'. 'Phytoplankton', in the most representative articles, saved relationship with 'diversity' (Laskar & Gupta, 2009; Thakur et al., 2013), 'nutrients' (Dove & Chapra, 2015), 'phosphorus' and 'dominance algal' (Smith, 1983), 'algal growth regulation' (Xu et al., 2010) and 'blooms'

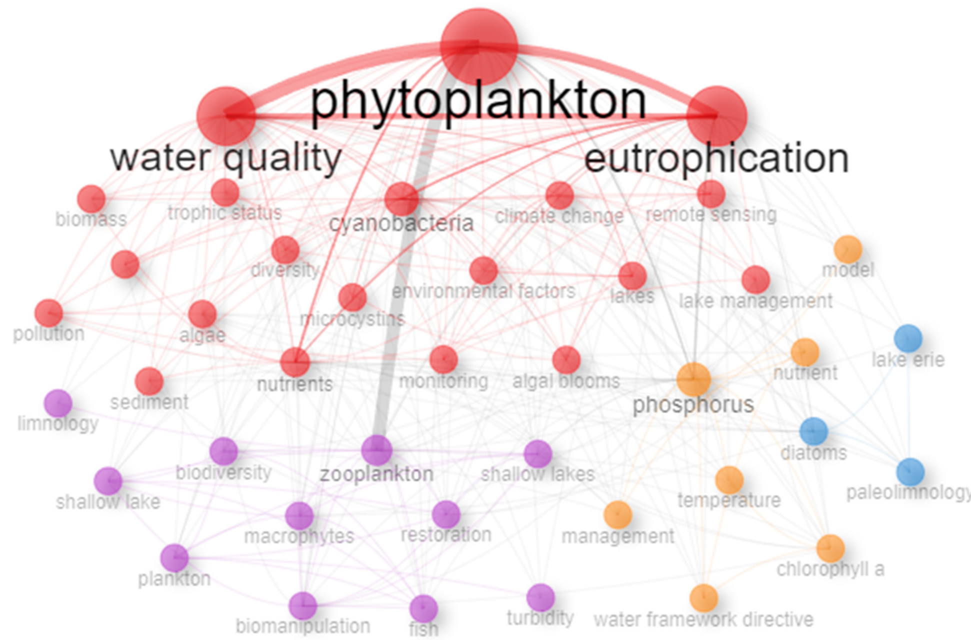

Figure 5. Conceptual structure of the research based on the co-occurrence of author' keywords (50 top words) based on the cluster method (Source: Bibliometrix Package in R, Aria & Cuccurullo (2017). The nodes represent the keywords and their size varies according to the number of times they are repeated in the data, and the colored clusters show the association or affinity of the keywords according to the study of the subtopic.

(Ho et al., 2019). Relevant articles about 'water quality' had relationship with 'eutrophication' (Smith & Schindler, 2009), 'anoxia' (Scavia et al., 2014), 'nutrients enrichment' (Bergström & Jansson, 2006), 'nitrogen' and 'phosphorus' and 'phytoplankton growth' (Abell et al., 2010), 'cyanobacteria blooms' (Huisman et al., 2018), 'management of lakes' (Otten et al., 2012; Matthews, 2014; Li et al., 2020), 'lake water management' (Reeders & de Vaate, 1990; Fahnenstiel et al., 1995), 'control and mitigating' (Sukenik & Kaplan, 2021), 'factors and predictions' (Wang et al., 2021), and 'remote sensing technics' for water quality assessment (Tyler et al., 2006). Complementary, the next topics were denoted too, 'human activities' and 'climate factors' (Zhang et al., 2022), and 'lakes trophic states' (Kasprzak et al., 2008; Trolle et al., 2011; Dove & Chapra, 2015).

3.6.2. Purple cluster

Some topics associated in this cluster were 'diversity' (Shanthala et al., 2009; Thakur et al., 2013; Jindal et al., 2014), 'restoration' (Gulati et al., 2008; Han et al., 2022), 'macrophytes' (Søndergaard et al., 2017; Hilt et al., 2018) and 'biomanipulation' (Drenner & Hambright, 1999; Jeppesen et al. 2012; Peng et al., 2021; Yin et al., 2022).

