TREND ANALYSIS OF RESEARCH ON PHYTOPLANKTON TRAITS AS ECOLOGICAL INDICATORS

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Abstract. This study employs bibliometric analysis to identify trends and research hotspots in the use of phytoplankton traits as ecological indicators. We analyzed 3352 articles published in the Web of Science Core Collection database from 2000 to 2023, focusing on phytoplankton traits, their role as indicators, and their application in aquatic ecosystem monitoring. This study reveals a significant increase in publications on this topic, particularly since 2010. The United States, China, and Germany emerged as leading contributors in this field. Our analysis identifies four major research clusters: (1) using phytoplankton traits to indicate environmental changes in rivers, lakes, and oceans, (2) using phytoplankton traits as bioindicators for specific environmental factors like nutrients and pollutants, (3) exploring the molecular mechanisms of phytoplankton trait variations and new species discoveries, and (4) investigating the relationship between phytoplankton traits and the food web dynamics. Research on phytoplankton traits is rapidly advancing, with significant potential to enhance understanding and monitoring of aquatic ecosystems. Future research directions include further investigating the molecular mechanisms of trait changes, developing more robust bioindicators for specific pollutants, and exploring the ecological implications of trait variations in food webs.
Keywords: *bibliometrics, publication trends, research hotspots, indicating function, morphology*

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Introduction

Phytoplankton are critical primary producers in aquatic ecosystems. They play a key role in supplying dissolved oxygen to aquatic environments, initiating food web dynamics (Sun et al., 2020), and serving as a primary food source for numerous marine organisms. As a result, phytoplankton directly impact fisheries production (Wu et al., 2008; Wang et al., 2014; He et al., 2022; Wei et al., 2023; Xie et al., 2024). For example, excessive phytoplankton biomass can lead to algal blooms, affecting water quality and the growth of underwater organisms (Wu et al., 2008). Numerous studies highlight the importance of phytoplankton community characteristics and their spatiotemporal variations in water quality monitoring, pollution assessment, and aquatic ecosystem management (Medwed et al., 2021; Hu et al., 2024). The changes in phytoplankton species composition, community structure, and abundance directly affect water quality, energy flow within system, element cycling, and biological resources (Kókai et al., 2015; Rimet et al., 2015, 2018).

The study of phytoplankton has a history of nearly 200 years, dating back to 1828 when J.V. Thompson in England and 1845 when J. Müller in Germany began their research. The first phase focused on collection, observation, and morphological classification (Round et al., 1987; Santhanam et al., 2019). In 1889, the North Atlantic Plankton Expedition in Germany and its published "Results of the Plankton Expedition" laid the foundation for marine phytoplankton research. The "Flora and Fauna of the Gulf of Naples" by the Marine Biological Station in Naples, Italy, and the "Scientific Results of the Prince of Monaco's Explorations" by the Monaco Oceanographic Institute made significant contributions to the classification and morphological study of marine phytoplankton. The second phase, following the 1920s, focused on the natural ecology of marine phytoplankton, with emphasis on their spatiotemporal distribution and relationship to the marine environment, as well as the effects of various environmental factors on the growth, development, and reproduction of various marine phytoplankton. The third phase, since the 1960s, has closely combined the study of natural phytoplankton ecology with experimental ecology and has developed into experimental research in on-site enclosure ecosystems. In the 1970s, the first international conference on harmful algal blooms marked the first concentrated discussion and summary of the characteristics of harmful phytoplankton (Round et al., 1987; Guiry, 1992; Albay et al., 2007; Santhanam et al., 2019). In 1998, Russian scientists discovered that the morphology of the diatom *Aulacoseira Thwaites* in Lake Baikal was significantly related to eutrophication caused by human activities. In waters with high trophic levels, the diatom cell wall exhibited thickened siliceous layers and reduced algal chain length (Kozhova et al., 1998). Green algae were well adapted to high-light environments, and there was a clear positive correlation between their cell size and the light intensity (Schwaderer et al., 2011). The morphological characteristics of some species of Dinophyceae were significantly affected by sunlight and temperature,

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exhibiting diverse adaptive changes (Takano et al., 2008; García-Oliva et al., 2022). The rise of high-throughput sequencing technology had significantly improved the efficiency of researchers in identifying various traits of phytoplankton species and allowed them to delve into the molecular mechanisms of their response to environmental factors at a molecular level (Jung et al., 2010; Apothéloz-Perret-Gentil et al., 2017). Meanwhile, as understanding of pollutants had deepened, some researchers had found that specific morphological changes in phytoplankton had significant potential for indicating pesticides, heavy metals, and organic pollutants (Gautam et al., 2017; Wood et al., 2019), while others had focused on the role of different phytoplankton traits in food web and food chain dynamics (Samhouri et al., 2009; Moens et al., 2014; García-Oliva et al., 2022).

