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Phytoplankton community response to seasonal eutrophication in Maninjau Lake, West Sumatra, Indonesia

PUTI SRI KOMALA[1], TRI RETNANINGSIH SOEPROBOWATI[2,♥], NOVERITA DIAN TAKARINA[3], LUKI SUBEHI[4], MARTA WOJEWODKA-PRZYBYL[5], BUDHI PRIMASARI[1], TIVANY EDWIN[1], LIA ARLINA[1], REGINA MARDATILLAH[1]

[1]Department of Environmental Engineering, Faculty of Engineering, Universitas Andalas. Jl. Limau Manis, Padang 25163, West Sumatra, Indonesia
[2]Department of Biology, Faculty of Science and Mathematics, Universitas Diponegoro. Jl. Prof. Soedarto, Semarang 50275, Central Java, Indonesia. Tel./fax.: +62-24-7474754, ♥email: trsoeprobowati@live.undip.ac.id
[3]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Indonesia. Jl. Lingkar, Depok 16424, West Java, Indonesia
[4]Research Center for Limnology and Water Resources, National Research and Innovation Agency. Jl. M.H. Thamrin No. 8, Central Jakarta 10340, Jakarta, Indonesia
[5]Institute of Geological Sciences, Polish Academy of Sciences. 02-093 Warsaw, Poland

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Abstract. *Komala PS, Soeprobowati TR, Takarina ND, Subehi L, Wojewodka-Przybyl M, Primasari B, Edwin T, Arlina L, Mardatillah R. 2026. Phytoplankton community response to seasonal eutrophication in Maninjau Lake, West Sumatra, Indonesia. Biodiversitas 27 (2): d270232. https://doi.org/10.13057/biodiv/d270232*. The aim of this study is to analyze the seasonal trophic status of Maninjau Lake using the Comprehensive Trophic Status Index (CTSI) and to examine its spatial and temporal relationship with the phytoplankton community structure. The water and phytoplankton samples were collected from 10 sampling points in accordance with SNI 6989-57-2008 and the ecological protocol. Results show that CTSI values ranged from 62.59 to 73.28, indicating eutrophic to hypereutrophic conditions. The trophic sub-indices showed TSI-TP values of 53.24-82.20, TSI-TN values of 50.97-61.49, and TSI-Chl-a values of 52.98-62.07. Based on spatial analysis, the trophic status is relatively homogeneous across all sampling locations, indicating widespread nutrient loading in the lake. On the other hand, higher CTSI values during the rainy season and temporal variation of CTSI are significant. The increase in CTSI was associated with a change in phytoplankton dominance from Bacillariophyceae under eutrophic conditions to Cyanophyceae under hypereutrophic conditions, reflecting tolerance to increased nutrient concentrations. The hypereutrophic status of Maninjau Lake favored opportunistic taxa, as indicated by an increase in the dominance index and decreases in diversity and evenness. Rainfall contributes to shaping phytoplankton community dynamics, affecting the trophic status of the lake. This study highlights that integrating CTSI, phytoplankton ecological indices, and rainfall variability provides a useful framework for assessing air quality degradation and ecosystem stability in tropical lakes.

Keywords: Eutrophication, floating net cages, Maninjau Lake, phytoplankton, spatial-temporal

INTRODUCTION

Maninjau Lake is a deep caldera lake with a volume of 9.79 km³ and a maximum depth of 165-168 m, and is located in West Sumatra, Indonesia (De Maisonneuve et al. 2019; Subehi et al. 2021). The lake has served as a vital socio-economic asset, supporting hydropower generation, capture fisheries, tourism, and aquaculture, with floating net cages (FNC) as the dominant fish production system (Komala et al. 2023). The lake is experiencing excessive nutrient loading of nitrogen (N) and phosphorus (P) from FNC aquaculture. This condition has accelerated eutrophication processes and stimulated algal blooms (Yu et al. 2022).

Aquacultures and cultural eutrophication have caused environmental stress to the lake (De Maisonneuve et al. 2019; Makmur et al. 2020). By 2022, more than 20,000 FNC units were operating in the lake (BAPPEDA Kab. Agam 2022). It led to the discharge of excess fish feed and fish excretions into the lake, elevating nutrient inputs and exacerbating eutrophication. This has also contributed to reduced water transparency, damage to aquatic habitats, and increased fish mortality (Sulastri et al. 2022; Yu et al. 2022).

Aquatic biota are threatened by persistent eutrophication, which can degrade water quality and cause severe declines in dissolved oxygen. One indicator sensitive to ecosystem imbalance and environmental degradation is an excessive increase in phytoplankton abundance (Yu et al. 2022). Therefore, it is important to conduct systematic and comprehensive monitoring of the lake's trophic status and overall water quality (Tanjung et al. 2024).

The Comprehensive Trophic Status Index (CTSI) is one of the methods for evaluating trophic status, which considers several water quality parameters, including Secchi depth (SD), chlorophyll a (Chl-a), total phosphorus (TP), total nitrogen (TN), and chemical oxygen demand (COD) (Tang et al. 2019). A clearer and more comprehensive assessment of pollution levels and potential ecosystem degradation in relation to trophic status can be achieved through CTSI assessments, thereby supporting more effective water resource management.

Phytoplankton communities also serve as biological markers of ecological health in lakes, and their composition

and diversity are strongly associated with trophic states (Muhtadi et al. 2020; Othman et al. 2024). Eutrophic systems typically reflect reduced diversity and dominance of tolerant taxa, which thrive under high nutrient concentrations and low oxygen levels (Lenard et al. 2019; Essa et al. 2024). The trophic status of Maninjau Lake shifted from mesotrophic to hypereutrophic between 2009 and 2019, followed by low phytoplankton diversity (27 species) and an increase in fish mass mortality (Sulastri et al. 2019; Komala et al. 2020). These ecological changes have a significant impact on the sustainability of fisheries and water resources (Sulastri et al. 2022).

Studies of other lake systems further highlight the importance of trophic assessment, as depicted by Lake Baikal, which shows high seasonal variability and productivity, with spring dominance of diatoms under oligotrophic conditions (Mineeva and Bondarenko 2024). In contrast, eutrophication in Baiyangdian Lake decreased plankton diversity and increased eutrophication potential, primarily driven by high nitrogen and phosphorus levels (Tang et al. 2019). These opposite conditions highlight the importance of integrating trophic status assessment with phytoplankton dynamics to develop effective conservation strategies.

With this background, this study aims to analyze spatial and temporal variation in Maninjau Lake's trophic status using the Comprehensive Trophic Status Index (CTSI) and to evaluate phytoplankton dynamics as an indicator of the lake's ecological health. The study emphasizes identifying seasonal patterns in trophic status and investigating the role of phytoplankton in reflecting the ecosystem response to increased nutrient levels. Therefore, this study is expected to provide insights into seasonal eutrophication processes and serve as a basis for effective lake management strategies by integrating spatial and temporal monitoring with phytoplankton-based assessments.

MATERIALS AND METHODS

Study area

This research was conducted at Maninjau Lake, located in Tanjung Raya Regency, West Sumatra Province, Indonesia (Figure 1). This lake is a volcanic caldera system located about 461 m above sea level. Maninjau Lake covers approximately 99.5 km², has an average depth of 105 m, and a maximum depth of nearly 165 m. The lake holds approximately 10.3 billion m³ of water in a river basin area of 149 km². The surrounding area is characterized by humid tropical conditions, with an average wind speed of 23.4 km/h, relative humidity reaching 95.20%, and average monthly rainfall of approximately 325.8 mm. Hydrologically, the lake receives inflows from 88 rivers of various sizes, the largest of which is up to 8 m wide. These extensive inflows, combined with a relatively long water residence time of 9-12 years, support nutrient accumulation and enhance the lake's internal loading processes. Maninjau Lake is classified as a tropical monomictic lake, which experiences one major mixing period associated with the transition between the rainy and dry seasons. These seasonal mixing conditions, together with slow water renewal, greatly influence nutrient distribution, vertical oxygen stratification, and phytoplankton dynamics. These characteristics make Maninjau Lake an important natural system for studying eutrophication processes and broader ecological responses in tropical lake environments.

