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The Role of Phytoplankton as an Indicator of Trophic Status and Primary Productivity in Marine Waters

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Abstract
Phytoplankton are fundamental components of marine ecosystems because they function as primary producers and sensitive ecological indicators of environmental change. This study aimed to analyze the role of phytoplankton as indicators of trophic status and primary productivity in marine waters through a literature synthesis approach. The research employed a literature review method using a narrative-systematic review design based on PRISMA guidelines by analyzing 78 international scientific articles published between 2009 and 2024 from Scopus, Web of Science, and Google Scholar databases. Data were analyzed using thematic synthesis to identify relationships among phytoplankton community structure, trophic conditions, and primary productivity. The results showed that phytoplankton abundance, chlorophyll-a concentration, biomass, and taxonomic composition were strongly influenced by nutrient dynamics, temperature, water column stratification, and oceanographic processes such as upwelling. Dinoflagellates and cyanobacteria tended to dominate under eutrophic conditions, whereas small-sized phytoplankton were more prevalent in oligotrophic waters. In conclusion, phytoplankton are effective bioindicators for assessing trophic status and marine primary productivity. These findings highlight the importance of integrating biological and oceanographic parameters in marine ecosystem monitoring to support sustainable coastal management.

Keywords: chlorophyll-a; eutrophication; phytoplankton; primary productivity.

INTRODUCTION

Phytoplankton are fundamental components of marine ecosystems because they function as the primary producers that sustain marine food webs through photosynthesis and contribute significantly to the global carbon cycle. Variations in phytoplankton abundance, composition, and distribution have long been recognized as important ecological indicators due to their rapid response to changes in the physical and chemical conditions of aquatic environments, including temperature, nutrients, light availability, and oceanographic dynamics (Brewin et al., 2021; Dokulil & Qian, 2021). On a global scale, phytoplankton account for nearly half of the Earth's primary productivity; therefore, changes in their community structure have major implications for trophic balance, fisheries productivity, and the stability of marine ecosystems (Karlusich et al., 2020). Consequently, phytoplankton studies are essential for understanding the ecological functioning of marine waters comprehensively.

Marine primary productivity is influenced by nutrient availability, light intensity, temperature, water column stratification, and oceanographic processes such as upwelling and vertical mixing. Nutrients such as nitrogen, phosphorus, and iron regulate phytoplankton growth, while light and temperature determine photosynthetic efficiency (Browning & Moore, 2023; Wu et al., 2021). Strong stratification may inhibit nutrient supply, whereas upwelling and vertical mixing enhance primary productivity by transporting nutrients into surface waters (Chen et al., 2021; Brandt et al., 2023). Under favorable conditions, increased nutrient availability supports phytoplankton growth and elevates the trophic status of aquatic systems, whereas in oligotrophic environments only certain groups are capable of adapting to nutrient limitations (Gregg & Rousseaux, 2019; Wu et al., 2021). The structure of phytoplankton communities, particularly the dominance of diatoms, dinoflagellates, or cyanobacteria, is frequently used to identify the trophic level and primary productivity of marine environments. Therefore, phytoplankton not only reflect the biological condition of marine waters but also serve as effective bioindicators for assessing ecological dynamics and environmental quality.

However, global climate change, coastal eutrophication, and increasing anthropogenic nutrient loads have caused significant alterations in phytoplankton community structures across many marine regions worldwide (Henson et al., 2021; Tsikoti & Genitsaris, 2021). Ocean warming and intensified stratification can alter the spatial and temporal distribution of phytoplankton, while increased nitrogen and phosphorus inputs from human activities accelerate eutrophication and promote the dominance of certain species, including harmful algal blooms (HABs), which may disrupt marine ecosystem stability. Stronger stratification resulting from ocean warming can restrict nutrient supply to the euphotic zone, whereas nitrogen and phosphorus runoff from terrestrial sources may trigger HABs that threaten ecosystem stability (Glibert, 2020). These conditions indicate that the relationship between phytoplankton, trophic status, and primary productivity has become increasingly complex, particularly at the local scale, which remains insufficiently explored in scientific studies. Therefore, research specifically examining phytoplankton community structure as both an indicator of trophic status and a determinant of primary productivity is urgently needed to support water quality monitoring, early detection of eutrophication, and sustainable coastal management planning.