With the increasing involvement of researchers and deepening research, the number of articles on phytoplankton trait is constantly increasing. However, the relevant information is vast and scattered. The current research hotspots and future research trends in this field are unclear. Appropriate methods and tools are needed to analyze and summarize the research hotspots and trends in phytoplankton trait. Bibliometric methods usually use mathematical and statistical models to analyze the quantitative characteristics of literature. This method analyzes literature information, such as the number of publications and authors, through quantitative processing, creating visualizations that help researchers better understand the research field's dynamic changes and development trends (Börner et al., 2003). This study utilized VOS viewer software (Van Eck et al., 2010) to visually analyze the literature on phytoplankton trait published in the Web of Science Core Collection database from 2000.1.1 to 2023.12.31. This analysis aimed to obtain the research hotspots efficiently and future development trends of phytoplankton trait, providing a reference for future research directions.

Materials and methods

Literature retrieval and selection

The choice of database has a significant impact on the data retrieved and the accuracy and effectiveness of the bibliometric analysis (Wang et al., 2018). The literature data in this article came from the Web of Science (WOS) Core Collection database.

Advanced search in the WOS database was used, with the time range of 2000.1.1 to 2023.12.31, the document type as research papers (Articles), and the search formula setting as: A= “phytoplankton OR algae OR diatom”, B= “trait OR guild OR morphological OR morphology”, C= “indicating OR indicator OR bioindicator”. The logical relationship between search formula A, search formula B, and search formula C was set to AND. After excluding duplicates and non-reviewed publications, a total of 3352 articles were obtained.

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Analysis methods

This study used the software Microsoft Office Excel 2016 and Endnote 20 to perform statistical analysis and chart generation for the number of publications, related disciplines, and journal information (Wang et al., 2023). VOSviewer (version 1.6.19) software was used to generate scientific knowledge maps, performing co-occurrence and cluster analysis on cooperation networks (countries, authors), keywords, and published journals. In the co-occurrence maps generated by VOSviewer, each color of keywords represented a cluster, the size of each circle representing the relative frequency of occurrence of that keyword, and the number and thickness of the connecting lines between keywords reflecting the closeness and intensity of their connection (Ayub et al., 2021).

Results and analysis

Analysis of literature publication trends

The number of publications in a certain field over different periods intuitively reflected the research trends of that field (*Figure 1*). The earliest paper on phytoplankton trait was published in 2000, indicating that this type of research pattern began to emerge at that time. From 2000 to 2003, the number of publications each year remained above 40. In 2010, the number of publications in the research field of phytoplankton traits exceeded 100, and rapidly increased since 2010. Between 2019 and 2023, the number of publications remained above 230.

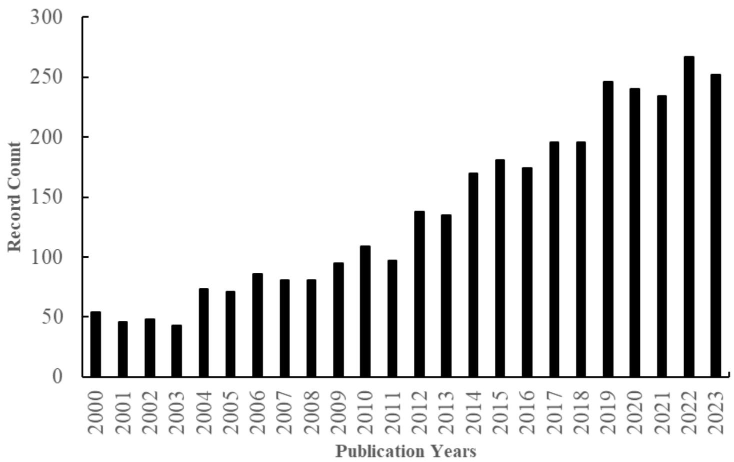

Figure 1. *Publication trend chart*

Analysis of research countries and cooperation networks

VOSviewer software was used to visualize the cooperation network of countries with more than 10 publications. The analysis results were shown in *Figure 2*. Countries

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including the United States, Japan, Australia, Germany, and New Zealand started researching phytoplankton trait earlier than China. The influence and quality of different countries' papers were measured by the number of citations and h-index (*Table 1*). Research found that the United States ranked first in the number of articles published in this field, with a total of 456 articles, accounting for 21.12% of the total publications. The average number of citations per article was 29.79, and the h-index was 71, the highest among the top 10 countries in terms of number of publications in this field. This pattern implied that the United States had the earliest and most in-depth research in this area. China ranked second, with 575 articles published, accounting for 17.15% of the total publications. The average number of citations per article was 18.51, and the h-index was 50, suggesting that China developed rapidly in this area. China, the United States, and Germany occupy the central position in *Figure 2*, indicating that these countries frequently collaborated with other countries and had a certain degree of influence. In addition, all of the top 10 countries in terms of number of publications had high h-indices and average number of citations per article, indicating that these countries were generally at the same developing stage of research in this field.