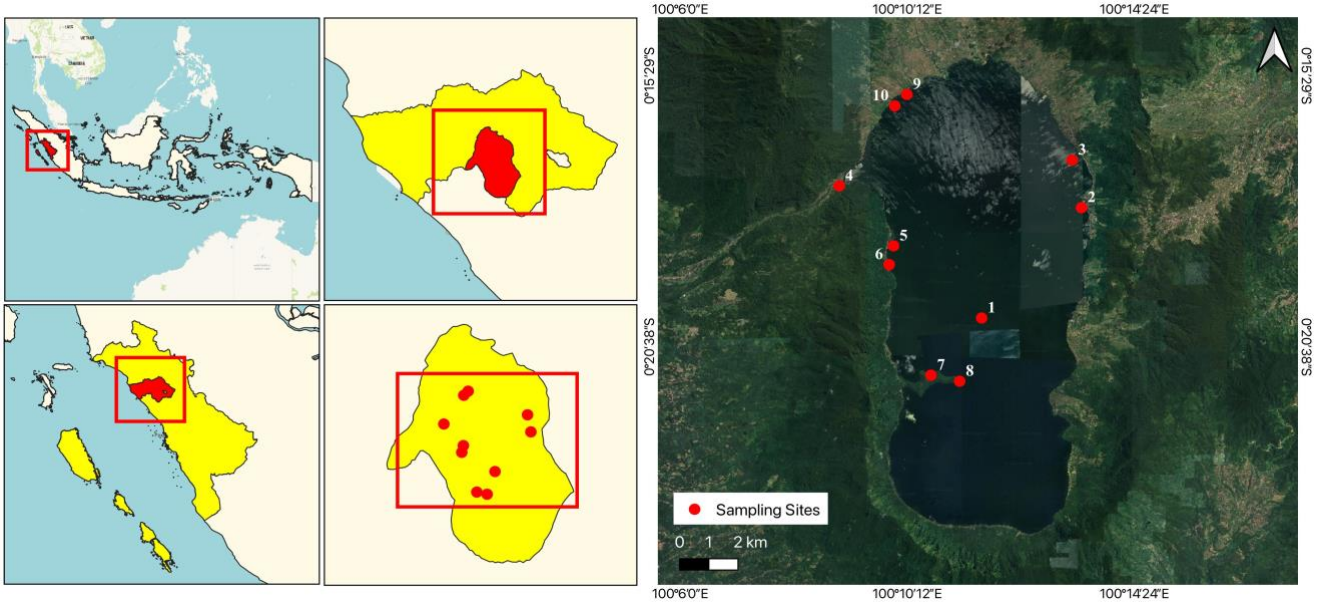

Figure 1. Map of the study area, location at Maninjau Lake, Agam Regency, West Sumatra, Indonesia. 1. Middle of the lake, 2. Pangkal Tanjung, 3. Unpopulated area, 4. Antokan, 5. Batang Kurambik, 6. Hotel, 7. Floating Net Cages, 8. North, 9. Settlement, 10. Tampang river

Table 1. Description of sampling locations

Sampling locations	Coordinate	Description
Middle of the lake	S 0°20'9.22"S, E 100°11'37.36"	Middle of the lake
Pangkal Tanjung	S 0°21'4.48"S, E 100°10'33"	Nagari Tanjuang Sani Medium FNC area Medium settlement
Unpopulated area	S 0°21'10.757", E 100°10'56.610"	Nagari Tanjuang Sani No settlement and no FNC
Antokan	S 0°17'34.413", E 100°8'56.652"	Nagari Koto Malintang Maninjau Lake outlet
Batang Kurambik	S 0°15'49.967", E 100°10'11.643"	Nagari Koto Gadang Maninjau Lake inlet Agricultural area
Hotel	S 0°17'59.325", E 100°13'25.469"	Nagari Maninjau Relatively densely populated areas Medium FNC
Floating Net Cages	S 0°16'1.216", E 100°10'1.788"	Nagari Bayur Center FNC Medium settlement Moderate agricultural area
North	S 0°15'54.124", E 100°10'9.376"	Nagari Bayua Talao area Medium settlement Medium FNC and Unpopulated
Settlement	S 0°19'4.321", E 100°9'52.047”	Nagari Tanjung Sani Highly populated area A high number of FNC Medium-scale FNC
Tampang river	S 0°18'42.829", E 100°9'56.922"	Nagari Tanjung Sani Located away from residential and Medium FNC

Table 2. Development of the floating net cage cultivation sector

Year	Number of FNC
2016	16.734
2017	16.921
2018	17.563
2019	17.563
2020	17.563
2021	17.417
2022	23.359

Source: Syandri (2020); BAPPEDA Agam (2022); Soejarwo et al. (2022); Komala et al. (2023)

Table 3. Laboratory testing parameters

Test parameters	Reference
COD	SNI 6989.73:2009
Total N	SNI 06.6989.30.2005
Total P	SNI 06.6989.31.2005
Klorofil-a	Acetone method using spectrophotometer

Specifically, this study was conducted at 10 sampling sites representing the inlet zone, the middle of the lake, fish-farming areas, and outlets (Figure 1). The geographical coordinates of each station are presented in Table 1. Sampling was carried out in 3 periods: September 2022 and January to March 2023, with two main observation layers: the surface (0-1 m) and the bottom layer (10-15 m). Fish farming with FNC in Maninjau Lake is one of the sources of livelihood for the people around the lake. Cages are installed at varying distances from the lake's edge, ranging from 25 to 150 m. The number of FNC from 2016 to 2022 is shown in Table 2.

Procedures

Water sampling

Determining the location and point of water sampling was based on SNI 6989.57:2008, the guidelines for surface water sampling in the context of water and wastewater analysis. Water sampling was conducted using the composite sampling method. Samples were collected in 500 mL glass bottles, sealed airtight to prevent air entry, preserved according to the test parameters listed in Table 3, and then labeled and stored in a cool box. The water samples were then analyzed at the Department of Environmental Water Laboratory, Environmental Engineering, Universitas Andalas, Indonesia.

This study analyzed physicochemical parameters, including temperature, pH, DO (Dissolved Oxygen), brightness, TN, TP, Chl-a, and COD. In-situ parameters including, pH, DO, and temperature, were measured using a multiparameter water-quality meter (YSI ProDSS) calibrated daily before sampling. Laboratory analysis for COD, TN, TP, and Chl-a was carried out according to the Indonesian National Standard (SNI) listed in Table 3. Each measurement is performed in duplicate, and the results are presented as average values to ensure data accuracy and reproducibility. Rainfall and wind speed data corresponding to the sampling periods (September 2022, January 2023, and March 2023) were incorporated to support the interpretation of temporal variability in water quality parameters and trophic status obtained from the Meteorology, Climatology, and Geophysical Agency of Agam Regency (BMKG).

Phytoplankton sampling

The phytoplankton sampling technique was based on the book “Ecological Methods for Field and Laboratory Investigation” (García-Rodríguez et al. 2012) and the work of Jia et al. (2020). Plankton samples were conducted using a No. 31 plankton net, drawn vertically from 0.5 to 1 m in depth. The samples were collected, filtered, and transferred into 30 mL plastic bottles for phytoplankton identification. 3-4 drops of Lugol's solution were added to preserve the samples and prevent phytoplankton proliferation or changes. Samples were stored in a cool box, transported to the laboratory, and refrigerated at 4°C until analysis.

Comprehensive Trophic State Index (CTSI) calculation

The trophic status of lakes is calculated using the CTSI method based on the Trophic Status Index (TSI) parameters, including SD, Chl-a, TP, TN, and COD, as listed in Equation 1 (Tang et al. 2019). CTSI was previously used to evaluate trophic status in China by accounting for the complex responses arising from interactions among various physical, chemical, and biological factors (Chen et al. 2021).

$$CTSI = \sum_{j=1}^{m}[W_j \times TSI(j)] \quad (1)$$

Where TSI(j) is the j_{th} Trophic State Index among TSI(Chl-a), TSI(TN), TSI(TP), TSI(SD), and TSI(COD), calculated by Equations 2-6; m is the number of trophic state indices, and m = 5; Wj is the weight of TSI(j), based on Chl-a content, and is expressed by Equation (7).

$$TSI(Chl\text{-}a) = 10 \times (2.5 + 1.086 \times \ln Chl\text{-}a) \quad (2)$$

$$TSI(TP) = 10 \times (9.436 + 1.624 \times \ln TP) \quad (3)$$

$$TSI(TN) = 10 \times (5.453 + 1.694 \times \ln TN) \quad (4)$$

$$TSI(SD) = 10 \times (5.118 - 1.94 \times \ln SD) \quad (5)$$

$$TSI(COD) = 10 \times (0.109 + 2.661 \times \ln (COD) \quad (6)$$

$$Wj = \frac{r_{ij}^2}{\sum_{j=1}^{m} r_{ij}^2} \quad (7)$$

Where, r_{ij} is the correlation coefficient between the j_{th} index content and Chl-a concentration. The coefficient values can be 1, 0.84, 0.82, -0.83, and 0.83 for Chl-a, TP, TN, SD, and COD, respectively. CTSI values range from 0 to 100. The trophic status of the lake is classified as oligotrophic (Oligo) 0<CTSI≤30, mesotrophic (Meso) 30<CTSI≤50, slightly eutrophic (Slight-Eutro) 50<CTSI≤60, moderately eutrophic (Mod-Eutro) 60<CTSI≤70, and hyper-eutrophic (Hyper-Eutro) 70<CTSI≤100.

Phytoplankton identification and enumeration

The phytoplankton sample was settled for 24 hours, and the number of cells per milliliter was calculated based on the measured cell volume. A 5 mL sample of phytoplankton was placed on a glass slide and analyzed using a Primo Star Zeiss microscope equipped with an Axiocam 105 color camera. The phytoplankton images were observed under a microscope at 40x magnification, with the images captured and displayed on a computer. The species observed under the microscope were photographed and well-documented (Tang et al. 2019). Identification of phytoplankton was carried out by comparing the observed physical characteristics with those listed in the books of Prescott (1978), Yamaji (1979), and Bellinger and David (2015). Following this, the diversity index (H'), evenness index (E), and dominance index (C) were computed.

Diversity Index (Shannon-Wiener Index, H). The Shannon-Wiener diversity index (H), also known as the Shannon diversity index (D), is the most commonly applied 186 measure of relative diversity. It assesses diversity by factoring in both species richness (the total number of species 187 present) and their proportional abundance. Environments with high diversity levels are generally seen as healthy and stable, 188 whereas low diversity often signals environmental stress or disruption. The value of the Shannon-Wiener index can be seen 189 in Equation 8 (Ju et al. 2019).

$$H' = -\sum_{n}^{S} = 1\ pi \ln pi \qquad Pi = \frac{ni}{N} \quad (8)$$

Where, H': Shannon-Wiener diversity index; n: Number of individuals of the i-th species; N: Total number of individuals. Criteria: H'<1: Low diversity; 1<H'<3: Moderate diversity; H'>3: High diversity.