3.6.3. Orange cluster

This cluster grouped important topics, where the most relevant themes were related with 'phosphorus' (Smith, 1983; Xu et al., 2010; Tong et al., 2017), 'modelling' and 'forecast' (Bhagowati & Ahamad, 2019; Vinçon-Leite & Casenave, 2019; Bhagowati et al., 2022), 'mitigating' (Paerl et al., 2020), 'management' (Paerl et al., 2011; Otten et al., 2012), 'water framework directive' based on phytoplankton community (Padisák et al., 2006), multi-parametric models biological, physical, chemical, morphological parameters (Moss et al., 2003) or remote sensing models (Ansper & Alikas, 2019).

3.6.4. Blue clusters

This cluster concentered three topics, 'paleolimnology' with inclusion of 'diatoms' study to understand past ecological states in lakes (Battarbee et al., 2014; Short et al., 2022) and scientific contribution of the 'Lake Erie' researches in lake eutrophication (Scavia et al., 2014), 'lake restoration' (Makarewicz & Bertram, 1991), 'climate warming' and 'oxygen dissolved' in the water column (Blumberg & Di Toro, 1990),

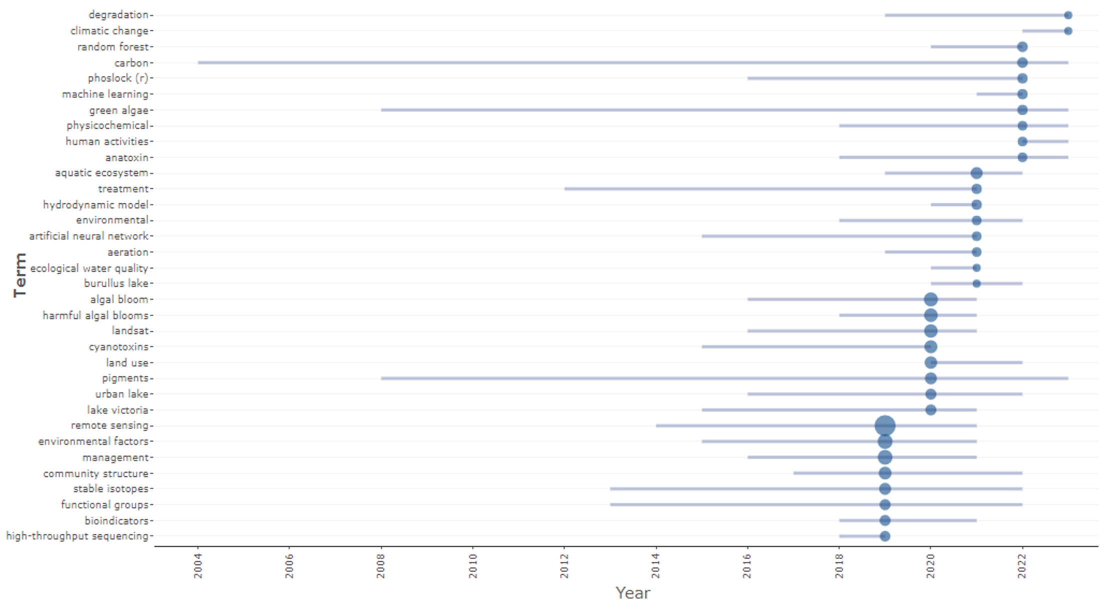

Figure 6. Trending topic in PLWQA (Source: Bibliometrix Package in R, Aria & Cuccurullo (2017). The blue spheres indicate the frequencies (20, 40, and 60) of the keywords in the analyzed data, the sphere varies in size depending on the frequency scale.

'hydrodynamic-biological models' and 'water quality' (Leon et al., 2011).

3.7. Thematic trends

The trending topics (Figure 6) illustrate ten main topics investigated annually between 2019 and 2023 in PLWQA. In each year, the magnitude of the topic's frequency was represented in a circle, and the horizontal line shows the topic's development period. In each keyword is cited one relevant article of the annual development period.