Based on this urgency, the present study aims to analyze the role of phytoplankton as indicators of trophic status and primary productivity in marine waters through a comprehensive ecological approach. This study is expected to strengthen the scientific basis for evaluating marine environmental quality, contribute to conservation strategies and coastal resource management, and serve as an important reference for addressing the impacts of climate change on marine ecosystems. In addition, the findings are expected to broaden the understanding of the relationship between phytoplankton community dynamics and the sustainability of marine ecosystem productivity at both regional and global scales.

RESEARCH METHODS

Research Design

This study employed a literature review method using a narrative-systematic review design to synthesize scientific findings regarding the role of phytoplankton as indicators of trophic status and primary productivity in marine waters. This approach was selected because it enables a comprehensive, systematic, and critical exploration, evaluation, and integration of previous studies, thereby generating a strong conceptual understanding of phytoplankton ecological dynamics in marine environments (Tranfield et al., 2003; Snyder, 2019). The study population consisted of all scientific articles relevant to phytoplankton, primary productivity, eutrophication, and trophic indicators in marine waters available in internationally recognized databases. Preliminary literature searches were conducted through Scopus, Web of Science, and Google Scholar.

The inclusion criteria comprised reputable international journal articles discussing the relationship between phytoplankton and trophic status or primary productivity in marine waters, including studies with empirical data or conceptual analyses supported by scientific evidence. Meanwhile, opinion articles, non-peer-reviewed proceedings, studies conducted in freshwater ecosystems, and articles with unclear methodologies were excluded from the analysis. The main variables analyzed included phytoplankton abundance, community composition, chlorophyll-a concentration, trophic status, primary productivity, eutrophication, and oceanographic factors such as nutrients, temperature, light availability, stratification, and upwelling. The literature search process used combinations of the keywords phytoplankton, trophic indicator, primary productivity, chlorophyll-a, marine waters, and eutrophication to ensure the relevance and comprehensiveness of the scientific sources included in the study.

Research Procedure

The research procedure followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, consistency, and validity in the literature selection process (Page et al., 2021). The stages of the study included article identification through keyword searches, screening based on titles and abstracts, full-text review, extraction of primary data, and synthesis of research findings. The extracted data included research methods, study locations, trophic indicators used, phytoplankton variables, and the main findings of each study. Furthermore, the results were synthesized using a thematic synthesis approach to identify patterns in the relationships between phytoplankton community structure, trophic status, and primary productivity in greater depth (Thomas & Harden, 2008).

Literature Analysis Stages

Data analysis was conducted qualitatively through thematic synthesis to identify conceptual relationships among studies and to develop scientific generalizations based on consistent findings. The validity of the review was strengthened through cross-checking among sources, evaluation of journal reputation, assessment of methodological clarity, and examination of the consistency of reported findings (Kitchenham & Charters, 2007). Through this method, the study is expected to produce a valid, comprehensive, and applicable scientific synthesis that can serve as a foundation for monitoring marine water quality, early detection of eutrophication, and sustainable coastal ecosystem management.

RESULTS AND DISCUSSION

Findings of the Literature Review

The structure of phytoplankton communities is one of the most widely used biological indicators for assessing trophic status and primary productivity in marine waters. Variations in phytoplankton biomass, cell size, and taxonomic composition exhibit sensitive responses to changes in environmental conditions such as nutrient availability, temperature, light intensity, and water mass dynamics. The synthesis of various studies indicates that increases in nutrient concentrations are generally followed by increases in phytoplankton biomass and shifts in the dominance of particular species, especially diatoms and dinoflagellates. Therefore, phytoplankton community analysis can be used to describe the fertility level of marine waters as well as the ecological condition of marine ecosystems.

The synthesis results demonstrate that chlorophyll-a concentration, phytoplankton abundance, and cell size structure (size spectrum) are the primary indicators most frequently used to determine the trophic status of marine waters. Waters with high nutrient levels tend to exhibit greater phytoplankton biomass and dominance of large-sized species such as diatoms. In contrast, oligotrophic conditions are generally characterized by phytoplankton communities dominated by smaller species that are more adaptive to nutrient limitations. These findings indicate that changes in phytoplankton community structure are strongly influenced by nutrient dynamics and oceanographic conditions.