Dominance Index (Simpson's Index, C). The dominance index analysis used in his study is Simpson's dominance index (C), which ranges from 0-1. A value closer to 1 indicates higher dominance by a single species, while values closer to 0 suggest a more even distribution among species. The formula for calculating the phytoplankton dominance index is presented in Equation 9 (Ju et al. 2019).

$$C = \sum \left(\frac{ni}{N}\right)^2 \quad (9)$$

Where, C: Dominance index; ni: Number of individuals of the 1st species; N: Number of individuals.

Evenness Index (Pielou's Index, E). The evenness index indicates the relative abundance of a species in a community and the distribution pattern of the biota. The evenness index used refers to Pielou's evenness index. The value of this evenness index is between 0 to 1. If the evenness index is 0, indicate that the species distribution is uneven. If the evenness index is 1, the evenness between species is relatively even, with the same number of individuals of each species. The formula for calculating the phytoplankton evenness index is presented in Equation 10 (Ju et al. 2019).

$$E = \frac{H'}{\ln S} \quad (10)$$

Where, E: Evenness index; H': Shannon-Wiener diversity index; S: Number of species in the community.

Statistical analysis

The Data used in the statistical analysis included results from trophic status parameter measurements, and the supporting secondary data statistical procedures comprised tests of data distribution, normality, and homogeneity. The Shapiro-Wilk test was used to assess normality because the sample size was less than 50. Data were considered normally distributed if the significance value (*p*-value) exceeded 0.05, and non-normally distributed if the *p*-value was below 0.05. When the assumptions of normality and homogeneity were met, a one-way Analysis of Variance (ANOVA) was conducted to determine significant differences in trophic status parameters across sampling sites and periods. For data that did not meet these assumptions, the non-parametric Kruskal-Wallis test was used as an alternative to evaluate group differences. Additionally, Pearson's correlation analysis was used to examine the relationships between trophic status parameters and phytoplankton community structure. The parameters analyzed are the evenness index, Shannon-Wiener diversity index, and Simpson dominance index.

RESULTS AND DISCUSSION

Spatial and temporal variations in trophic status

The CTSI analysis results presented in Figure 2 indicate that the trophic status of Maninjau Lake ranges from 62.59 to 73.28, indicating moderate to hyper-eutrophication. This condition indicates that the lake is facing significant nutrient inputs and water quality degradation. Spatially (Figure 2.A), locations experiencing strong anthropogenic impacts, such as floating net cages (FNC) and dense populations, such as location 10 (Jorong Sungai Tampang) and location 7 (Nagari Bayur), show high CTSI values of 70.77 to 74.94. Conversely, location 3 (Jorong Pangkal Tanjung), which has no FNCs or settlements, has the lowest CTSI values, ranging from 57.52 to 66.65, indicating relatively healthier conditions. A one-way ANOVA revealed no significant differences in CTSI (p: 0.088), indicating relatively uniform trophic status throughout the lake. This pattern is consistent with evenly distributed pollution sources, particularly related to FNC activities, as supported by increased TN and TP levels across all locations (Table 4).

TSI TN values ranged from 50.97 to 61.46, with the highest value observed at location 7 (Nagari Bayur), the area with the highest number of FNCs. TSI TP values ranged from 53.24 to 82.20, with a maximum in the Sungai Tampang area, where several FNCs operate. These findings align with Komala et al. (2023), who reported that areas with high FNC density experienced a significant decline in water quality. Intensive aquaculture activities contribute significantly to the nitrogen (N) and phosphorus (P) load in water, mainly through feed residues and fish excretion, thereby accelerating eutrophication (Yang et al. 2008; Martín Hernándaez et al. 2021).

Temporally (Figure 2.B), the highest CTSI was recorded in January 2023 (rainy season) with values ranging from 65.91 to 77.61, while the lowest values, ranging from 51.16 to 67.99, occurred in March 2023 (early dry season). One-way ANOVA analysis showed statistically significant temporal variation in CTSI values ($p = 0.022$), indicating the influence of season and rainfall on the trophic status of Maninjau Lake. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), the rainy season in Indonesia is expected to occur from September to November 2022, with the highest intensity in December 2022 and January 2023. In general, the period from September to December corresponds to the rainy season, while the following months are usually classified as the dry season. The rainfall recorded in September 2022 (0.00-80 mm; Table 5) correlated with an increase in TSI TN levels of 58.89 and TSI TP levels of 67.76 (Table 6).

The increased CTSI during the wet season is linked to intense rainfall, which amplifies surface runoff and delivers soil particles, agrochemicals, and untreated sewage into the lake (Dou et al. 2019; Chen et al. 2020). The nearshore zones of Maninjau Lake are eutrophic owing to elevated phosphorus content relative to the Ranggeh River (Sulawesty et al. 2020). These fluctuations over time underscore the importance of including seasonal factors in water-quality evaluations for tropical lakes, given that rainfall volume immediately affects nutrient influx (Goshu et al. 2020; Fadum and Hall 2023). Parallel seasonal behaviors are evident in other tropical water bodies, such as Lake Toba and Lake Sentani, where heavy rains, coupled with anthropogenic pressures, cause intermittent surges in nutrient accumulation and accelerate eutrophication processes (Sulastri et al. 2022; Tanjung et al. 2024). These findings indicate that the trophic condition of Maninjau Lake ranges from moderately eutrophic to hypereutrophic. Spatial differences among sampling locations were relatively limited, suggesting that nutrient enrichment is distributed broadly across the lake rather than confined to specific areas. This pattern corresponds with the widespread presence of floating net cage (FNC) aquaculture, which continuously contributes to nutrient inputs.

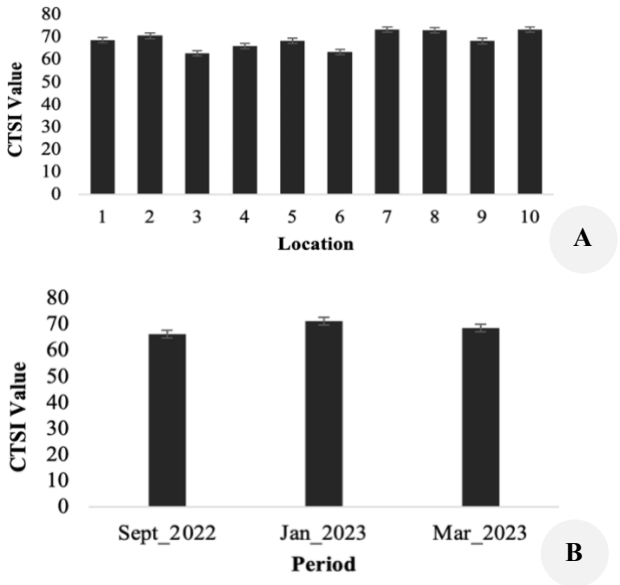

Figure 2. A. Spatial, and B. Temproral of CTSI of Maninjau Lake. CTSI values without units (scale 0-80)

Table 4. The spatial distribution of TSI values

Location	TSI Cha	TSI TN	TSI TP	TSI SD	TSI COD
1	55.81	54.72	75.41	54.59	101.73
2	62.07	55.40	76.83	54.34	103.48
3	55.29	51.93	53.24	50.78	101.73
4	57.05	56.65	64.13	46.23	105.09
5	60.87	54.34	77.57	46.62	101.73
6	59.52	52.35	53.66	45.46	105.09
7	60.20	61.49	75.46	61.83	106.87
8	52.98	50.97	79.58	74.14	106.87
9	59.34	55.64	68.32	52.16	105.09
10	59.23	52.52	82.20	67.38	105.09

Table 5. Rainfall during the sampling period

Period	Rainfall (mm)	Wind speed (km/h)
September 2022	0.00-80.00	1.40-2.90
January 2023	0.00-70.00	1.40-3.60
March 2023	0.00-61.50	0.40-4.30

Table 6. Temporal distribution of TSI values

Period	TSI Cha	TSI TN	TSI TP	TSI SD	TSI COD
September 2022	59.57	55.89	67.76	51.49	104.24
January 2023	57.51	53.85	76.39	63.40	106.04
March 2023	57.64	54.06	67.99	51.16	102.56

In contrast, temporal variability was more pronounced. CTSI values increased markedly during the rainy season, likely reflecting enhanced nutrient transport through runoff and catchment inflow. Sites characterized by intensive FNC activities, particularly Nagari Bayur and Sungai Tampang, exhibited the highest TN- and TP-based TSI values, indicating localized nutrient accumulation.

The findings suggest that eutrophication in Maninjau Lake cannot be attributed to a single driving factor but instead reflects the interaction between seasonal hydrological processes and continuous anthropogenic pressures. Changes in water dynamics during the rainy season appear to intensify nutrient redistribution, while human activities around the lake maintain a persistent nutrient supply. Effective management, therefore, requires attention not only to seasonal variability but also to aquaculture practices occurring in high-density production areas.

