

# Integrated assessment of eutrophication in Lake Rawa Pening, Central Java, Indonesia, using multivariate statistical methods

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**Abstract.** Rahman A, Haeruddin, Prakoso K, Tyas DE, Jati OE, Arifati A. 2026. *Integrated assessment of eutrophication in Lake Rawa Pening, Central Java, Indonesia, using multivariate statistical methods. Biodiversitas 27 (5): d270519. <https://doi.org/10.13057/biodiv/d270519>.* Lake Rawa Pening, located in Central Java, Indonesia, is a shallow tropical lake affected by anthropogenic eutrophication. This study aims to determine the lake's trophic status and explore association patterns among water quality variables. Water samples were collected at five stations over four periods (February 2024, July 2024, February 2025, and July 2025), representing the rainy and dry seasons. Trophic status was determined using Carlson's Trophic State Index (TSI), while temporal variation and relationships among variables were analyzed using ANOVA, Pearson correlation, and Principal Component Analysis (PCA). Total Phosphorus (TP) used in TSI calculation was estimated from orthophosphate (PO<sub>4</sub>-P) based on an empirical conversion. Nitrate (0.28-0.80 mg/L) and orthophosphate (0.29-0.41 mg/L) concentrations were relatively high, while chlorophyll-a ranged from 8.39 to 38.05 mg/m<sup>3</sup>. All TSI values exceeded 67, classifying the lake as hypereutrophic. Significant temporal differences were found for water depth, Secchi depth, water temperature, nitrate, and chlorophyll-a ( $p < 0.05$ ). PCA identified dominant gradients associated with turbidity, nitrate, dissolved oxygen, and inverse relationships with Secchi depth and chlorophyll-a. These results indicate persistent eutrophication with multivariate interactions among water quality variables. Continuous water quality monitoring and integrated watershed management are crucial to prevent degradation and restore the balance of the Lake Rawa Pening ecosystem.

**Keywords:** Eutrophication, Lake Rawa Pening, Principal Component Analysis, seasonality, Trophic State Index

## INTRODUCTION

Lakes are important freshwater ecosystems that regulate the natural hydrological cycle and provide essential ecosystem services, including water supply, biodiversity support, and food production (Wu et al. 2021; Zhang et al. 2022; Zhao et al. 2025). However, many lakes worldwide have become eutrophic due to excessive nutrient accumulation originating from aquaculture feed residues, agricultural runoff, urbanization, and industrial waste discharge (Wang et al. 2019; Woolway and Merchant 2019; Akinnawo 2023; Suresh et al. 2023). Elevated nutrient inputs degrade water quality, alter aquatic community structure, trigger harmful algal blooms, and threaten ecological integrity as well as socio-economic stability (Murphy and Sprague 2019; Akinnawo 2023). Consequently, eutrophication has become a major threat to aquatic ecosystems and fisheries on a global scale (Gissi et al. 2021; Dai et al. 2023).

Lake Rawa Pening is one of the Indonesian lakes experiencing severe water quality problems, particularly eutrophication. In lakes and other water bodies, eutrophication is closely associated with land-use change and various anthropogenic activities (Maulidyna et al. 2019; Lukhele and Msagati 2024), which increase nutrient concentrations in the water column (Lin et al. 2022; Subedi et al. 2025). Previous studies have reported that Lake Rawa

Pening has undergone sedimentation, rising nutrient levels (Mardiatno et al. 2023), and rapid proliferation of water hyacinth (Prasetyo et al. 2021).

Eutrophication can cause a decline in water quality (Li et al. 2024), including low oxygen (anoxic) conditions that can potentially lead to fish and invertebrate mortality, as well as changes in ecosystem structure (Olisah et al. 2022; Akinnawo 2023). This process is primarily driven by increased inputs of nitrogen and inorganic phosphate from anthropogenic activities such as aquaculture, agricultural runoff, and domestic waste (Piranti et al. 2020; Liu et al. 2022). However, in shallow tropical lakes, trophic responses are often influenced by interactions between nutrients, water physical conditions, and seasonal hydrological dynamics, so relationships between variables are not always linear and simple.

Multivariate statistical approaches such as Principal Component Analysis (PCA) are widely used to explore the structure of water quality data and identify association patterns between variables (Muniz and Oliveira-Filho 2023; Gao et al. 2024). On the other hand, the Carlson Trophic State Index (TSI) provides a quantitative measure for classifying the trophic state of water bodies. These two approaches have complementary roles: TSI provides an indication of trophic level, while PCA helps understand patterns of variation between variables. Therefore, using both together can provide a more comprehensive

understanding of water quality dynamics, without assuming direct causal relationships.