The findings of this study are consistent with those of Browning and Moore (2023), who reported that nitrogen and phosphorus nutrient ratios significantly influence primary productivity and phytoplankton community structure in marine environments. Ridho et al. (2020) also found that increased chlorophyll-a concentrations were positively correlated with phytoplankton abundance in eutrophic coastal regions. Furthermore, Saragih et al. (2024) emphasized that the combined use of biotic and abiotic parameters provides a more accurate assessment of trophic status compared to the use of a single parameter alone. Nevertheless, several studies have shown that phytoplankton responses to environmental changes may vary among regions due to differences in oceanographic characteristics, pollution intensity, and local climate dynamics.

Table 1. Synthesis of Phytoplankton Indicators as Determinants of Trophic Status and Primary Productivity

Researcher	Main Indicators	Research Findings	Implications
Browning & Moore (2023)	N:P nutrient ratio and chlorophyll-a	Nutrient availability determines phytoplankton biomass	Determines the level of primary productivity
Ridho et al. (2020)	Phytoplankton abundance and chlorophyll-a	Phytoplankton abundance increases in eutrophic waters	Serves as a bioindicator of water quality
Saragih et al. (2024)	Water transparency, nutrients, and phytoplankton	The combination of biotic and abiotic indicators provides greater accuracy	Enables a more comprehensive diagnosis of trophic status
Kafrissen et al. (2022)	Nutrient distribution and primary productivity	Nutrients influence changes in phytoplankton community structure	Determines marine ecosystem dynamics
Al-Mur (2025)	Phytoplankton diversity and chlorophyll-a	Community structure changes due to environmental pressures	Indicator of eutrophication and pollution

Source: Literature synthesis results, 2025.

Overall, this synthesis demonstrates that phytoplankton play a crucial role as bioindicators in monitoring marine water quality and primary productivity. Changes in phytoplankton community structure may serve as early indicators of eutrophication, nutrient pollution, and ecological changes associated with climate change. The implications of these findings highlight the importance of integrating phytoplankton parameters with other oceanographic factors in marine environmental monitoring systems to support sustainable coastal zone management.

Phytoplankton as Indicators of Trophic Status

Changes in water conditions from oligotrophic to eutrophic states are reflected in the rapid response of phytoplankton communities to increasing dissolved nutrient concentrations. Increases in nitrogen and phosphorus are generally followed by higher chlorophyll-a concentrations and phytoplankton biomass, indicating enhanced primary productivity in marine waters. Under oligotrophic conditions, phytoplankton communities are typically dominated by small-sized species that are highly adapted to nutrient limitations, whereas eutrophic conditions are characterized by the dominance of dinoflagellates and cyanobacteria that are more tolerant of nutrient-rich environments and stable water columns (Henson et al., 2021; Glibert, 2020). This phenomenon demonstrates that changes in phytoplankton community structure can serve as sensitive indicators of shifts in the trophic status of marine ecosystems.

The synthesis results indicate that increasing nutrient loads significantly affect phytoplankton community structure and accelerate the eutrophication process in marine waters. Chlorophyll-a concentration shows a strong correlation with total nitrogen and phosphorus and is therefore frequently used as a primary indicator in determining the fertility level of marine ecosystems. In addition to increasing phytoplankton biomass, nutrient enrichment also alters species dominance toward groups with the potential to produce harmful algal blooms (HABs). Such conditions commonly occur in coastal regions experiencing high anthropogenic pressures from agricultural runoff, domestic waste, and industrial activities.

Table 2. Synthesis of Phytoplankton Responses to Eutrophication and Changes in Trophic Status (2020–2025)

Researcher	Research Focus	Main Findings	Implications
Henson et al. (2021)	Climate change and phytoplankton diversity	Shifts in phytoplankton distribution and composition due to ocean warming	Alters marine trophic structure
Glibert (2020)	Eutrophication and HABs	High nutrient concentrations trigger dinoflagellate dominance and algal blooms	Decline in water quality
West et al. (2021)	HABs and climate change	Temperature changes accelerate the blooming of certain phytoplankton species	Increased ecological risks
Browning & Moore (2023)	Marine nutrient limitation	Nitrogen and phosphorus regulate phytoplankton biomass	Determines primary productivity
Wu et al. (2021)	Ocean warming and nutrients	Warming and eutrophication alter phytoplankton community structure	Disrupts ecosystem stability

Source: Literature synthesis results, 2025.