Previous studies have shown that nutrient enrichment in Maninjau Lake originates from both external and internal sources (Nastuti et al. 2023). From a watershed perspective, the surrounding land use is dominated by agricultural areas, where the intensive application of nitrogen- and phosphorus-based fertilizers promotes nutrient accumulation. During periods of heavy rainfall, these nutrients are readily transported into the lake through surface runoff, accompanied by contributions from soil erosion and untreated domestic wastewater (Kurniati et al. 2021).

Internal loading further amplifies this condition. Floating Net Cage (FNC) aquaculture represents a substantial nutrient input through uneaten feed and fish excretion, increasing organic matter and dissolved nutrient concentrations that favor phytoplankton growth (Warsa and Haryadi 2019). Similar patterns have been reported in other Indonesian lakes, such as Toba and Singkarak, where expanding aquaculture activities accelerated the shift from mesotrophic toward eutrophic conditions (Rauf et al. 2018). Collectively, these observations indicate that sustained trophic enrichment in tropical lakes emerges from the combined influence of watershed-derived inputs and internally generated nutrient recycling.

Phytoplankton community composition

A total of 9 (nine) phytoplankton classes were identified (Table 7, Figure 3), comprising Bacillariophyceae (37 species), Chlorophyceae (18 species), Coscinodiscophyceae (3 species), Cyanophyceae (18 species), (3 Dinophyceae species), Euglenophyceae (4 species), Trebouxiophyceae (9 species), Zygnematophyceae (15 species), and Mediophyceae (1 species). The spatial distribution of phytoplankton classes across 10 sampling sites is shown in Figure 4.

Spatially, Bacillariophyceae is the most dominant phytoplankton. The highest abundance was recorded at location 2, Nagari Tanjung Sani Jorong Pangkal Tanjung (274 individuals), an area characterized by FNC activities and moderate settlement, followed by location 1 in the middle of the lake (216 individuals). Bacillariophyceae are widely distributed across the study sites, reflecting their capacity to tolerate a wide range of environmental conditions, including extreme habitats. and adapting quickly. Their growth is influenced by temperature and nutrient availability, and diatoms are widely used as bioindicators of water quality. In contrast, Euglenophyceae were the least abundant, with only one species. Furthermore, *Trachelomonas oblonga* was detected only at site 4 (Antokan), likely reflecting trophic conditions and other factors affecting the species' growth and metabolic processes.

Temporal observations showed that the phytoplankton community was primarily dominated by Bacillariophyceae, with Cyanophyceae forming the secondary group, while Euglenophyceae appeared only occasionally throughout the sampling period. Bacillariophyceae reached their highest abundance during Period 1 (September 2022) but gradually declined, reaching the lowest levels in Period 3 (March 2023). In contrast, Cyanophyceae displayed a transient increase during Period 2 (January 2023) before decreasing again toward the end of the observation period.

The temporary dominance of Cyanophyceae in Period 2 appears to be linked to favorable environmental conditions, particularly enhanced nutrient availability, warmer air temperatures, and relatively lower rainfall than in earlier months. These conditions likely created a more stable water column, which supported the proliferation of Cyanophyceae.

The recurrent predominance of Bacillariophyceae reflects their ecological flexibility and capacity to persist under varying environmental conditions. Increased rainfall between 2022 and 2023 (from 251.92 mm to 319.08 mm), together with a slight rise in wind speed (6.050-6.058 km/h), may have promoted mixing processes that favor diatom growth. Bacillariophyceae are well known for tolerating environmental fluctuations and maintaining relatively high reproductive rates compared with many other phytoplankton groups (Ajayan and Kumar 2018).

Earlier investigations described Maninjau Lake as eutrophic with relatively diverse phytoplankton communities in which Bacillariophyceae, Chlorophyceae, and Cyanophyceae were consistently represented in balanced proportions (Sulastri 2019). However, progressive nutrient enrichment has led to an increasing dominance of bloom-forming Cyanophyceae, particularly *Microcystis aeruginosa*. In addition, tolerant diatom taxa from Bacillariophyceae, such as *Synedra* spp., have also increased, indicating a shift toward eutrophic-hypereutrophic conditions (Sulastri 2019; Sulawesty et al. 2020; Sulastri 2022). This development culminated in a hypereutrophic condition, characterized by dominance of Cyanophyceae (*Microcystis aeruginosa*) and Bacillariophyceae (*Synedra acus*), as reported in later studies (Komala et al. 2023). The present study depicts that these phytoplankton groups persist and further indicates that rainfall regulates their dominance, with Bacillariophyceae favored during wetter, well-mixed conditions and Cyanophyceae increasing during drier, nutrient-rich periods.

Table 7. Species list of phytoplankton in Maninjau Lake, West Sumatra, Indonesia

Phylum/Species	Quantity	Phylum/Species	Quantity	Phylum/Species	Quantity
Bacillariophyceae		Chlorophyceae		Euglenophyceae	
Achnanthes brevipes	2	*Ankistrodesmus falcatus*	1	*Phacus caudatus*	1
Cocconeis diminuta	5	*Coelastrum cambricum*	11	*Phacus orbicularis*	1
Cocconeis placentula	80	*Coelastrum reticulatum*	16	*Trachelomonas hispida*	1
Cymbella affinis	1	*Gloeocystis vesiculosa*	3	*Trachelomonas oblonga*	2
Cymbella tumida	8	*Kirchneriella lunaris*	7	Mediophyceae	
Cymbella ventricosa	1	*Oedogonium* sp.	1	*Cyclotella comta*	26
Epithemia zebra	1	*Oedogonium geniculatum*	1	Thebouxiophyceae	
Eunotia arcus	13	*Pediastrum duplex*	2	*Actinastrum hantzschii*	96
Fragilaria capucina	24	*Pediastrum muticum*	1	*Chlorella vulgaris*	17
Fragilaria construens	15	*Quadrigula chodatii*	3	*Closteriopsis longissima*	2
Fragilaria sp.	2	*Scenedesmus acuminatus*	1	*Crucigenia quadrata*	25
Frustulia rhomboides	4	*Scenedesmus bijuga*	72	*Crucigenia rectangularis*	1
Frustulia vulgaris	2	*Scenedesmus dimorphus*	64	*Crucigenia tetrapedia*	1
Gomphonema gracile	7	*Scenedesmus longispina*	1	*Nephrocytium lunatum*	2
Gomphonema pumilum	24	*Scenedesmus obliquus*	1	*Oocystis lacustris*	2
Gyrosigma sp.	1	*Scenedesmus denticulatus*	1	*Oocystis parva*	2
Navicula anglica	4	*Selenastrum westii*	3	Zygnematophyceae	
Navicula bacillum	2	*Westella botryoides*	7	*Closterium gracile*	26
Navicula cryptocephala	24	Cyanophyceae		*Cosmarium contractum*	6
Navicula placentula	5	*Anabaena* sp.	1	*Cosmarium impressulum*	1
Navicula viridula	11	*Aphanocapsa* sp.	5	*Cosmarium undulatum*	106
Nitzschia clausii	3	*Chroococcus dispersus*	41	*Cosmarium pandriforme*	1
Nitzschia dissipata	5	*Chroococcus minutus*	26	*Netrium digitus*	1
Nitzschia palea	6	*Chroococcus turgidus*	56	*Euastrum bidentatum*	1
Nitzschia scalaris	6	*Lyngbya* sp.	2	*Pleurotaenium* sp.	1
Nitzschia vermicularis	1	*Merismopedia elegans*	289	*Spirogyra corrugata*	2
Pinnularia braunii	4	*Microcystis aeruginosa*	5	*Spirogyra setiformis*	1
Pinnularia major	1	*Microcystis botrys*	1	*Spondylosium* sp.	1
Pinnularia gibba	1	*Microcystis* sp.	21	*Staurastrum bigibbum*	168
Pinnularia mesolepta	3	*Phormidium tenue*	2	*Staurastrum gracile*	52
Pinnularia viridis	5	*Spirulina laxa*	54	*Staurastrum longiradiatum*	3
Rhopalodia gibberula	4	*Spirulina major*	1	*Staurastrum* sp.	4
Surirella caproni	1	*Spirulina* sp.	1		
Surirella robusta	3	*Spirulina subsalsa*	1		
Surirella tenera	1	*Oscillatoria* sp.	1		
Synedra acus	271	*Oscillatoria formosa*	302		
Synedra ulna	870	*Oscillatoria tenuis*	1		
Dinophyceae		Coscinodiscophyceae			
Ceratium hirundinella	410	*Melosira italica*	1		
Peridinium bipes	146	*Melosira* sp.	8		
Peridinium sp.	4	*Coscinodiscus lacustris*	2		

The dominance of Bacillariophyceae in Maninjau Lake corresponds with observations from other tropical aquatic systems, where this group tolerates variable environmental conditions and is often regarded as an indicator of moderate nutrient availability (Fu et al. 2022; Wang et al. 2024). In contrast, the seasonal increase of Cyanophyceae, particularly during the wet season when nutrient inputs intensify, aligns with patterns documented in Lake Ba Be (Vietnam) and other Southeast Asian lakes, where cyanobacterial blooms are closely associated with nutrient enrichment and temperature variability (Essa et al. 2024; Vinh et al. 2025).

Seasonal changes, particularly increased rainfall and wind speed, further facilitate their development, ultimately influencing the structure of the broader phytoplankton community (Mesman et al. 2022; Taurozzi et al. 2025). These findings underscore the critical role of environmental factors in regulating plankton community dynamics (Fu et al. 2022; Wang et al. 2024). The persistence of Bacillariophyceae under varying climatic conditions and trophic states further demonstrates their ecological adaptability.