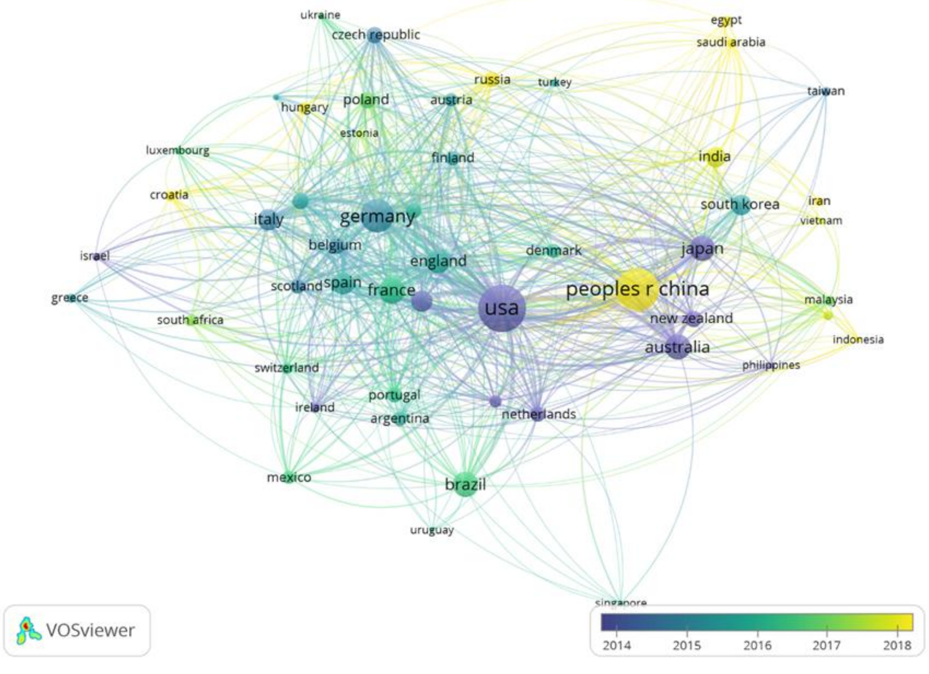

Figure 2. *National cooperation network map*

The analysis of research countries indicated that the most of the top 10 productivity countries are geographically close to the Atlantic Ocean (*Table 1*). The keyword clustering analysis revealed that the term "ocean" was identified 249 times, while "Atlantic" was identified on 24 occasions (*Fig. 3*), suggesting that in the main study countries, the research institutions overlap with the study areas.

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Table 1. *Analysis of the influence of papers from the top 10 countries in terms of number of publications*

Country	Documents	Times cited average per item	h-index
USA	708	29.79	71
China	575	18.51	50
Germany	344	33.22	58
France	219	33.85	46
Japan	207	19.43	34
Australia	202	33.35	42
Brazil	199	21.53	35
England	168	25.82	39
Spain	162	30.01	37
Italy	146	31.44	38

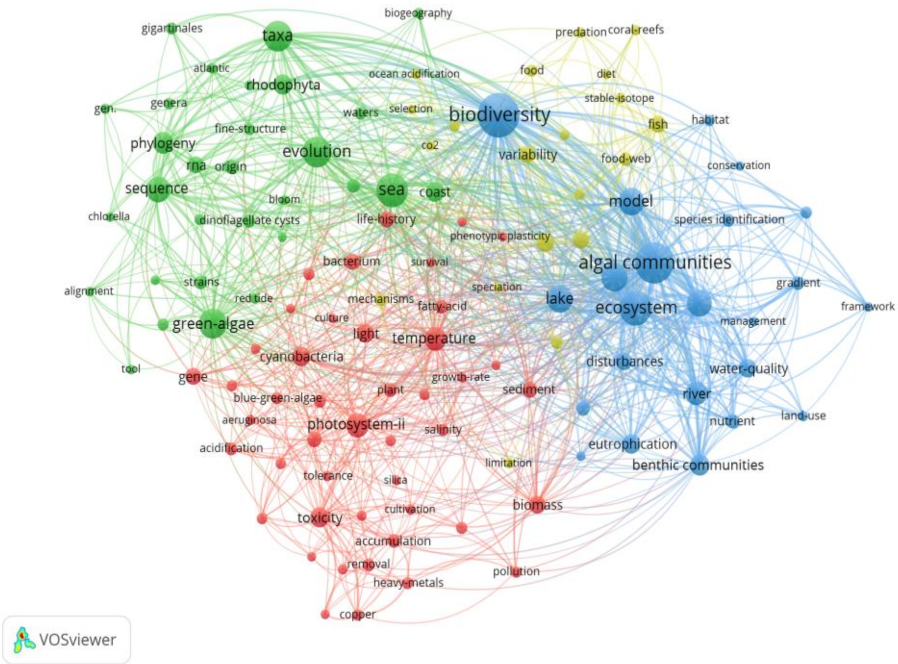

Figure 3. *Keyword co-occurrence cluster view*

Research authors and their cooperation networks

Rimet, Frederi (23 articles) published the most articles on phytoplankton trait among the 3352 articles, as shown in *Table 2*. Based on the calculation *formula (1)* (Price, 1963), authors with more than 3 publications were considered core authors in this field. There were a total of 584 core authors. Core authors have formed research teams represented by Rimet, Frederi; B-Béres, Viktoria; Wu, Naicheng; Liu, Guoxiang; Karsten, Ulf; etc. (*Figure 4*). Among them, the research team represented by Rimet, F. (Rimet et al., 2015; Marcel et al., 2017; Tapolczai et al., 2017) and the research team