Although Lake Rawa Pening has been extensively researched, most previous studies have focused on specific aspects, such as water hyacinth proliferation, sedimentation, or water resource function. Studies integrating trophic status assessment with multivariate water quality patterns are still relatively limited, particularly in the context of seasonal variation in shallow tropical lakes. Therefore, this study uses a combined TSI and PCA approach as an analytical application to evaluate trophic conditions and explore association patterns among water quality variables in Lake Rawa Pening.

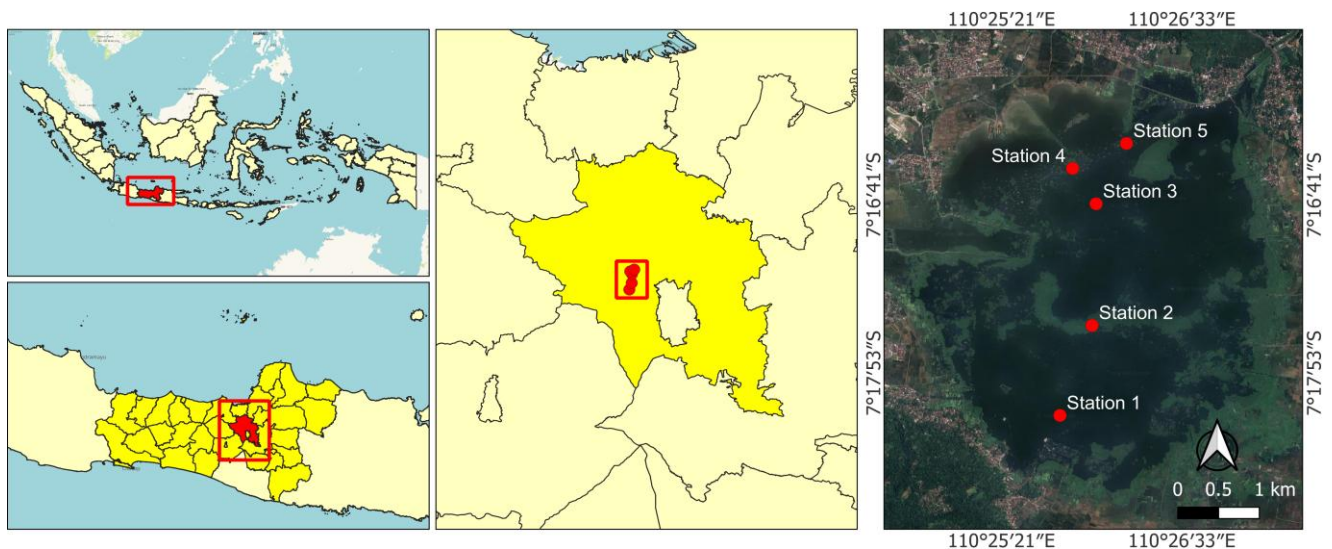
Based on this background, the research hypotheses are: (i) Lake Rawa Pening is in a eutrophic to hypereutrophic state, (ii) nutrient variables (nitrate and phosphate), water transparency, and trophic indicators exhibit association patterns that explain water quality variations. This study aims to determine the lake's trophic status using Carlson's TSI and explore association patterns among water quality variables using PCA and correlation analysis. The findings of this study are expected to provide a scientific basis for more comprehensive lake management in shallow tropical waters.

## MATERIALS AND METHODS

### Study area and sampling sites

Lake Rawa Pening is a shallow tropical lake located in Semarang District, Central Java Province, Indonesia, with a surface area of 2,670 ha (Sutrisno and Handoko 2024). The lake spans four sub-districts: Ambarawa, Tuntang, Bawen, and Banyubiru. Geographically, it lies at approximately 7°15'50"-7°18'54" south latitude and 110°24'30"-110°27'22" east longitude. Five sampling stations were established to represent the main hydrological zones and dominant anthropogenic influences within the lake (Figure 1 and Table 1). Stations were selected to represent spatial heterogeneity associated with river flow, open water conditions, aquaculture activities, and areas adjacent to agricultural land. This spatial differentiation is important because river flow and anthropogenic activities are known to influence nutrient dynamics within the lake system (Wei et al. 2022).

Station 1 is located near the river mouth, representing external nutrient input. Station 2 was placed in the middle pelagic zone to characterize open water conditions. Station 3 is located in an area dominated by floating net aquaculture. Station 4 is located near agricultural land, representing the potential influence of runoff. Station 5 was placed in a transition zone influenced by both aquaculture activities and river flow. This spatial configuration allows for the assessment of nutrient variability in Lake Rawa Pening.