Diversity index analysis (H')

The spatial and temporal distributions of phytoplankton diversity index (H') values are shown in Figure 5. Spatially, the highest diversity index (2.34) was found at Pangkal Tanjung (location 3), an unpopulated area, while the lowest (1.31) was at Tampang River (location 9), a residential zone characterized by intensive FNC. Temporally, the highest diversity index (2.85) occurred in March 2023, and the lowest (1.31) in January 2023. Based on the Shannon-Wiener diversity index, phytoplankton diversity

in Maninjau Lake is classified as moderate, with spatial values ranging from 1.73 to 2.34 and temporal values ranging from 1.31 to 2.85. This classification suggests a community sensitive to environmental fluctuations. Moderate diversity levels are commonly interpreted as reflecting a relatively even phytoplankton community structure in aquatic systems responding to variations in water quality and seasonal conditions (Murugesan et al. 2021).

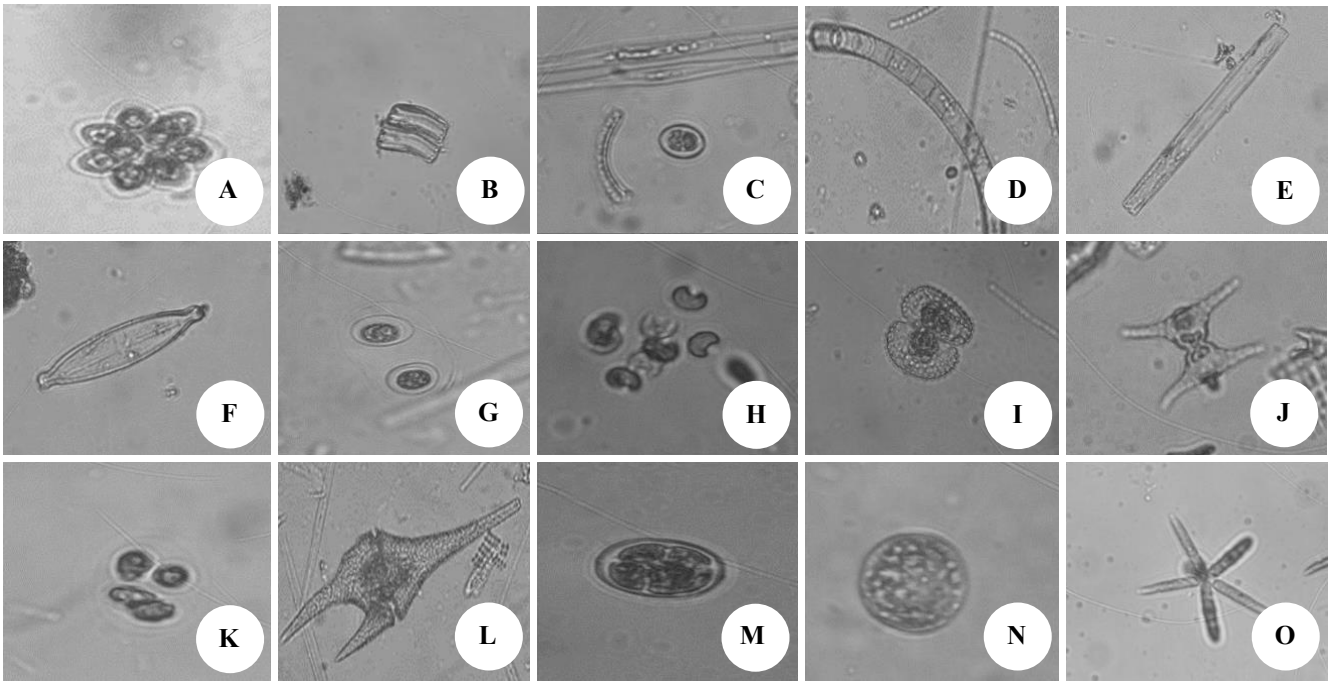

Figure 3. Classification of phytoplankton based on classes found in Maninjau Lake, West Sumatra, Indonesia. A. *Achnanthes brevipes*, B. *Cocconeis diminuta*, C. *Coelastrum cambricum*, D. *Melosira italica*, E. *Fragilaria capucina*, F. *Frustulia rhomboides*, G. *Gloeocystis vesiculosa*, H. *Kirchneriella lunaris*, I. *Cosmarium undulatum*, J. *Chroococcus minutus*, K. *Ceratium hirundinella*, L. *Cyclotella comta*, M. *Trachelomonas oblonga*, N. *Actinastrum hantzschii*, O. *Staurastrum longiradiatum*

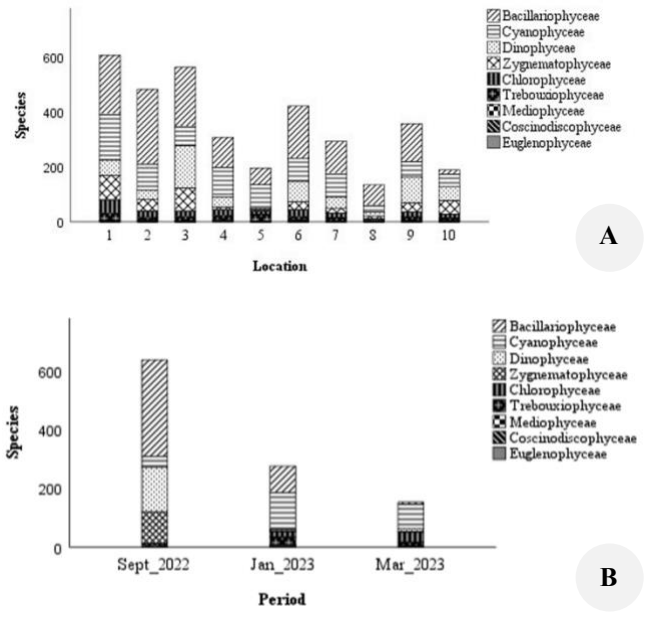

Figure 4. A. Spatial, and B. Temporal distribution of phytoplankton abundance in Maninjau Lake, West Sumatra, Indonesia

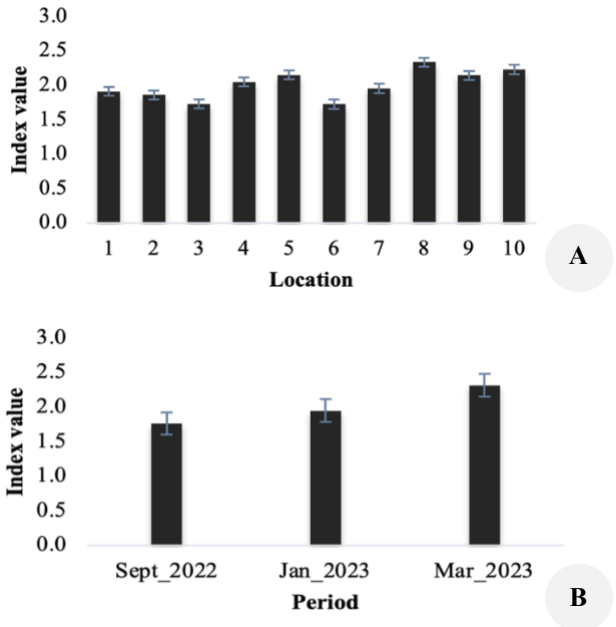

Figure 5. A. Spatial, and B. Temporal diversity index (H') of phytoplankton in Maninjau Lake, West Sumatra, Indonesia

Spatially, phytoplankton diversity across the lake is strongly influenced by the distribution of fish cage farms, with variations in diversity indices directly related to the number of fish cages at each location. The location with the highest number of fish cages, Nagari Bayur, has the highest TSI TN value (61.46), which in turn influences phytoplankton diversity. Data on the number of FNC units reported by the Regional Development Planning Agency (BAPPEDA) of Agam in the 2022 Regency are presented in Table 8. The use of floating fish cages in aquaculture can degrade water quality and alter phytoplankton composition (Wang et al. 2024). Komala et al. (2023) reported substantial water quality deterioration in Maninjau Lake, which was significantly in line with the rapid growth of floating net cages, which exceeded 20,000 units by 2022. The resulting hypereutrophic conditions and frequent *Microcystis* blooms have led to reduced phytoplankton diversity, reflecting a broader decline in ecosystem health, including reduced fisheries productivity and water quality degradation (Sulastri et al. 2019).

Temporally, variations in phytoplankton diversity can be attributed to environmental conditions during the sampling, particularly rainfall variability. The highest rainfall (16.19 mm) occurred in September 2022, whereas the lowest rainfall (9.52 mm) was observed in March 2023. Rainfall significantly shapes aquatic ecosystems and drives ecological and evolutionary processes (Dodds et al. 2019). The composition and structure of phytoplankton communities in the littoral areas of Maninjau Lake and the Ranggeh River changed over time, potentially affecting higher trophic levels, including diversity and ecosystem quality (Sulawesty et al. 2020). These changes are closely linked to fluctuations in environmental conditions, including water quality and diverse nutrient inputs, which affect phytoplankton communities, as reflected in the moderate Shannon-Wiener diversity index values obtained in this study. This finding aligns with Komala et al. (2023) and Sulawesty et al. (2020), who reported a low phytoplankton diversity index in Maninjau Lake. Reduced diversity indicates the dominance of certain phytoplankton species, particularly Bacillariophyceae and Chlorophyceae, which are more adaptive to eutrophic conditions due to increased anthropogenic nutrient input (Mohd-Din et al. 2025). Such low diversity of phytoplankton species is attributed to competitive exclusion mechanisms in nutrient-rich environments, resulting in homogenous phytoplankton communities and the suppression of less competitive taxa (Bužančić et al. 2016; Varga et al. 2024). Ecologically, these shifts suggest potential risks to lake ecosystem stability. The increase of Cyanophyceae, known for forming harmful algal blooms, can reduce water quality, reduce dissolved oxygen levels, and pose risks to aquatic organisms as well as human health (Loza et al. 2014; Yu et al. 2022).