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represented by Bácsiné-Béres, V. (Bácsiné-Béres et al., 2014, 2016; Várbíró et al., 2020) mainly focused on research related to biomonitoring of planktonic and benthic diatoms. The research team represented by Wu, N. (Sun et al., 2018; Guo et al., 2020; Wang et al., 2022; Hu et al., 2023) mainly focused on the benthic diatoms in hydrological environments and their indicative roles in the river. The research team represented by Liu, G. (Zhu et al., 2017; Zhang et al., 2018; Xiong et al., 2021, 2022) mainly focused on phylogenetic analysis and adaptive evolution of green algae. The research team represented by Karsten, U. (Karsten et al., 2006; Donner et al., 2017; Rippin et al., 2018; Sommer et al., 2020a, 2020b) mainly focused on morphological studies of algae in soil. The network analysis indicates that French authors Rimet, F. and Ector, L.; Victorian authors Bácsiné-Béres, V.; German authors Karsten, U.; and Korean authors Boo, S. M., among others, are strongly linked to other authors, suggesting that authors from these countries engage in more frequent collaboration and communication on an international scale. In contrast, Chinese authors Liu, G.; Liu, Q.; Wu, N., etc. are strongly linked with authors from their own countries and relatively less with authors from other countries. This suggests that Chinese authors collaborate more with authors from their own countries and have relatively fewer opportunities to communicate and cooperate with other international authors (*Fig. 4*).

$$N = 0.794\sqrt{M_{max}} \quad \text{(Eq.1)}$$

where, N: representing the minimum number of publications by core authors; Mmax: representing the number of publications by the author with the highest number of publications.

Table 2. *Top 10 authors in terms of number of publications*

Author	Documents	h-index	Institution	Country
Rimet, Frederi	26	21	National Research Institute for Agriculture, Food and Environment	France
Bouchez, Agnes	22	20	Universidad Nacional Autonoma de Mexico	Mexico
Karsten, Ulf	21	12	University of Rostock	Germany
Liu, Guoxiang	20	7	Institute of Hydrobiology. Chinese Academy of Sciences	China
Mann, David G.	19	13	Royal Botanic Garden Edinburgh	Scotland
Neustupa, Jiri	19	12	Charles University in Prague	Czech Republic
van de Vijver, Bart	19	9	Botanic Garden Meise	Belgium
Ector, Luc	18	10	Universite Clermont Auvergne	France
Singh, Prashant	15	7	Banaras Hindu University	India
Saunders, Gary W.	14	8	University of New Brunswick	Canada

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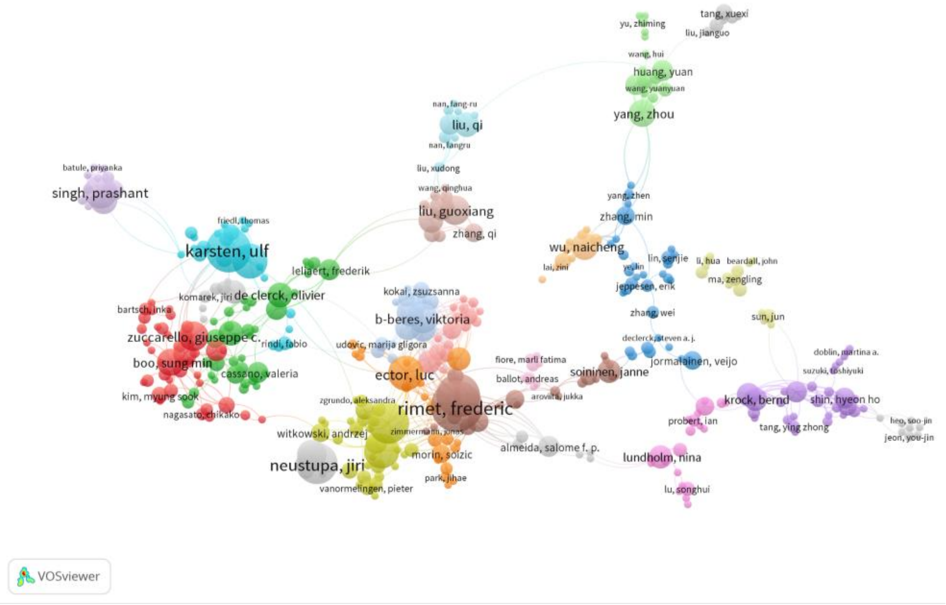

Figure 4. Map of author cooperation network

Analysis of co-occurrence of popular journals

Table 3 listed the top 20 journals in terms of the number of articles related to research on phytoplankton trait. Among them, the Journal of Psychology had the largest number of publications, with 136 articles. This was followed by the journals Phycologia and Ecological Indicators, with 93 and 88 articles respectively. Science of the Total Environment had the highest impact factor, at 8.6, followed by the journals Ecological Indicators and Harmful Algae, with impact factors of 6.6 and 5.6 respectively. () VOSviewer software was used to generate a map of popular journals (*Figure 5*). From the map, four clusters were observed. The first cluster (yellow area) included journals of the Journal of Phycology, Nova Hedwigia, Taxon, Cryptogamie Algologie, Algae, Phytotaxa, Fottea, Diversity-Basel, Protist, etc. The second cluster (blue area) included journals of Ecological Indicators, Freshwater Science, Frontiers in Ecology and Evolution, Freshwater Biology, Science of the Total Environment, etc. The third cluster (red area) included journals of PLOS One, Oecologia, Marine Biology, Frontiers in Marine Science, etc. The fourth cluster (green area) included journals of Harmful Algae, BMC Genomics, Algal Research-Biomass Biofuel, FEMS Microbiology Letters, Aquatic Toxicology, Chemosphere, Journal of Hazardous Materials, etc.