Thus, the ten most developed topics in the year 2019 were 'high throughput sequencing' (Li et al., 2019), 'bioindicators' (Parmar et al., 2016), 'functional groups' (Salmaso et al., 2015), 'stable isotopes' (Liu et al., 2018), 'community structure' (Davis et al., 2015), 'management' (Waajen et al., 2016), 'environmental factors' (Zhao et al., 2015), and 'remote sensing' (Dornhofer & Oppelt, 2016).

For the year 2020 were 'Lake Victoria' (Kashindye et al., 2015), 'urban lake' (Rosińska et al., 2017), 'pigments' (Gomes et al., 2020), 'land use' (Bucak et al., 2018), 'cyanotoxins' (Chaffin et al., 2019), 'landsat' (Tebbs et al., 2013), 'harmful algal blooms' (Paerl et al., 2016), and 'algal bloom' (Binding et al., 2018).

In the year 2021 denoted 'Burullus lake' (Elsayed et al., 2019), 'ecological water quality' (Stamou et al., 2019), 'aeration' (Wang et al., 2021), 'artificial neural network' (Wang & Wang, 2021), 'environmental' (Paerl & Otten, 2016), 'hydrodynamic model' (Dresti et al., 2023), 'treatment' (Fan et al., 2019), and 'aquatic ecosystem' (Sukenik & Kaplan, 2021).

In 2022, the relevant topics were 'anatoxins' (Chernova et al., 2016), 'human activity' (Yan et al., 2019), 'physicochemical' (Ray et al., 2021), 'green algae' (Li et al., 2023), 'machine learning' (Li et al., 2021), 'phoslock' (Nuernberg & LaZerte, 2016), 'carbon' (Ji et al., 2020), 'random forest' (Zhang et al., 2021). Finally, in 2023 denoted 'climate change' (Jeppesen et al., 2020), and 'degradation' (Zhang et al., 2022).

4. Discussion

4.1. Phytoplankton in the lake water quality studies

The publication of articles related to bibliometric analysis has been gaining a great notoriety due to the efficiency of its results for other researchers whose studies achieve high impact (Rose et al., 2020), therefore, this article builds a literature set with potential use for researchers in the field. A bibliometric review on phytoplankton in inland water quality assessments has been published by Liu et al. (2017), which includes preliminary bibliometric information on the main countries, institutions, authors, and journals. In our article, we make an in-depth scientific analysis on the knowledge about phytoplankton in lakes and the assessment of water quality based on bibliographic coupling and conceptual analysis with co-occurrence of keyword analysis, a great contribution to lake science.

Scientific production of this topic (PLWQA) has been growing, but production decreased in 2023, compare to 2022, probably due to the effect of the COV19 pandemic (Guzmán Duxtan, 2020), because many scientists experienced limitations in the development of their research in the area (Heo et al., 2022).

Lakes, globally recognized for their valuable ecosystem services (Zhu et al., 2022) and biodiversity (Dudgeon et al., 2006), face serious pollution problems, with wastewater standing out among the various polluting sources, with the first scientific report according to the Scopus database dating from 1914 (McLaughlin, 1914). Since then, several strategies have been implemented to assess water quality in these waterbodies, from those that include physical, chemical, and microbiological parameters (Uddin et al., 2021), to remote sensing technologies (Dornhofer & Oppelt, 2016). Furthermore, the loss of water quality in lakes due to pollution has been a concern on a global scale for several decades (McLaughlin, 1914; Dudgeon et al., 2006), and in this work, the first to relate water quality and phytoplankton in lakes, we report that the interest in developing this topic increases annually, as evidenced by the number of publications per year, similar to what happens with lake studies where the objective is to assess eutrophication (Kyriakopoulos et al., 2022), understand in depth the role of phosphorus (Gao et al., 2015) or nitrogen (Yao et al., 2018), and also those that address the issue of restoration (Lyu et al., 2020).

4.2. Relevant authors, countries and thematic development

Given the nature of this research, it was identified that among the most important authors in the PLWQA was Erik Jeppesen, whose main scientific contribution made together with Martin Søndergaard, Jens Jensen, Karl Havens, Orlane Anneville, Laurence Carvalho, Michael Coveney, Rainer Deneke, Martin Dokulil, Bob Foy, Daniel Gerdeaux, and Stephanie Hampton was the article (1060 citations) "Lake responses to reduced nutrient loading - An analysis of contemporary long-term data from 35 case studies" (Jeppesen et al., 2005), which gave important arguments for further research, for example, the recently published article explains the relationships between nutrients and chlorophyll in shallow lakes (Graeber et al., 2024) or another case reported how re-oligotrophication and warming stabilize phytoplankton networks (Fu et al., 2024).