**Figure 1.** Location of five sampling stations with different environmental characteristics in Lake Rawa Pening, a shallow tropical lake in Semarang District, Central Java, Indonesia

**Table 1.** Geographic coordinates and characteristics of sampling stations in Lake Rawa Pening, Semarang, Central Java, Indonesia

Station	South latitude (°S)	East longitude (°E)	Dominant characteristic	Rationale for selection
Station 1	7°18'10.35"	110°25'44.06"	River inlet zone	External nutrient loading
Station 2	7°17'33.79"	110°25'56.91"	Central open water	Pelagic condition
Station 3	7°16'44.31"	110°25'58.51"	Aquaculture area	Internal nutrient input from fish farming
Station 4	7°16'29.90"	110°25'49.07"	Near agricultural land	Potential agricultural runoff influence
Station 5	7°16'19.75"	110°26'10.67"	Mixed influence zone	Combined riverine and aquaculture effects

The geographic coordinates and characteristics of each station are presented in Table 1. The geographic coordinates of each station were determined using a GPS device at the same point during each sampling period to ensure spatial consistency. Sampling was conducted at the same time range, around 08:00-12:00 Western Indonesian Time (WIB), with the sampling sequence between stations consistent for each sampling period. Field variable measurements were conducted repeatedly at each station in accordance with SNI and APHA standards.

**Sample collection and water quality analysis**

Water samples were collected from five sampling stations in Lake Rawa Pening (Figure 1) during four sampling periods: February 2024 (rainy season), July 2024 (dry season), February 2025 (rainy season), and July 2025 (dry season). This sampling was designed to assess seasonal variability. The rainy season (February) is typically characterized by high rainfall and increased river flow, potentially increasing nutrient loads and hydrodynamic mixing, while the dry season (July) reflects relatively stable water column conditions with reduced external inputs (Olisah et al. 2022).

Sampling was conducted at the water surface at all stations, with the following variables measured: water depth (m), Secchi depth (m) was measured using a Secchi disk, turbidity (NTU) was measured using a turbidimeter DRT-15CE, water temperature (°C) using a thermometer, pH using a pH meter OHAUS ST400F, and Dissolved Oxygen (DO) (mg/L) using a DO meter Lutron DO-5510. All instruments were calibrated before use according to the manufacturer’s guidelines. Nitrate (mg/L), phosphate (mg/L), and phytoplankton chlorophyll-a (mg/m<sup>3</sup>) were measured by a UV-Vis spectrophotometer according to APHA (American Public Health Association 2017). Phytoplankton chlorophyll-a was analyzed by 90% acetone extraction. Quality Assurance/Quality Control (QA/QC) included analysis of blanks, duplicates, and reference standards. Depth, Secchi depth, water temperature, pH, and dissolved oxygen were recorded in situ at all stations. Turbidity, nitrate, phosphate, and chlorophyll-a were measured in the Fish and Environmental Resources Management Laboratory (PSDIL), Universitas Diponegoro.

There were no turbidity measurements in February 2025 due to instrument unavailability. These missing data were excluded from the multivariate analysis, which required a complete set of variables. Phosphate was measured as dissolved reactive phosphorus (orthophosphate, PO<sub>4</sub>-P). Total Phosphorus (TP) values used for the Trophic Status Index (TSI) calculation were estimated through a conversion based on the empirical relationship reported by Mitasari et al. (2025), namely TP = 0.066+1.771\*PO<sub>4</sub>. This approach assumes a linear relationship between PO<sub>4</sub> and TP in the studied aquatic system. However, because the proportion of PO<sub>4</sub> to TP can vary spatially and temporally, these estimates should be interpreted with caution as an indirect approximation, not an absolute representation.

**Data analysis**

*Trophic states estimation using TSI*

The eutrophication status of Lake Rawa Pening was assessed using the Trophic State Index (TSI). The TSI was calculated based on Total Phosphorus (TP), Secchi Depth (SD), and chlorophyll-a (Chl-a) using the equations proposed by Carlson (1977), as follows:

$$\begin{aligned}
 TSI_{SD} &= 10 \left( 6 - \frac{\ln SD}{\ln 2} \right) \\
 TSI_{Chl} &= 10 \left( 6 - \frac{2,04 - 0,68 \ln Chl}{\ln 2} \right) \\
 TSI_{TP} &= 10 \left( 6 - \frac{\ln \left( \frac{48}{TP} \right)}{\ln 2} \right) \\
 TSI &= \frac{(TSI_{SD} + TSI_{Chl} + TSI_{TP})}{3}
 \end{aligned}$$