Analysis of research hotspots and frontiers in phytoplankton trait

Research hotspots refer to a group of scientific issues or topics with a certain internal connection that is discussed together in a relatively large number of articles in a certain field during a certain period (Kurtz et al., 2011; Radziff et al., 2021).

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Table 3. *Top 20 journals in terms of number of publications*

Journal	Numbers of documents	Times Cited Average per item	Journal Impact Factor
Journal of phycology	136	32.11	3
Physiologic	93	22.27	2.1
Ecological indicators	88	37.02	6.6
Hydrobiologia	79	28.57	2.5
Harmful algae	75	26.53	5.6
European Journal of phycology	68	24.53	2.4
Science of the total environment	61	24.7	8.6
Journal of applied phycology	60	18.08	3.2
Plos one	55	35.64	3.3
Marine Ecology Progress series	42	33	2.5
Freshwater biology	39	44.26	3.5
Frontiers in marine science	39	7.44	3.7
Marine biology	38	34.05	2.3
Limnology and oceanography	33	32.45	4.4
Phycological research	32	13.09	1.4
Diatom research	30	14.47	1.7
Journal of experimental marine biology and ecology	30	27.5	2.1
Phytotaxa	30	7.77	1
Algal research-biomass biofuels and bioproducts	28	10.18	4.8
Frontiers in microbiology	28	15.93	5.1

From the perspective of bibliometrics, research-oriented papers with the largest number of citations in a certain research field usually represent the concentration of hotspots in that research field (Kurtz et al., 2011; Radziff et al., 2021). Keywords are also the essence and core of a paper, a highly condensed representation of the paper's topic, using standardized language. Keywords that appear frequently can be considered research hotspots in that field (Osareh, 1996; Kurtz et al., 2011; Radziff et al., 2021). By performing co-occurrence and cluster analysis on keywords related to phytoplankton trait using VOSviewer software, we can discover hotspots and focal points in this field. First, the keyword frequency threshold was set to 20, resulting in 201 keywords. To enhance the readability of the map, similar keywords were merged, and keywords used for searching and keywords unrelated to the topic were removed. Once again, the keyword frequency threshold was set to 20, resulting in 119 keywords. And the co-occurrence of the 119 keywords yields the configuration depicted in *Fig. 3*.

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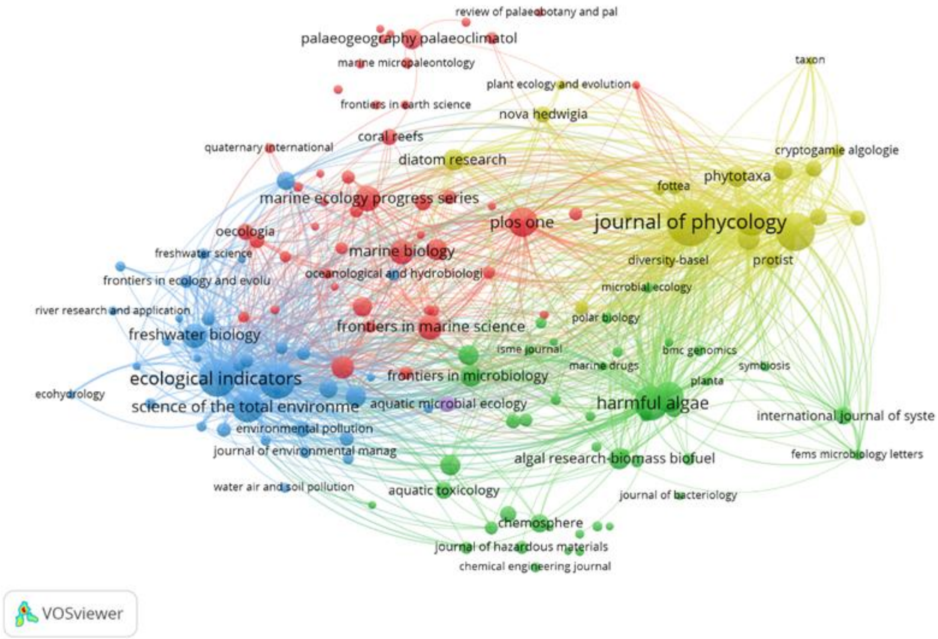