These findings are consistent with the study by Henson et al. (2021), which demonstrated that climate change and ocean stratification have altered the global distribution and diversity of phytoplankton communities. Glibert (2020) and West et al. (2021) further emphasized that eutrophication and increased anthropogenic nutrient inputs accelerate the occurrence of dinoflagellate blooms and harmful algal blooms (HABs) in coastal regions. Browning and Moore (2023) found that nitrogen and phosphorus nutrient ratios play a critical role in controlling phytoplankton biomass and marine primary productivity. Meanwhile, Wu et al. (2021) explained that the combined effects of ocean warming and nutrient enrichment lead to significant changes in phytoplankton community structure and marine ecosystem stability. Nevertheless, phytoplankton community responses may vary among regions depending on oceanographic characteristics, pollution intensity, and local climatic conditions.

In general, the dynamics of phytoplankton abundance and composition can be used as an early warning system for the degradation of marine water quality caused by eutrophication. The ability of phytoplankton to respond rapidly to nutrient changes makes them effective bioindicators for detecting ecological disturbances before more extensive impacts occur, such as hypoxia, mass mortality of marine organisms, and declines in fisheries productivity. Therefore, periodic phytoplankton monitoring is essential for supporting marine water quality management and mitigating pollution impacts in coastal areas.

Relationship Between Phytoplankton and Primary Productivity

Primary productivity in marine environments is the result of complex interactions between the biological characteristics of phytoplankton communities and the physical conditions of the water column in which these organisms live. High phytoplankton abundance does not always reflect high primary productivity unless it is supported by an efficient cell size structure and oceanographic dynamics capable of distributing nutrients into the euphotic zone. Recent studies indicate that phytoplankton cell size structure strongly influences photosynthetic efficiency and the ability to adapt to varying nutrient conditions. Small-sized phytoplankton tend to be more efficient in absorbing nutrients under oligotrophic conditions because they possess a higher surface-area-to-volume ratio compared to larger organisms (Zhang et al., 2025). Therefore, cell size composition is an important factor in determining the magnitude of primary productivity in marine waters.

In addition to biological factors, the physical conditions of the water column also play a crucial role in controlling nutrient distribution utilized by phytoplankton. Water column stratification caused by sea surface warming creates stable water layers that inhibit vertical mixing, thereby limiting nutrient transport from deeper waters into the euphotic zone. This condition leads to reductions in phytoplankton biomass and primary productivity, particularly in tropical and subtropical regions experiencing intensive increases in sea surface temperature (Henson et al., 2021; Wu et al., 2021). In contrast, upwelling phenomena and seasonal variability such as monsoon winds can enhance primary productivity through the transport of nutrient-rich deep waters to the ocean surface. Increased concentrations of nitrogen, phosphorus, and silicate in the euphotic zone stimulate rapid phytoplankton growth and significantly increase primary biomass (Brewin et al., 2021; Browning & Moore, 2023).

These findings indicate that phytoplankton responses not only reflect the trophic condition of marine waters but are also strongly influenced by physical oceanographic dynamics that regulate nutrient distribution within the water column. Interactions among phytoplankton community structure, ocean stratification, and upwelling processes constitute the primary mechanisms controlling the stability of marine primary productivity. Therefore, understanding the relationships between biological and physical factors in marine environments is essential for predicting changes in ocean productivity resulting from climate change and anthropogenic pressures on coastal and open-ocean ecosystems.