Evenness index analysis (E)

The evenness index (E), calculated using Pielou's evenness index, ranges from 0 to 1. As presented in Figure 6.A, the highest average evenness index is 0.72 at location 3, Pangkal Tanjung, an unpopulated area, while the lowest average is 0.57 at location 7, Nagari Bayur, an area with many fish cages. Temporally, the evenness index shown in Figure 6.B averaged 0.55 in September 2022 and increased to 0.79 in March 2023. These values indicate a relatively even distribution of phytoplankton species both spatially and temporally.

This pattern is consistent with the diversity index, which also reflects the even distribution of phytoplankton communities across Maninjau Lake, despite variations among sampling locations. The evenness index in this study differs from that reported by Komala et al. (2023), which was classified as low, ranging from 0.27 to 0.41. According to Odum (1993), that the evenness index of 0.26-0.50 indicates an uneven species distribution. Variability in evenness is closely related to environmental conditions, particularly nutrient availability and its spatial and temporal distribution. In this study, TN and TP exhibited significant spatial and temporal differences ($p<0.05$). A higher evenness index likely reflects both environmental factors, such as nutrient availability, and the adaptive capacity of phytoplankton species (Fontana et al. 2018).

Table 8. Number of FNC at the sampling location

Location	Number of FNC
Tanjung Sani	55.81
Nagari Maninjau	62.07
Nagari Bayur	55.29
Sungai Rangeh	57.05
Sungai Tampang	60.87
Sigiran	59.23

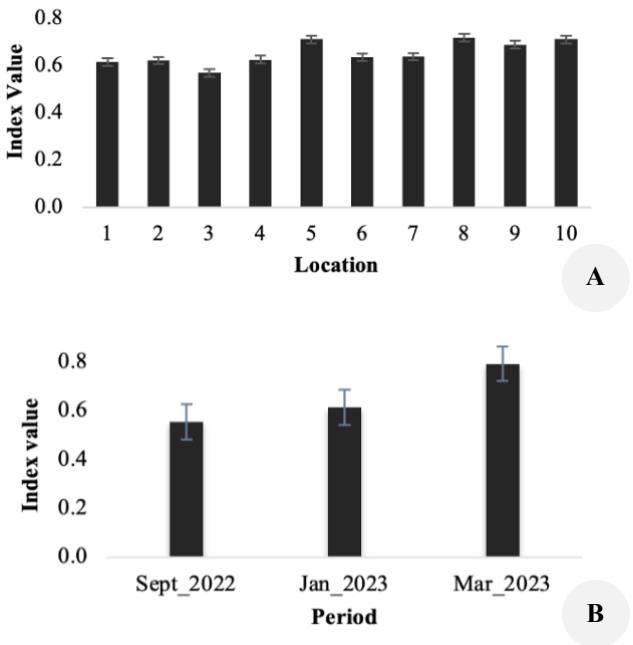

Figure 6. A. Spatial, and B. Temporal evenness index (E) of phytoplankton in Maninjau Lake, West Sumatra, Indonesia

These nutrient-related patterns are further supported by trophic state indicators, as reflected in TN TSI and TP TSI, which did not show significant differences ($p>0.05$), likely because pollution was evenly distributed across the sampling locations. Macronutrient factors, such as nitrogen and phosphorus, have a significant impact on phytoplankton growth (Lu et al. 2023). In addition to nutrient availability, resource limitations, such as low light intensity, may promote spatial separation between phytoplankton populations (Fontana et al. 2018). This is consistent with the previous finding that light limitation increases the evenness of multidimensional traits in phytoplankton populations (Fontana et al. 2019). Overall, these results emphasize the complex interactions between nutrient dynamics, light availability, and water physics in shaping phytoplankton diversity and evenness.

Analysis of dominance index (C)

As depicted in Figure 7A, the highest average dominance index value is 0.32 at location 7, Nagari Bayur, the center of FNC activities, while the lowest is 0.19 at location 8, the Talao area (North). This variation is potentially influenced by FNC activities that generate organic waste inputs. The phytoplankton dominance index at a specific site is affected by multiple environmental drivers, including nutrient availability, light intensity, and human activities such as settlements and water utilization (Dengg et al. 2023; Bera et al. 2025). TN TSI, TP TSI, and brightness spatially changed with significance >0.05. Phytoplankton growth is primarily influenced by changes in external environmental factors, particularly nutrient supply and light penetration (Loza et al. 2014). Environmental parameters related to hydrology show diverse influences on phytoplankton assemblages (Wu et al. 2024).

As shown in Figure 7.B, the temporal average phytoplankton dominance index was highest at 0.28 in September 2022, while the lowest value, 0.15, occurred in March 2023. This difference was influenced by variations in environmental conditions between sampling periods, particularly the surface water temperature, which ranged from 18.80-21.80°C in September and increased to 19.10-23.30°C in March.

Temperature rises associated with the climate crisis appear to be one of the key drivers of the observed changes. Increasing lake temperatures can reshape phytoplankton community structure by promoting the dominant species that are more tolerant of high temperatures and environmental extremes (Kraemer et al. 2021). In addition, rainfall fluctuations during the observation period contributed to the dynamics of the phytoplankton community. Although statistical analysis did not detect significant differences ($p>0.05$), rainfall variations still have an ecological impact through increased runoff and nutrient input into the water, which can trigger changes in phytoplankton composition and dominance (Wilson et al. 2019; Kraemer et al. 2021).

Based on the dominance index (<0.5), neither spatially nor temporally does any phytoplankton genus dominate the others. Phytoplankton dominance in lakes is affected by multiple factors. In Matano Lake, the community is relatively unstable and may be experiencing eutrophication (Sentosa et al. 2017). Sulawesty et al. (2020) noted that the phytoplankton dominance index in Maninjau Lake was higher than that of the Ranggeh River, attributed to phosphorus concentrations. Factors contributing to the phytoplankton dominance index include nutrient availability, which plays a vital role in shaping phytoplankton dominance in Maninjau Lake (Sulastri et al. 2022).

Correlation of trophic status and phytoplankton in Maninjau Lake

The results of the TSI correlation test on the H, C, and E of phytoplankton in Maninjau Lake are presented in Table 9. The correlations between TSI and H and C in phytoplankton were moderate, with significance values of 0.002 and 0.004 (<0.05). Meanwhile, the relationship between TSI and E was strongly correlated, with a significance value of 0.00 (<0.05). The correlation between TSI and C was 0.533 (moderate), and between TSI and E, it was 0.723 (strong).

In general, the structure and dynamics of the phytoplankton community in Maninjau Lake reflect the response to changes in water trophic status, as indicated by CTSI values. Changes in the phytoplankton community are more influenced by temporal changes in CTSI than by spatial changes. Spatially, relatively homogeneous CTSI values under moderate-eutrophic conditions result in a relatively uniform phytoplankton composition between locations, dominated by Bacillariophyceae. Conversely, temporally, an increase in CTSI values is associated with a shift in dominance from Bacillariophyceae to Cyanophyceae, particularly under conditions of high temperature, low rainfall, and increased nutrient concentrations, followed by a decrease in diversity and uniformity and an increase in dominance, thus indicating a decrease in phytoplankton community stability.

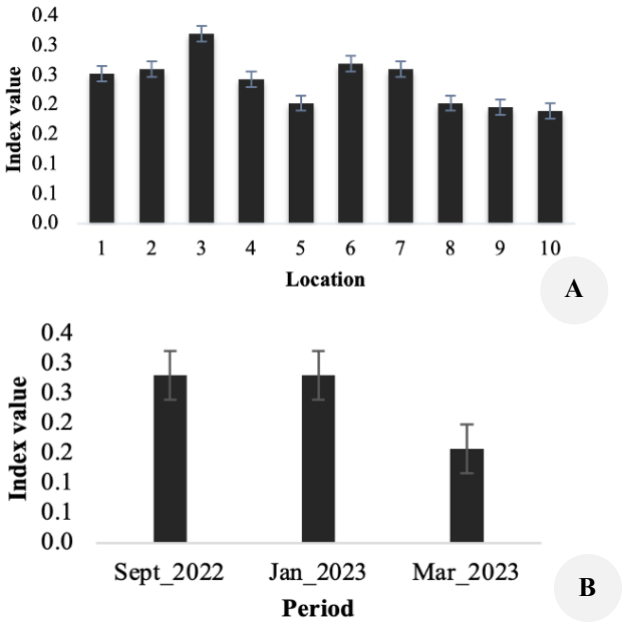

Figure 7. A. Spatial, and B. Temporal dominance index (C) of phytoplankton in Maninjau Lake, West Sumatra, Indonesia