Figure 5. Popular Journal Network Map

The different colors represent distinct groupings, with the size of the circle indicating the frequency of occurrence. Larger circles signify a higher frequency of occurrence. The connecting lines between circles indicate the probability of co-occurrence, with denser lines denoting a closer relationship with other keywords. In figure 5, “biodiversity, algal communities, ecosystem, sea, evolution” were the 5 most frequent keywords. Among them, biodiversity appeared 419 times, algal communities appeared 369 times, ecosystem appeared 264 times, sea appeared 249 times, lake appeared 159 times, river appeared 116 times, and evolution appeared 206 times, and they were closely related to other keywords on the map (*Fig. 3*). This indicated that research on phytoplankton traits tended to compare differences between different species, as well as the relationship between the composition of different phytoplankton and ecosystems, and the evolution of phytoplankton. From the co-occurrence cluster view of keywords, the research on phytoplankton trait mainly presented four clusters. Blue represented cluster 1, with keywords including chlorophyll-a, benthic communities, eutrophication, environments, river, nutrient, land use, sediment, disturbances, water quality, algal communities, gradient, ecosystem, model, lake, species identification, biodiversity, conservation, framework. Red represented cluster 2, with keywords including copper, heavy-metals, pollution, chlorella-vulgaris, accumulation, toxicity, cultivation, silica, biomass, tolerance, acidification, photosystem-ii, salinity, gene, blue-green algae, plant, growth rate, cyanobacteria, light, temperature, culture, fatty-acid, bacterium. Green represented cluster 3, with keywords including tool, green algae, red tide, alignment, strains, chlorella, dinoflagellate cysts, blooms, sea, coast, sequence, origin, population,

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evolution, phylogeny, fine-structure, waters, gen., genera, Atlantic, Rhodophyta, gigartinales, taxa, biogeography. Yellow represented cluster 4, with keywords including zooplankton, fish, habitat, stable-isotope, diet, food, predation, coral-reefs, co_2, selection, acidification, speciation, limitation, and food-web.

Discussion

The indicative role of phytoplankton trait or aquatic ecosystems

As a key component of aquatic ecosystems, phytoplankton plays an indispensable role in assessing water quality, monitoring global changes, and evaluating the health of ecosystems. It is not only ideal biological indicator for water environments such as lakes, wetlands, rivers, oceans, and reservoirs but also important component of monitoring in extreme environments such as glaciers and saline-alkaline lands (Vogt et al., 2010; Stenger-Kovács et al., 2014; Falasco et al., 2018; Wu et al., 2019). However, in many monitoring studies, especially those with a large amount of data, it is not easy to accurately identify differences at the species level. Using phytoplankton trait for classification can significantly reduce research costs (Cormier et al., 2020). In this study, research on phytoplankton trait was broadly divided into two categories: one used trait to directly indicate environmental changes, and the other one classified phytoplankton according to specific trait or differences in trait manifestations, processing the classification data to reflect the environmental state.

In river ecosystems, phytoplankton size, the degree of bending of filamentous diatoms, survival coping strategies, and morphological characteristics were often used to directly or indirectly indicate environmental changes. Berthon et al. (2011) reported that large diatoms are more common in nutrient-rich environments, while small diatoms are more dominant in nutrient-poor conditions. Furthermore, organic pollution has a significant impact on the cell size and morphology of diatoms, with polluted environments tending to reduce the number of large diatom species, while small diatom species may be more tolerant. Sun et al. (2018) pointed out that the cell size of diatom communities was sensitive to seasonal changes, with large cells dominating in winter and spring, and small cells dominating in summer and autumn. Wang et al. (2020) found that the cell size and filament bending degree of *Aulacoseira Thwaites* were good indicators of river nutrient status, with large and curved filaments often appearing in nutrient-rich water bodies, while small and straight filaments were more prominent in oligotrophic areas. Stenger-Kovács et al. (2013) studied the response of three diatom trait (high profile, low profile, and motility) to different pressures and disturbances. They found that the low-profile guild dominates when resources are scarce, the high-profile guild dominates when resources are abundant, and the motile guild is suitable for intermediate nutrient levels and is most sensitive to nutrient changes. Global climate change and local influences lead to hydrological changes in rivers, particularly increased intermittent flow. This process, known as lentification, causes a shift in

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aquatic ecosystems and has severe consequences for biological communities (Falasco et al., 2018). Falasco et al. (2018) explored the relationship between diatom trait and the environment after the identification process and found that small, motile species were more abundant in summer, while attached species were limited during identification. Graco-Roza et al. (2021) found that flow regulation allows species with specific characteristics such as flagellated and mucilaginous species to survive in large numbers in nutrient-rich dammed areas. However, as flow velocity increases further away from the dam, the number of these species decreases. Riato et al. (2022), combined with the National Rivers and Streams Assessment (NRSA) database, developed diatom multimetric indices (MMIs) to classify diatom traits into (Mobile, Tube-living colony, Colonial, Non-colonial, Filament colony, etc.) to indicate water environment characteristics. They found that genus-level data divided by trait can provide biological assessment intensity comparable to species-level data. Compared to traditional species-level methods, this method uses genus-level data, which is simpler, less costly, and eliminates differences in species-level identification or nomenclature.