Where, TSI: Trophic State Index, SD: Secchi Depth (m), Chl: Chlorophyll-a (mg/m<sup>3</sup>), TP: Total Phosphorus (mg/m<sup>3</sup>), TSI<sub>SD</sub>: Trophic State Index for Secchi depth, TSI<sub>Chl</sub>: Trophic State Index for chlorophyll-a, TSI<sub>TP</sub>: Trophic State Index for total phosphorus. Carlson’s TSI categories are presented in Table 2. For TSI calculations, TP concentrations initially expressed in mg/L were converted to mg/m<sup>3</sup> to ensure unit consistency with the Carlson equation (1 mg/L = 1000 mg/m<sup>3</sup>). Chlorophyll-a concentrations remained in mg/m<sup>3</sup>. All equations were implemented using standard units to avoid scaling bias in trophic state estimates. Considering the limitations of TP estimation, TSI results are used as a comparative indicator supported by multivariate analysis, not as the sole basis for determining trophic status.

*Statistical analysis*

The dataset consists of measurements from five sampling stations across four sampling periods (February 2024, July 2024, February 2025, and July 2025), resulting in a total of 20 station-level observations per variable (5 stations × 4 periods). Statistical analysis was performed using Jamovi version 2.3.21. To test for temporal differences in water quality variables, a one-way Analysis of Variance (ANOVA) was performed with sampling period as a fixed factor (four levels), using station-level values (n = 5 per period) as independent observations. This design maintained spatial variability and avoided the loss of information associated with period averages. Statistical significance was set at p < 0.05. When significant differences were detected, a Tukey’s HSD post hoc test was applied to identify differences between periods. Turbidity was excluded from the ANOVA because measurements were unavailable for one sampling period (February 2025).

**Table 2.** Category of Trophic State Index (TSI) Carlson

Trophic State Index (TSI)	Category
< 47	Ultraoligotrophic
47-52	Oligotrophic
52-59	Mesotrophic
59-63	Eutrophic
63-67	Highly eutrophic
> 67	Hypereutrophic

Principal Component Analysis (PCA) was used to explore the multivariate structure of the variables, with water depth, Secchi depth, turbidity, temperature, pH, dissolved oxygen, nitrate, orthophosphate ( $\text{PO}_4\text{-P}$ ), and chlorophyll-a, standardized (z-score). Prior to analysis, all variables were tested for normality and met the assumptions of normal distribution, thus supporting the use of PCA. Because turbidity data were not available for a single period, PCA and Pearson correlation were performed using listwise deletion to include only complete observations ( $n = 15$ ; 5 stations  $\times$  3 periods). Therefore, the PCA results do not represent the entire period equally, and interpretation of principal components is based on the available data subset. Furthermore, neither ANOVA nor PCA explicitly accounts for the repeated-measures structure at the same station, so inferential results should be interpreted with caution as indicative of patterns. Moving forward, a mixed-effects model approach or a repeated-measures framework is recommended to produce more robust estimates.

## RESULTS AND DISCUSSION

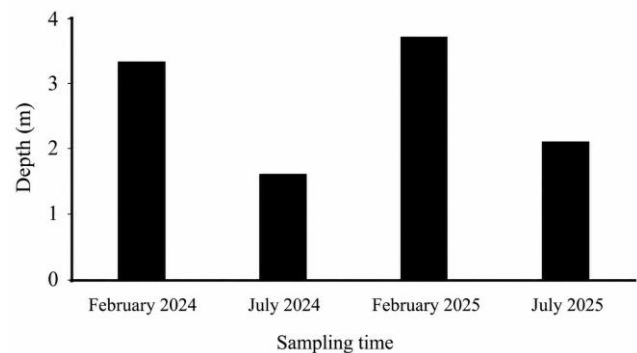
### Water quality dynamics

Water quality monitoring data collected during four sampling periods during the dry and rainy seasons of 2024-2025 (Table 3) show varying water quality variables. Water quality results showed significant differences between time periods for depth, Secchi depth, water temperature, nitrate, and chlorophyll-a. The depth of Lake Rawa Pening during the study ranged from 1.59 to 3.59 m, with the lowest depth in July 2024 and the highest in February 2025 (Figure 2). These depth results indicated that Lake Rawa Pening is very shallow (Holgerson et al. 2022). In shallow lakes, thermal stratification between seasons is usually rare, and water mixing patterns are more homogeneous (Piccioni et al. 2021; Holgerson et al. 2022).