Table 9. Correlation value of TSI and phytoplankton Index

Parameters	Pearson correlation	Sig. (2-tailed)	Description
Diversity index (H)	0.533	0.002	Moderate
Dominance index (C)	0.515	0.004	Moderate
Evenness index (E)	0.723	0.000	Strong

Source: Calculation results using SPSS (2025)

Compared with other tropical lakes in Southeast Asia, Maninjau Lake exhibits eutrophication patterns consistent with those of Laguna de Bay (Philippines) and Songkhla Lake (Thailand), both of which are influenced by a combination of agricultural runoff, domestic effluents, and aquaculture expansion (Pradit et al. 2010; Quecke et al. 2024). However, the internal nutrient recycling in Maninjau Lake appears stronger, driven by its morphometric and hydrodynamic characteristics, specifically, its deep basin, long residence time, and frequent stratification events. Under anoxic bottom conditions, phosphorus release from sediments can sustain high nutrient levels even when external inputs are reduced. This internal feedback mechanism has also been reported in tropical reservoirs such as Kenyir Lake (Malaysia**)**, confirming that nutrient control strategies must address both external loading and sediment nutrient release. The comparison highlights that while the drivers of eutrophication are regionally similar, the relative contribution of internal processes can vary substantially depending on lake morphology and mixing dynamics. Increasing trophic status is associated with reduced diversity, greater species dominance, and lower phytoplankton evenness (Tang et al. 2019). This suggests that eutrophication or increased nutrient concentrations can cause major changes in aquatic ecosystems, with impacts on community diversity, dominance, and evenness (Shi et al. 2023). Therefore, the presence of phytoplankton can be used as an indicator to assess the trophic status of a given water body (Tang et al. 2019). Phytoplankton are one of the biological parameters suggested for determining the ecological status of surface waters (Yang et al. 2023). As such, phytoplankton dynamics in these aquatic systems are strongly influenced by changes in trophic status. Increased eutrophication can promote the growth of more competitive species, reduce phytoplankton diversity, and lead to the dominance of specific species, ultimately decreasing the overall stability of the aquatic ecosystem. Therefore, monitoring of TSI is important to anticipate changes in phytoplankton community dynamics and maintain the balance of aquatic ecosystems.

In conclusion, the Comprehensive Trophic Status Index (CTSI) indicates that Maninjau Lake consistently experiences eutrophic to hypereutrophic conditions, with scores of 62.59 to 73.28. During the rainy season, all CTSI elements rise, indicating increased nutrient input from incoming water. This increase in nutrients is followed by a shift in dominance from Bacillariophyceae to Cyanophyceae, a taxon that is tolerant to high nutrient loads. Under hyper-eutrophic conditions, certain species dominate, leading to declines in diversity and uniformity and altering the balance and stability of the lake ecosystem. High rainfall intensity in this region, coupled with the monomictic tropical lake type, which is prone to upwelling, increases nutrient flow from the surrounding area. These results confirm that CTSI integrated with environmental factors can be used effectively to assess changes in lake water quality and used as a basis for implementing comprehensive nutrient control measures, including stricter aquaculture regulations and water flow management in catchment areas. Regular assessment of lake trophic status using CTSI can serve as an indicator of sustainable lake ecological health.

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REFERENCES

Ajayan AP, Ajit Kumar KG. 2017. Phytoplankton as biomonitors: A study of Museum Lake in Government Botanical Garden and Museum, Thiruvananthapuram, Kerala India. Lakes Reserv Sci Policy Manag Sustain Use 22 (4): 403-415. https://doi.org/10.1111/lre.12199.

BAPPEDA Kab. Agam. 2022. Data on Floating Net Cages in Lake Maninjau in 2022. Bappeda Agam Regency. https://bappeda.agamkab.go.id/View-dokumen/data-keramba-jaring-apung-di-danau-maninjau-tahun-2022.html.

Bellinger EG, David C. Sigee. 2015. Freshwater Algae; Identification, Enumeration and Use as Bioindicators. 2 Ed. John Wiley & Sons, Ltd., United Kingdom. https://doi.org/10.1201/9781482294583-4.

Bera S, Paul S, Haridevi CK. 2025. Diversity and ecology of pollution tolerant phytoplankton along Patalganga estuary, West Coast of India. Reg Stud Mar Sci. 82: 104027. https://doi.org/10.1016/j.rsma.2025.104027.

Bužančić M, Ninčević Gladan Ž, Marasović I, Kušpilić G, Grbec B. 2016. Eutrophication influence on phytoplankton community composition in three bays on the eastern Adriatic coast. Oceanologia 58 (4): 302-316. https://doi.org/10.1016/j.oceano.2016.05.003.

Chen Q, Huang M, Tang X. 2020. Eutrophication assessment of seasonal urban lakes in China Yangtze River Basin using Landsat 8-derived Forel-Ule index: A six-year (2013-2018) observation. Sci Total Environ 745: 135392. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.135392.

Chen Q, Wang S, Ni Z, Guo Y, Liu X, Wang G, Li H. 2021. No-linear dynamics of lake ecosystem in responding to changes of nutrient regimes and climate factors: Case study on Dianchi and Erhai lakes, China. Sci Total Environ 781: 146761. https://doi.org/10.1016/j.scitotenv.2021.146761.

Dengg M, Stirling CH, Safi K, Lehto NJ, Wood SA, Seyitmuhhamedov K, Reid MR, Verburg P. 2023. Bioavailable iron concentrations regulate phytoplankton growth and bloom formation in low-nutrient lakes. Sci Total Environ 902: 166399. https://doi.org/10.1016/j.scitotenv.2023.166399.

Dodds WK, Bruckerhoff L, Batzer D, Schechner A, Pennock C, Renner E, Tromboni F, Bigham K, Grieger S. 2019. The freshwater biome gradient framework: Predicting macroscale properties based on latitude, altitude, and precipitation. Ecosphere 10 (7): e2786. https://doi.org/10.1002/ecs2.2786.

Dou M, Ma X, Zhang Yan, Zhang Yongyong, Shi Y. 2019. Modeling the interaction of light and nutrients as factors driving lake eutrophication. Ecol Modell 400: 41-52. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2019.03.015.

Essa DI, Elshobary ME, Attiah AM, Salem ZE, Keshta AE, Edokpayi JN. 2024. Assessing phytoplankton populations and their relation to water