In lakes and reservoirs, researchers tend to classify phytoplankton according to specific trait or differences in trait manifestations for their research. Rangel et al. (2016) compared the functional groups (FG), morphology-based functional groups (MBFG), and traditional single-species taxonomy methods and found that MBFG can effectively capture the ecological strategies of cyanobacteria that form blooms and can be used to monitor the development of cyanobacteria HABs on temporal and spatial scales. Cormier et al. (2020) used a dataset of over 200 lakes to compare the accuracy of models based on 20 morphological traits with models based on species classification in inferring lake water pH, salinity, depth, and total phosphorus concentration. The results show that although the models based on morphological traits are slightly less accurate than those based on species, they still exhibit strong predictive power and are generally more accurate than analyses based on genus and family. Furthermore, morphological trait combinations’ richness is more strongly correlated with pH, salinity, and lake depth than species richness. Derot et al. (2020) studied 469 lakes and compared 21 phytoplankton trait, including phylogeny (presence of Chlorophyceae and presence of Euglenophyceae), cell size (nanoplankton (smallest size) and microplankton (largest size)), and life forms (solitary or colonial). They found that the phylogenetic group, filamentous forms, and the presence of ornamentation are the main traits related to changes in physico-chemical parameters (Derot et al., 2020).

Marine ecosystem research tended to combine molecular techniques with traditional microscopy or electron microscopy (Chen et al., 2007; Kesici et al., 2013; An et al., 2017). Research that used trait to directly indicate environmental changes or classified phytoplankton according to specific trait or differences in trait manifestations was less common. In extreme environment research, scientists tended to study the adaptive performance of phytoplankton trait in the environment. For example, Fragoso et al. (2018) found that diatom species in Arctic waters generally had lower optimal growth

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temperatures, higher cell wall silicification, the ability to form colonies, and the ability to produce resting spores. These were characteristics adapted to cold, high silicate, and sea ice melt environments. In contrast, diatom species in the North Atlantic generally had higher optimal growth temperatures, larger surface area-to-volume ratios, and weaker cell wall silicification. These characteristics facilitated survival and prosperity in warmer, eutrophic environments (Fragoso et al., 2018).

In the field of phytoplankton trait, molecular biology has been employed almost exclusively in studies of marine ecosystems, whereas its use has been less prevalent in investigations of riverine and lacustrine ecosystems. This suggests that phytoplankton morphology has been a more intensively studied subject in marine ecosystems.

Indicative role of phytoplankton trait for specific environmental factors

Phytoplankton trait can not only indicate the state of the water environment, but also sensitively reflect changes in specific environmental factors. Large numbers of researchers use phytoplankton to monitor physico-chemical environmental conditions, trophic changes, and pollutants. Unlike research that indicates the entire water environment status, this type of research focuses more on the indicative role of phytoplankton in a single or a few environmental factors.

Phytoplankton's adaptability to changes in physico-chemical environments provides an important ecological window for studying the effects of environmental changes on organisms. Phytoplankton can reflect the dynamic changes of environmental factors such as light, temperature, pH, and salinity through changes in their ecological strategies, life cycles, and morphological characteristics. When *Sargassum vulgare* was transplanted from its naturally occurring low pH environment (pH 6.7) to a high pH environment (pH 8.1), its photosynthetic pigment content increased by 40% with an increment in chloroplast size (Porzio et al., 2017). Shin et al. (2013) found that the calcareous spines of *Scrippsiella trochoidea* cysts would dissolve when the pH was below 7.39 in the hypoxic zone of eutrophic areas, indicating that low pH would lead to morphological changes in *Scrippsiella trochoidea* cysts.

In terms of nutrient monitoring, phytoplankton trait also have reliable environmental indicator functions. Researchers can effectively assess the concentration of nitrogen, phosphorus, silicon, and other nutrients in waters by analyzing phytoplankton trait, and then determine the health of water quality. Trobajo et al. (2004) studied the influence of environmental variables on the morphology of a diatom species called *Nitzschia frustulum* and explored its potential use as a bioindicator. The results showed that salinity was the main factor influencing cell length, width, and fibula density, while the nitrogen-phosphorus ratio and water flow also influenced fibula density and width. Kahlert et al. (2014) revealed a significant positive correlation between the total nitrogen and total phosphorus concentrations in Swedish highland rivers and the valve width of the freshwater diatom *Achnanthidium minutissimum*, and proposed a method for evaluating nutrient levels based on diatom valve width. Building on this research,

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Vilmi et al. (2015) found that the explanatory power of the total nitrogen and total phosphorus concentrations in lake water on the change rate of *Achnanthidium minutissimum* valve width reached 60%, indicating that diatom valve width better reflects the level of nutrient pollution in water bodies than its species diversity index. Lavoie et al. (2009, 2014) created an index library called IDEC, consisting of 648 diatom species, for monitoring trophic levels in rivers in eastern Canada. Kuefner et al. (2020) investigated the correlation between cell wall thickness of benthic diatoms and nutrient concentrations in 41 lakes in northern Europe and found a negative relationship, implying that in lakes with higher nutrient levels, diatom valves were smaller and the algae were lighter.