The differences in water depth between the dry and rainy seasons observed in this study are likely related to variations in hydrological conditions, such as rainfall, runoff, river flow, and evaporation (Fergus et al. 2022; Liu et al. 2025). The decrease in depth during the dry season may reflect reduced water input and increased evaporation,

while the increase in depth during the rainy season is consistent with additional water from runoff and inflow. Furthermore, the observed depth variations may also be related to sedimentation and organic matter accumulation, although these processes were not directly measured in this study. Previous studies in Lake Rawa Pening have shown that sedimentation, land-use changes, and the development of macrophytes (such as water hyacinth) potentially contribute to the decrease in depth in Lake Rawa Pening (Mardiatno et al. 2023). Climate change alters the hydrological conditions and water temperature of the lake and reduces the amount of water entering the lake, which further worsens water quality (Woolway et al. 2022).

Secchi depth and turbidity ranged from 0.42 to 0.78 m and 4.35 to 10.16 NTU, respectively (Figure 3). Secchi depth indicates low water clarity with eutrophic conditions and turbidity ranging from moderate to quite high for freshwater bodies. In shallow eutrophic lakes, the causes of decreased Secchi depth and increased turbidity are increased phytoplankton concentrations, sediment input from watershed erosion, and sediment resuspension in the shallow bottom (Liu et al. 2019). Low Secchi depth and moderate to high turbidity reduce the photic zone, encouraging the dominance of macrophytes/aquatic plants and increasing DO during the day when photosynthesis occurs (Martinsen et al. 2022).

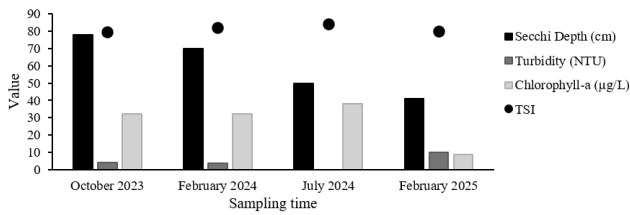


**Figure 2.** Depth of Lake Rawa Pening, Semarang, Central Java, Indonesia, from February 2024 to July 2025

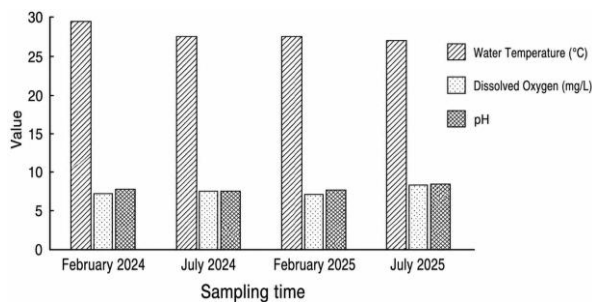
**Table 3.** Water quality parameters of Lake Rawa Pening, Semarang, Central Java, Indonesia, from February 2024 to July 2025

Variable	February 2024	July 2024	February 2025	July 2025	p-value
Depth (m)	3.24 ± 0.44 <sup>a</sup>	1.59 ± 0.35 <sup>b</sup>	3.59 ± 0.97 <sup>a</sup>	2.03 ± 0.82 <sup>a</sup>	0.001*
Secchi depth (m)	0.78 ± 0.14 <sup>a</sup>	0.67 ± 0.12 <sup>a</sup>	0.5 ± 0.05 <sup>b</sup>	0.42 ± 0.02 <sup>b</sup>	0.001*
Turbidity (NTU)	4.35 ± 0.98	4.35 ± 0.98	-	10.16 ± 1.22	-
Water temperature (°C)	29.6 ± 0.9 <sup>a</sup>	26.7 ± 1.7 <sup>b</sup>	27.5 ± 0.4 <sup>b</sup>	27.4 ± 1.2 <sup>b</sup>	0.014*
pH	7.62 ± 0.13 <sup>a</sup>	7.38 ± 0.19 <sup>a</sup>	7.65 ± 0.17 <sup>a</sup>	8.05 ± 0.77 <sup>a</sup>	0.133
Dissolved oxygen (mg/L)	7.1 ± 0.8 <sup>a</sup>	7.5 ± 0.3 <sup>a</sup>	7.1 ± 0.4 <sup>a</sup>	8.2 ± 1.2 <sup>a</sup>	0.258
Nitrate (mg/L)	0.28 ± 0.04 <sup>a</sup>	0.44 ± 0.05 <sup>a</sup>	0.8 ± 0.07 <sup>b</sup>	0.64 ± 0.15 <sup>b</sup>	< 0.001*
Orthophosphate (mg/L)	0.29 ± 0.31 <sup>a</sup>	0.31 ± 0.09 <sup>a</sup>	0.41 ± 0.37 <sup>a</sup>	0.34 ± 0.13 <sup>a</sup>	0.936
Chlorophyll-a (mg/m <sup>3</sup> )	31.05 ± 10.64 <sup>a</sup>	34.75 ± 9.64 <sup>a</sup>	38.05 ± 7.07 <sup>a</sup>	8.39 ± 1.97 <sup>b</sup>	0.001*
TSI	79.12 ± 4.6 <sup>a</sup>	82.39 ± 2.27 <sup>a</sup>	84.3 ± 4.23 <sup>a</sup>	80.25 ± 1.83 <sup>a</sup>	0.213