Chlorophyll-a as a Proxy for Productivity

Chlorophyll-a is the primary pigment of phytoplankton and is widely used as a proxy for primary productivity because of its close relationship with phytoplankton biomass and photosynthetic rates in marine waters. Chlorophyll-a concentrations can be measured directly using spectrophotometric and fluorometric methods or indirectly through ocean color remote sensing technologies. Tilstone et al. (2021), in Remote Sensing of Environment, demonstrated that chlorophyll-a estimates derived from MODIS-Aqua, VIIRS, and Sentinel-3 OLCI sensors accurately represent the distribution of marine primary productivity in the open Atlantic Ocean. Furthermore, Lee and Marra (2022) explained that chlorophyll-a has a strong empirical relationship with carbon fixation rates and is therefore frequently used as a practical indicator for estimating primary productivity across various spatial and temporal scales.

Advances in satellite technology have enabled continuous chlorophyll-a monitoring from coastal regions to the open ocean with extensive spatial coverage and high temporal resolution. Su et al. (2021) found that machine learning approaches based on OLCI data improve the accuracy of chlorophyll-a estimation in coastal waters characterized by complex optical properties due to high concentrations of suspended sediments and colored dissolved organic matter (CDOM). Kolluru and Tiwari (2022) also demonstrated that integrating remote sensing algorithms with machine learning techniques enhances the precision of global chlorophyll-a distribution mapping. These findings highlight that field validation and algorithm development are critical factors in improving the accuracy of satellite-based interpretations of primary productivity.

In addition to its broad spatial coverage, remote sensing–based chlorophyll-a monitoring is highly effective for assessing the temporal dynamics of marine primary productivity. Yu et al. (2023) developed a global chlorophyll-a dataset to detect trends in marine primary productivity changes associated with climate change and long-term oceanographic dynamics. Chlorophyll-a time-series data are widely used to identify phytoplankton bloom events, responses to upwelling, and the impacts of water column stratification caused by ocean warming. Thus, chlorophyll-a functions not only as an indicator of phytoplankton biomass but also as an effective diagnostic tool for monitoring the quality and productivity of marine ecosystems at local to global scales.

Changes in Taxonomic Composition as Signals of Eutrophication

Changes in the taxonomic composition of phytoplankton communities represent one of the most sensitive biological indicators for detecting water quality degradation caused by eutrophication and increasing anthropogenic nutrient loads. The transition of marine waters from oligotrophic to chronically eutrophic conditions not only increases phytoplankton biomass but also alters community structure through the dominance of certain opportunistic species. Numerous studies have shown that increasing nitrogen and phosphorus concentrations are often accompanied by greater dominance of dinoflagellates and cyanobacteria capable of triggering harmful algal blooms (HABs) (Glibert, 2020; West et al., 2021). These conditions demonstrate that phytoplankton communities respond rapidly to changes in water quality and can therefore serve as early indicators of marine ecosystem degradation.

Recent studies have shown that certain dinoflagellate groups possess high adaptive capacity under nutrient-rich conditions and stable water columns resulting from stratification. Glibert (2020) explained that increased nutrient inputs from anthropogenic activities such as agricultural runoff, domestic waste discharge, and aquaculture accelerate the dominance of specific phytoplankton species capable of proliferating explosively. Such conditions frequently trigger bloom events that lead to decreased dissolved oxygen concentrations, mass mortality of marine organisms, and human health disturbances caused by toxins produced by several HAB species. In addition to increasing ecological risks, the dominance of certain species also causes simplification of phytoplankton communities, where species sensitive to environmental changes gradually disappear.

Changes in phytoplankton community composition occur not only at local scales but have also been consistently observed across coastal regions worldwide. Henson et al. (2021) demonstrated that climate change and increasing ocean temperatures reduce global phytoplankton diversity, particularly in regions experiencing strong stratification. West et al. (2021) further emphasized that the combined effects of eutrophication and ocean warming intensify the frequency and magnitude of harmful phytoplankton blooms in coastal waters. Meanwhile, Browning and Moore (2023) found that imbalances in nitrogen and phosphorus ratios can alter trophic community structure and accelerate the dominance of opportunistic species. These findings indicate that shifts in phytoplankton taxonomic composition are strongly influenced by interactions among oceanographic conditions, nutrient dynamics, and anthropogenic pressures.