The second representative author was Yunlin Zhang, who together with Xiaohan Liu, Boqiang Qin, Kun Shi, Jianming Deng, and Yongqiang Zhou published the article (162 citations) "Aquatic vegetation in response to increased eutrophication and degraded light climate in Eastern Lake Taihu: Implications for lake ecological restoration" (Zhang et al., 2016).

On the other hand, China stood out as the country with the highest recent scientific production on the study topic (PLWQA), and also leads in related topics, such as control of phytoplankton growth (Xu et al., 2010), harmful cyanobacterial blooms (Paerl et al., 2011) or mitigation of harmful cyanobacterial algal blooms (Paerl et al., 2020). Similarly, recent articles refer to the use of deep learning applied to drone-borne sensing to assess cyanobacterial blooms (Shin et al., 2024), the quantification of chlorophyll-*a* based on multi-source remote sensing data (Wang & Chen, 2024), and the dynamics of chlorophyll-a in lakes using machine learning model (Wang et al., 2024).

The United States, the second great producer of scientific literature according to our results, with a focus similar to that of China, has its main articles have developed on cyanobacterial blooms (Huisman et al., 2018), eutrophication (Smith & Schindler, 2009), and climate change (Paerl & Paul, 2012).

Progress on cyanobacterial blooms during part of 2024 was focused on assessing factors influencing cyanobacteria blooms (Gibbs et al., 2024), organic matter and mercury methylation in lake sediments (Wang et al., 2024), and eco-friendly management of harmful cyanobacterial blooms (Aba et al., 2024).

Eutrophication in lakes is related to the loss of water quality, a common problem in global lakes. Last year, 2023, scientists were researching long-term phytoplankton community dynamics and eutrophication acceleration (Kröger et al., 2023), phytoplankton overgrowth control (Geletu, 2023), lake recovery from eutrophication (Salonen et al., 2023), and phytoplankton community responses to the eutrophication process (Çetin, 2023; Lanza et al., 2024).

4.3. Thematic trends

During the present review, lake degradation was highlighted as a common problem with a global focus

(Jenny et al., 2020), with strong relationships with eutrophication (Häder et al., 2020). Likewise, studies seeking to understand its triggering in depth are still ongoing (Li et al., 2021). However, anthropic factors have been well studied as one of the main causes of eutrophication and the phytoplankton blooms (Salmaso & Tolotti, 2021). There is interest in the development of advanced monitoring techniques, such as remote sensing (Rolim et al., 2023) to molecular techniques, such as environmental DNA (Liu et al., 2020); and the analysis of information using complex models, such as machine learning (Yan et al., 2022) or process and data-based models (Rousso et al., 2020) or more complex models that include nutrient, hydrology, climatic disturbances and others parameters that allow explaining and predicting algal bloom events (Brookfield et al., 2021).

Furthermore, cyanobacterial blooms are frequent in eutrophic and hypereutrophic lakes (Tanvir et al., 2021), so recent studies have focused efforts on offering alternatives for eutrophication management (Qin et al., 2023), including biotreatment proposals (Kakade et al., 2021) or the use of vascular plants to mitigate cyanobacterial blooms (Nezbrytska et al., 2022), and the development of strategies for lake recovery (Hartig et al., 2020). Finally, climate change in the context of PLWQA refers to increased species extinction, biodiversity loss, and urgent actions for lake restoration (Ho & Goethals, 2020).

5. Conclusions

The scientific development of PLWQA shows a positive trend, that is, it will continue to develop globally. There is high development in related topics with emphasis on lake responses, nutrients, eutrophication, phytoplankton and cyanobacterial blooms. The research trend, in line with advances in recent years, is focused on the study of climate change and degradation. In this context, this comprehensive analysis allowed us to interpret the development of research related to PLWQA.

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