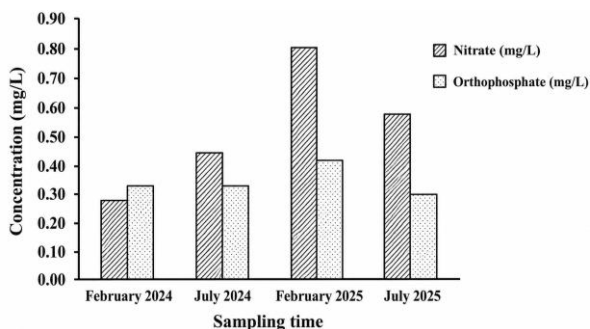
Note: “-”: No turbidity data in February 2025, “\*”: Indicates significant differences among sampling times (one-way ANOVA,  $p < 0.05$ )



**Figure 3.** Variations in Secchi depth, turbidity, chlorophyll-a concentration, and Trophic State Index (TSI) of Lake Rawa Pening, Semarang, Central Java, Indonesia, from February 2024 to July 2025



**Figure 4.** Temporal variations in temperature, Dissolved Oxygen (DO), and pH in Lake Rawa Pening, Semarang, Central Java, Indonesia, from February 2024 to July 2025



**Figure 5.** Temporal variations in nitrate and orthophosphate concentrations in Lake Rawa Pening, Semarang, Central Java, Indonesia, from February 2024 to July 2025

The water temperature and pH in this study were 26.7–29.6°C and 7.38–8.05, respectively. These water temperatures are within the optimal temperature range for aquatic organisms in tropical waters, between 25–30°C. Water temperature has a very important influence on the biological activity and the growth of aquatic organisms. Some things that affect water temperature are weather, humidity, and the intensity of sunlight entering the water (Siddique et al. 2024). The pH value indicates neutral to slightly alkaline conditions. Several studies have also shown that high pH values are caused by high primary productivity and low CO<sub>2</sub> (Zepernick et al. 2021; Many et al. 2024). pH affects most chemical and biological processes in water. pH is one of the most important water quality variables for assessing the health status of aquatic ecosystems (Saalidong et al. 2022). Each sampling season

had nearly the same pH. Sampling 2 (July 2024) showed a low pH (7.4) (Figure 4).

Dissolved Oxygen (DO) concentrations ranged from 7.1 to 8.2 mg L<sup>-1</sup> throughout the sampling period, indicating relatively oxygen-rich surface conditions. Because measurements were taken during daytime surface sampling, the relatively high DO concentrations may be related to photosynthesis in the euphotic layer. However, daily DO fluctuations were not measured in this study; therefore, a potential nocturnal decrease due to respiration and organic matter decomposition cannot be confirmed from the available data. Dissolved oxygen increases in the euphotic part of the water column because of the enrichment of photosynthetic communities (Fusi et al. 2023). High water temperature and dissolved oxygen promote phytoplankton growth and metabolic activity, resulting in increased chlorophyll-a concentrations (Thayne et al. 2023).

The nitrate and orthophosphate concentrations of the four samples ranged from 0.28 to 0.8 mg/L and 0.29–0.41 mg/L, respectively (Figure 5). Orthophosphate concentrations showed a fairly wide range in February 2024 (0.05–0.72 mg/L) and February 2025 (0.15–1.05 mg/L), indicating spatial heterogeneity likely influenced by local nutrient sources during these periods. Both nutrients indicate high nutrient levels for freshwater. The primary causes of such high nutrient levels almost always involve external and/or internal loading. External sources include agricultural runoff (fertilizers), domestic wastewater, erosion, and land conversion in watersheds. Internal loading occurs when phosphorus stored in sediments is released into the water column under reducing conditions or due to mechanical resuspension in shallow lakes (Qin et al. 2019). Nutrient input into lakes can accelerate algae growth rapidly (Qin et al. 2025) and has the potential to cause a decline in water quality (Li et al. 2024).