In pollution monitoring, phytoplankton have been widely used in monitoring and removal research of organic pollutants, heavy metals, pesticides, and new pollutants due to their sensitive responses to environmental toxins. Gautam et al. (2017) studied the morphological and physiological effects of heavy metal pollution on the diatom *Gomphonema pseudoaugur* and found that heavy metals could lead to an increase in the size and deformation of the diatom’s lipids. This can be a valuable indicator for biomonitoring. Wood et al. (2019), based on the sensitivity of diatoms to agricultural pollutants such as herbicides, developed a new biomonitoring index - SPEARherbicides, classifying 289 benthic diatom species as SPEAR or notSPEAR, which can detect the impact of agriculture on benthic diatom communities, including herbicide toxicity and nutrient pollution. It can be used to identify communities at risk from agricultural impacts and evaluate changes in sensitive diatom taxa.

Phytoplankton evolution and phylogeny

Research on the phylogeny of phytoplankton, the discovery of new species, and the characteristics of their habitat is an important part of modern ecology and taxonomy. Currently, the molecular biology database for phytoplankton is not comprehensive enough. In research on phylogeny and the discovery of new species, morphological characteristics still play an important role (Karnkowska et al., 2015; Falasco et al., 2018; Namba et al., 2021). Karnkowska et al. (2015) determined the phylogenetic relationships between Euglenophyceae through analysis of nucleotide sequence data for three nuclear-encoded genes (nSSU, nLSU, hsp90), one chloroplast-encoded gene (cpSSU), and one nuclear-encoded chloroplast gene (psbO). They used the phylogenetic tree to analyze eight commonly used morphological characteristics. Namba et al. (2021) discovered green algae on the shells of six *Clausiliidae snails* collected from nine locations in Japan. Based on morphological observation and molecular phylogenetic analysis, the authors proposed a new species of attached algae, *Annulotesta cochlephila*. Magalhães et al. (2021) isolated two unrecorded *Hemiselmis species* from the Brazilian and Japanese seas. They conducted morphological, phycobiliprotein spectral, molecular phylogenetic, and ITS2 secondary structure analyses (Magalhães et al., 2021).

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Relationship between phytoplankton trait and food webs, food chains

The role of phytoplankton in food webs and food chains, and their interactions with consumers, is an important topic of ecological research. Among phytoplankton traits, researchers are more concerned about the relationship between phytoplankton size and predation. Moens et al. (2014) studied the ability of three food chains (deposit feeder, epistrate feeder, predator) to utilize microalgae and assessed whether diatom cell size and consumer size were major drivers of their feeding. They indicated that none of the nematode species with whole-cell ingestion showed a preference for a particular diatom size. García-Oliva et al. (2022) studied the relationship between the dominance of Mixotrophic dinoflagellates (MTD) and changes in phytoplankton size distribution, indicating that large MTD prey on small MTD.

Future trends and perspectives

Scientists' interest in research on phytoplankton trait increased significantly in recent years. This article, based on bibliometric methods, used VOSviewer software to perform co-occurrence and cluster analysis on the number of publications, cooperation networks (countries, authors, journals), and keywords of the 3352 articles obtained on the indicator function of phytoplankton trait. Our study provided a reference for future research directions on phytoplankton trait. Through bibliometric visualization analysis of recent research literature in the field of phytoplankton trait, the following conclusions were drawn: (1) The number of articles published in the field of phytoplankton trait continued to increase from 2008 to 2019, with Marine Freshwater Biology, Environmental Sciences Ecology, and Plant Sciences having the most publications. (2) The United States, China, and Germany ranked among the top three in terms of the number of publications in this field. (3) In recent years, research on phytoplankton trait mainly focused on the following aspects: (a) The relationship or indicative role of phytoplankton composition or specific phytoplankton species in relation to the environment has been investigated. The research methods have included two approaches: one is using trait to directly indicate environmental changes; the other is classifying phytoplankton based on specific trait or differences in trait manifestations, and processing the classification data to reflect the environmental state. In terms of research regions, both types of research have been primarily focused on rivers and lakes. (b) The indicative role of phytoplankton traits in relation to specific environmental factors, including light, temperature, nitrogen, phosphorus, and other nutrients, as well as pollutants such as benzo[a]pyrene, polycyclic aromatic hydrocarbons, heavy metals, and microplastics, has been extensively studied. (c) Research on the molecular mechanisms underlying the trait of new phytoplankton species, including classification at the family and genus levels, genetic evolution (e.g., chloroplast), etc., has progressed significantly. (d) Research on the relationship between phytoplankton trait and food chains and food webs has been ongoing.

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The following are some thoughts on future research directions for phytoplankton trait: (1) What is the molecular mechanism of the morphological changes that some phytoplankton exhibit in response to environmental changes, and are there any new phytoplankton traits? (2) What common characteristics do species that can indicate environmental toxins share, providing further support for monitoring toxic and harmful pollutants? (3) Further improve the whole-genome sequencing of phytoplankton, which will help discover more new morphological species and promote research on valuable phytoplankton traits. (4) How can the proportion of different trait phytoplankton in food chains and food webs be used to address ecological environmental problems?

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