Overall, changes in phytoplankton species composition provide more diagnostic information than biomass or chlorophyll-a measurements alone. Taxonomic analysis of phytoplankton communities can reveal the direction of ecosystem change and the potential environmental risks that may emerge in the future, such as hypoxia, degradation of benthic habitats, and disruption of marine food webs. Therefore, periodic monitoring of phytoplankton communities is essential for supporting early warning systems for water quality degradation and sustainable coastal ecosystem management.

Integration of Biotic and Abiotic Indicators

The synthesis of various studies demonstrates that determining the trophic status of marine waters becomes more accurate when biotic indicators such as phytoplankton are analyzed together with abiotic parameters, including dissolved nutrient concentrations, temperature, salinity, water transparency, and dissolved oxygen (DO). This integrated approach enables researchers not only to identify changes occurring within phytoplankton communities but also to understand the environmental factors driving those changes. Several studies have shown that integrating phytoplankton community structure with the physicochemical parameters of marine waters provides a more comprehensive interpretation of trophic status compared to the use of a single indicator. Rosadi et al. (2020) found that the combination of nutrient parameters, chlorophyll-a, DO, and plankton community structure effectively identifies the degree of eutrophication in marine environments. In addition, Naik et al. (2020) and Samawi et al. (2020) emphasized that variations in temperature, salinity, and nutrient availability are closely associated with phytoplankton distribution and trophic dynamics in aquatic ecosystems. Meanwhile, Glibert (2020) and West et al. (2021) explained that increased anthropogenic nutrient inputs combined with changes in temperature and hydrodynamic conditions are the major factors controlling eutrophication and primary productivity in coastal regions. They further demonstrated that the combined effects of eutrophication and ocean warming accelerate harmful phytoplankton blooms and disrupt the stability of coastal ecosystems.

In marine ecological analyses, multivariate statistical methods such as principal component analysis (PCA) and canonical correspondence analysis (CCA) are widely used to identify complex relationships between environmental parameters and phytoplankton community responses. These techniques are capable of mapping dominant environmental gradients influencing species distribution and grouping observation sites based on similar ecological characteristics. Findings from numerous studies indicate that nutrient ratios, such as nitrogen-to-phosphorus (N:P) and nitrogen-to-silicate (N:Si), exert stronger influences on community composition than absolute nutrient concentrations alone. Browning and Moore (2023) found that imbalances in nutrient ratios can alter trophic structure and determine which phytoplankton groups are more competitive in utilizing available resources in marine waters.

Low N:Si ratios generally support diatom dominance because this group requires silicate for frustule formation. In contrast, high N:P ratios tend to favor the growth of dinoflagellates and certain cyanobacteria that are more tolerant of eutrophic conditions and nutrient imbalances. In addition to chemical factors, physical parameters such as temperature, salinity, and water column stratification also play essential roles in controlling the vertical distribution of phytoplankton and their photosynthetic efficiency. Henson et al. (2021) demonstrated that increased stratification caused by ocean warming can limit vertical mixing and reduce nutrient supply to the euphotic zone, thereby significantly affecting primary productivity and phytoplankton community structure.

Overall, the integration of biotic and abiotic indicators provides a more diagnostic analytical framework for understanding trophic dynamics and marine water quality. This integrated approach captures the complex interactions between environmental pressures and biological responses simultaneously, making it more effective for monitoring dynamic coastal ecosystems. The implications of this synthesis suggest that combining phytoplankton community analysis with physical and chemical oceanographic parameters is essential for supporting early detection of eutrophication, marine water quality management, and mitigation of environmental changes in marine ecosystems.

CONCLUSION

The findings of this study demonstrate that phytoplankton play a crucial role as ecological indicators in determining the trophic status and primary productivity of marine waters. Changes in phytoplankton abundance, biomass, chlorophyll-a concentration, and taxonomic composition were found to be closely correlated with nutrient dynamics and the physicochemical conditions of marine environments, thereby effectively reflecting the transition of waters from oligotrophic to eutrophic conditions. Furthermore, the integration of biotic and abiotic indicators through multivariate approaches provides a more comprehensive and diagnostic interpretation of trophic conditions compared to the use of single parameters alone. Therefore, phytoplankton function not only as primary producers within marine ecosystems but also as practical bioindicators for the early detection of eutrophication, monitoring of marine water quality, and sustainable ecosystem-based coastal management.

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