### Trophic status and phytoplankton biomass (Chlorophyll-a)

Based on Carlson's Trophic State Index (TSI) classification, all TSI values exceeded 67, confirming that Lake Rawa Pening was hypereutrophic throughout all sampling periods. Phytoplankton chlorophyll-a concentrations of 8.39–38.05 mg/m<sup>3</sup> indicate high phytoplankton biomass. Chlorophyll-a showed a negative correlation with turbidity and a positive correlation with Secchi depth (Table 4). Photosynthetic activity of phytoplankton and macrophytes, which absorb CO<sub>2</sub> and produce dissolved oxygen, leading to an increase in pH (Hamdhani 2024). In this study, this interpretation is indirectly supported by the multivariate structure, where chlorophyll-a correlates with key physicochemical parameters, indicating that phytoplankton biomass is an important component of the trophic system.

Although TSI values indicated hypereutrophic conditions throughout the observation period, PCA and correlation results indicate that variability in this dataset is not dominated by a single nutrient parameter, but rather by a combination of factors such as turbidity, transparency, and dissolved nutrients. Thus, the identified hypereutrophic conditions likely reflect the overall trophic status of the system, while the spatial and temporal variations measured in this study are more related to interactions between

turbidity, nutrient availability, and light penetration. Given the limited dataset size and the data reduction resulting from listwise deletion, PCA results are treated as exploratory and should not be used to infer causally the primary controlling mechanisms.

**Multivariate structure and correlation between water quality variables**

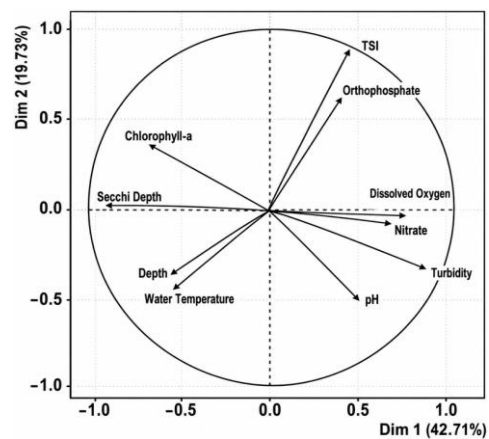
Water quality variables exhibited variability across all sampling periods and stations, indicating the multivariate nature of the lake system. This pattern was explored using PCA (Figure 6) and correlation analysis (Table 4), which revealed associations between several water quality variables. PCA results showed that the first principal component (PC1) explained 42.71% of the total variance, while PC2 explained 19.79%, resulting in a cumulative explained variance of 62.5% for the first two axes. PC1 consisted of positive loadings for turbidity ( $r = 0.89$ ), dissolved oxygen ( $r = 0.70$ ), and nitrate ( $r = 0.69$ ), and strong negative loadings for Secchi depth ( $r = -0.90$ ) and chlorophyll-a ( $r = -0.72$ ), while PC2 was primarily associated with TSI ( $r = 0.86$ ) and orthophosphate ( $r = 0.64$ ). This pattern suggests a multivariate gradient involving water transparency, suspended particles, nutrients, and trophic conditions.

Correlation analysis results support this pattern, particularly the strong negative relationship between turbidity and Secchi depth and the association between turbidity and nitrate. Chlorophyll-a showed a negative relationship with turbidity and a positive relationship with Secchi depth, indicating that increases in phytoplankton biomass do not always occur in the most turbid water conditions. Meanwhile, orthophosphate showed relatively weak relationships with most variables but was strongly correlated with TSI, consistent with its role in determining trophic status. Phosphorus is widely recognized as a key nutrient regulating eutrophication processes in freshwater ecosystems (Wang et al. 2025).

Pearson correlation analysis (Table 4) indicated a relationship between several water quality variables, based on coefficient values and statistical significance ( $n = 15$ ). Turbidity was positively correlated with dissolved oxygen and nitrate, and strongly negatively correlated with Secchi

depth, reflecting the inverse relationship between suspended particles and water transparency (Carlson 1977). Furthermore, nitrate was also negatively correlated with Secchi depth, indicating that increased dissolved nutrients are associated with decreased transparency. Therefore, large and continuous nitrate (nutrient) inputs contribute to eutrophication, reducing sunlight penetration, and lowering dissolved oxygen concentrations in the water column (He et al. 2023).