parameters as early alerts and biological indicators of the aquatic pollution. Ecol Indic 159: 111721. https://doi.org/10.1016/j.ecolind.2024.111721.
Fadum JM, Hall EK. 2023. Nitrogen is unlikely to consistently limit primary productivity in most tropical lakes. Ecosphere 14 (3): e4451. https://doi.org/10.1002/ecs2.4451.
Fontana S, Thomas MK, Reyes M, Pomati F. 2018. Resource supply drives even spacing of individuals along multiple trait axes in light-limited phytoplankton populations. bioRxiv 6 (4): 338129. https://doi.org/10.1101/338129.
Fontana S, Thomas MK, Reyes M, Pomati F. 2019. Light limitation increases multidimensional trait evenness in phytoplankton populations. ISME J 13 (5): 1159-1167. https://doi.org/10.1038/s41396-018-0320-9.
Fu W, Shu Y, Yi Z, Su Y, Pan Y, Zhang F, Brynjolfsson S. 2022. Diatom morphology and adaptation: Current progress and potentials for sustainable development. Sustain Horizons 2: 100015. https://doi.org/10.1016/j.horiz.2022.100015.
García-Rodríguez FJ, Gil-Soto E, Ruiz-Rosa I. 2012. New Methods in University Entrepreneurship Education: A Multidisciplinary Teams Approach. New Delhi: Co. Ltd. https://doi.org/10.4236/ce.2012.326132.
Goshu G, Strokal M, Kroeze C, Koelmans AA, de Klein JJM. 2020. Assessing seasonal nitrogen export to large tropical lakes. Sci Total Environ 731: 139199. https://doi.org/10.1016/j.scitotenv.2020.139199.
Jia J, Gao Y, Zhou F, Shi K, Johnes PJ, Dungait JAJ, Ma M, Lu Y. 2020. Identifying the main drivers of change of phytoplankton community structure and gross primary productivity in a river-lake system. J Hydrol 583 (13): 124633. https://doi.org/10.1016/j.jhydrol.2020.124633.
Ju YR, Lo WT, Chen CF, Chen CW, Huang ZL, Dong C Di. 2019. Effect of metals on zooplankton abundance and distribution in the coast of southwestern Taiwan. Environ Sci Pollut Res 26 (33): 33722-33731. https://doi.org/10.1007/s11356-018-2169-x.
Komala PS, Silvia S, Windi S. 2023. Phytoplankton dynamics and its relation to physicochemical parameters in the dry season of Maninjau Lake, West Sumatra, Indonesia. J Ecol Eng 24 (9): 218-231. https://doi.org/10.12911/22998993/169233.
Komala PS, Soeprobowati TR, Takarina ND, Subehi L, Wojewódka-Przybył M, Primasari B, Edwin T, Ridwan R, Rahmadiningsih E, Mardatillah R. 2023. Spatio-temporal Changes of Water Quality Based on Water Quality Index Method in Tropical Lake of Indonesia. Water Air Soil Pollut 234 (9): 594. https://doi.org/10.1007/s11270-023-06599-9.
Kraemer BM, Pilla RM, Woolway RI, Anneville O, Ban S, Colom-Montero W, Devlin SP, Dokulil MT, Gaiser EE, Hambright KD, et al. 2021. Climate change drives widespread shifts in lake thermal habitat. Nat Clim Chang 11 (6): 521-529. https://doi.org/10.1038/s41558-021-01060-3.
Kurniati RI, Komala PS, Zulkarnaini Z. 2021. Analisis beban pencemar total nitrogen dan total fosfat akibat aktivitas antropogenik di Danau Maninjau. Jurnal Ilmu Lingkungan 19 (2): 355-364. https://doi.org/10.14710/jil.19.2.355-364.
Loza V, Perona E, Mateo P. 2014. Specific responses to nitrogen and phosphorus enrichment in cyanobacteria: Factors influencing changes in species dominance along eutrophic gradients. Water Res 48 (1): 622-631. https://doi.org/10.1016/j.watres.2013.10.014.
Lu Y, Tuo Y, Zhang L, Hu X, Huang B, Chen M, Li Z. 2023. Vertical distribution rules and factors influencing phytoplankton in front of a drinking water reservoir outlet. Sci Total Environ 902: 166512. https://doi.org/10.1016/j.scitotenv.2023.166512.
Martín Hernándaez E, Martín M, Ruiz-Mercado GJ. 2021. A geospatial environmental and techno-economic framework for sustainable phosphorus management at livestock facilities. Resour Conserv Recycl 175: 105843. https://doi.org/10.1016/j.resconrec.2021.105843.
Mesman JP, Ayala AI, Goyette S, Kasparian J, Marcé R, Markensten H, Stelzer JAA, Thayne MW, Thomas MK, Pierson DC, Ibelings BW. 2022. Drivers of phytoplankton responses to summer wind events in a stratified lake: A modeling study. Limnol Oceanogr 67 (4): 856-873. https://doi.org/10.1002/lno.12040.
Mohd-Din M, Hii KS, Kassim NS, Mohd Azmi NF, Baharudin SN, Gu H, Leaw CP, Lim PT. 2025. Diversity and distribution of micro-phytoplankton and harmful microalgae along the Malaysian coasts of Malacca Strait and South China Sea. Reg Stud Mar Sci 81: 103947. https://doi.org/10.1016/j.rsma.2024.103947.
Murugesan K, Juma IMIA, Hokal NMA. 2021. Seasonal influence of water quality on the assemblage and diversity of phytoplankton along Dubai Creek, Arabian Gulf. Reg Stud Mar Sci 47: 101928. https://doi.org/10.1016/j.rsma.2021.101928.
Nastuti R, Soeprobowati TR, Utomo S. 2023. Land use changes toward water quality status of Lake Maninjau West Sumatera. E3S Web Conf 448: 03046. https://doi.org/10.1051/e3sconf/202344803046.
Odum EP. 1993. Dasar-dasar Ekologi. Gadjah Mada University Press, Yogyakarta. [Indonesian]
Pradit S, Wattayakorn G, Angsupanich S, Baeyens W, Leermakers M. 2010. Distribution of trace elements in sediments and biota of Songkhla Lake, Southern Thailand. Water Air Soil Pollut 206 (1-4): 155-174. https://doi.org/10.1007/s11270-009-0093-x.
Prescott G. 1978. How to Know Freshwater Algae. 3rd Edition. McGraw-Hill Science, Dubuque.
Quecke EL, Peralta-Limachi S, Baluyot JC, Diaz LA, Carag HM, Marjan P, Sta Ana J, Cheng F, Ulrich AC, Hicks KA, et al. 2024. Bioanalytical Monitoring of Laguna Lake (Philippines) to assess water research priorities associated with organic chemical pollution and cyanobacterial blooms. ACS ES T Water 4 (12): 5320-5331. https://doi.org/10.1021/acsestwater.4c00359.
Rauf A, Javed M, Ghazala J. 2018. Uptake and accumulation of heavy metals in water and planktonic biomass of the River Ravi, Pakistan. Turkish J Fish Aquat Sci 19 (10): 857-864. https://doi.org/10.4194/1303-2712-v19_10_05.
Sentosa AA, Hedianto DA, Satria H. 2017. Eutrophication potential in lake matano based on its phytoplankton community and water quality. Limnotek 24 (2): 61-73.
Shi J, Ni L, Liu J, Xu C, Zhang J, Chen X. 2023. Spatiotemporal distribution of phytoplankton community structure and its relationship with environmental factors in Hongze Lake, China. Urban Clim 52: 101746. https://doi.org/10.1016/j.uclim.2023.101746.
Soejarwo PA, Koeshendrajana S, Apriliani T, Yuliaty C, Deswati RH, Sari YD, Sunoko R, Sirait J. 2022. Management of Floating Net Cages (FNC) aquaculture in an effort to save Maninjau Lake. Jurnal Kebijakan Sosial Ekonomi Kelautan dan Perikanan 12 (1): 79-87.
Sulastri, Henny C, Nomosatryo S. 2019. Keanekaragaman fitoplankton dan status trofik Perairan Danau Maninjau di Sumatera Barat, Indonesia. Pros Sem Nas Masy Biodiv Indon 5: 242-250. https://doi.org/10.13057/psnmbi/m050217. [Indonesian]
Sulastri, Nomosatryo S, Henny C, Sulawesty F. 2022. Functional groups of phytoplankton and their relationship with environmental factors in Lake Maninjau, West Sumatra, Indonesia. IOP Conf Ser Earth Environ Sci 1062 (1): 012012. https://doi.org/10.1088/1755-1315/1062/1/012012.
Sulawesty F, Yustiawati Y, Aisyah S. 2020. Komunitas fitoplankton di Daerah Litoral Danau Maninjau dan Sungai Ranggeh, Kabupaten Agam kaitannya dengan kandungan nutrien. Oseanologi dan Limnol di Indonesia 5 (1): 47. https://doi.org/10.14203/oldi.2020.v5i1.289.
Syandri H. 2020. Danau Maninjau Antara Keramba Jaring Apung dan Pariwisata. LPPM Universitas Bung Hatta, Padang.
Tang C, Yi Y, Yang Z, Zhou Y, Zerizghi T, Wang X, Cui X, Duan P. 2019. Planktonic indicators of trophic states for a shallow lake (Baiyangdian Lake, China). Limnologica 78 (43): 125712. https://doi.org/10.1016/j.limno.2019.125712.
Taurozzi D, Cesarini G, Di Santo C, Scalici M. 2025. Beyond the flow: Ecological insights from diatom communities of a Mediterranean intermittent river. Environ Res 285 (1): 122284. https://doi.org/10.1016/j.envres.2025.122284.
Varga E, Weidman RP, Song Z, McKay RM. 2024. Environmental drivers of phytoplankton community dynamics in an agriculturally-influenced tributary in the lower Great Lakes. Sci Total Environ 939: 173411. https://doi.org/10.1016/j.scitotenv.2024.173411.
Vinh PQ, Ha NTT, Thao NTP, Linh NT, Oanh LT, Phuong LT, Huyen NTT. 2025. Monitoring the trophic state of shallow urban lakes using Landsat 8/OLI data: A case study of lakes in Hanoi (Vietnam). Front Earth Sci 19 (1): 25-40. https://doi.org/10.1007/s11707-021-0949-y.
Wang Q, Yang Q, Zhu L, Cui Z, Qu K, Wei Y. 2024. Environmental controls on the seasonal variations of diatoms and dinoflagellates in the Qingdao coastal region, the Yellow Sea. Mar Environ Res 198: 106524. https://doi.org/10.1016/j.marenvres.2024.106524.
Warsa A, Haryadi Jo. 2019. Beban masukkan fosfor dari kegiatan budidaya dan dampaknya terhadap status kesuburan Danau Maninjau, Sumatera Barat. Jurnal Ecolab 13 (1): 1-10. https://doi.org/10.20886/jklh.2019.13.1.1-10.
Wilson J, Ucharm G, Beman JM. 2019. Climatic, physical, and biogeochemical changes drive rapid oxygen loss and recovery in a

marine ecosystem. Sci Rep 9: 16114. https://doi.org/10.1038/s41598-019-52430-z.

Wu Y, Peng C, Li G, He F, Huang L, Sun X, Wu S. 2024. Integrated evaluation of the impact of water diversion on water quality index and phytoplankton assemblages of eutrophic lake: A case study of Yilong Lake. J Environ Manag 357: 120707. https://doi.org/10.1016/j.jenvman.2024.120707.

Yamaji I. 1979. Illustrations of the marine plankton of Japan. Hoikusha Publishing Company, Osaka. https://doi.org/10.24198/jaki.v5i1.26504.

Yang F, He B, Zhou Y, Li W, Zhang X, Feng Q. 2023. Trophic status observations for Honghu Lake in China from 2000 to 2021 using Landsat Satellites. Ecol Indic 146 (4): 109898. https://doi.org/10.1016/j.ecolind.2023.109898.

Yang XE, Wu X, Hao HL, He ZL. 2008. Mechanisms and assessment of water eutrophication. J Zhejiang Univ Sci B 9 (3): 197-209. https://doi.org/10.1631/jzus.B0710626.

Yu G, Zhang S, Qin W, Guo Y, Zhao R, Liu C, Wang C, Li D, Wang Y. 2022. Effects of nitrogen and phosphorus on chlorophyll a in lakes of China: A meta-analysis. Environ Res Lett 17 (7): 074038. https://doi.org/10.1088/1748-9326/ac7d64.