The integration of TSI, PCA, and correlation analysis provides a complementary framework for understanding the dynamics of eutrophication in Lake Rawa Pening. TSI values consistently classify the lake as hypereutrophic, indicating high nutrient levels and aquatic productivity. However, PCA indicates that the first two principal components explain approximately 62.5% of the variance, with PC1 associated with the turbidity gradient, nitrate, DO, and transparency (Secchi depth), and PC2 associated with TSI and orthophosphate. This pattern suggests that water quality variation in this dataset reflects multivariate interactions between suspended matter, nutrients, and trophic conditions, rather than the dominance of a single parameter (Mamun et al. 2021; Abdul and Arunbabu 2025).



**Figure 6.** PCA biplot of water quality parameters in Lake Rawa Pening, Semarang, Central Java, Indonesia

**Table 4.** Correlation matrix of water quality parameters in Lake Rawa Pening during the sampling period

	D	SD	Tu	WT	pH	DO	N	P	Chl
D	—								
SD	0.46	—							
Tu	-0.30	-0.84	—						
WT	0.61	0.59	-0.31	—					
pH	-0.03	-0.47	0.57	-0.20	—				
DO	-0.38	-0.47	0.60	-0.23	0.51	—			
N	-0.41	-0.60	0.68	-0.20	-0.04	0.32	—		
P	-0.09	-0.20	0.22	-0.10	-0.12	0.26	0.20	—	
Chl	0.18	0.61	-0.78	0.01	-0.41	-0.42	-0.61	-0.25	—
TSI	-0.37	-0.26	0.07	-0.48	-0.12	0.32	0.10	0.83	0.01

Note: D: Depth, SD: Secchi Depth, Tu: Turbidity, WT: Water Temperature, pH: Potential of Hydrogen, DO: Dissolved Oxygen, N: Nitrate, P: Orthophosphate, Chl: Chlorophyll-a. Low Positive Correlation High, Low Negative Correlation High

The correlation results indicate a strong relationship between turbidity and transparency, as well as between turbidity and nitrate. Meanwhile, orthophosphate exhibits a relatively weaker relationship with most variables, although it is strongly correlated with TSI. These findings indicate that orthophosphate has a weaker multivariate relationship than nitrate and turbidity. However, this should not be interpreted as evidence that phosphorus is less important in eutrophication dynamics, given that total phosphorus was not measured directly and the TSI relies in part on estimates of total phosphorus. Therefore, the role of phosphorus remains relevant in the context of trophic status (Paerl and Otten 2013). Overall, hypereutrophic conditions reflect the general trophic status of the water body, while PCA and correlations indicate that spatial and temporal variations in water quality are more related to interactions between water transparency, turbidity, and dissolved nutrients. This confirms that water quality dynamics in shallow lakes are complex and cannot be explained by a single nutrient variable (Tong et al. 2020).

The management implications of these findings suggest that single-indicator-based approaches, such as the TSI alone, are insufficient to identify environmental factors associated with water quality variability. Therefore, management strategies need to consider various sources of stress, both external and internal, including controlling nutrient inputs from watersheds and managing aquaculture activities. Efforts such as erosion control, riparian vegetation restoration, optimizing feed efficiency, and regulating fish cage density can be important steps in managing shallow tropical lakes with hypereutrophic conditions (Paerl and Otten 2013; Tong et al. 2020).

In conclusion, this study shows that Lake Rawa Pening is consistently classified as hypereutrophic across all sampling periods, as indicated by chlorophyll-a concentrations ranging from 8.39 to 38.05 mg m<sup>-3</sup> and TSI values above the hypereutrophic threshold (> 67). Significant seasonal differences were detected for depth, Secchi depth, water temperature, nitrate, and chlorophyll-a, indicating temporal variability. PCA showed that the first two principal components explained 62.5% of the variance, with patterns involving turbidity, nitrate, dissolved oxygen, transparency (Secchi depth), and TSI and orthophosphate. Together with the correlation results, these findings indicate a multivariate association pattern in water quality. However, this pattern is exploratory and cannot be interpreted as the primary controlling mechanism of eutrophication. Orthophosphate showed a relatively weaker association compared to several other variables, but this does not indicate a lack of phosphorus, given that total phosphorus was not measured directly and TSI estimates rely partly on conversion from phosphate. Research limitations, including the lack of turbidity data for a single period and the lack of repeated measurement analysis, should be considered when interpreting the results. Future research is recommended to measure total phosphorus directly and use a more robust analytical approach. Nevertheless, the integration of TSI and multivariate analysis in this study provides a useful baseline for

understanding the complexity of trophic dynamics and supporting more comprehensive lake management.

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