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Research article

Vertical and Horizontal Distribution Of Aquatic Nutrient Concentrations and Sedimentary Organic Carbon in Rawa Pening Lake, Indonesia

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Abstract

Current information and interactions between water and sediment have not been reported, so it is necessary to describe the interaction in the C and N/P ratio of Rawa Pening lake. This research found that P is a limiting factor which indicates the need for P control. It can also be seen that DOC has a fairly strong relationship and contribution to the increase in N and P concentration. NO_3 is a compound of the N group that plays the most important role in aquatic fertility. The highest sedimentary organic C was found at a depth of 10 cm with a concentration of 401 gC/kg. The lower zone of water also experiences excess nutrients, potentially leading to reduction conditions. Nutrient control is necessary to prevent microalgae growth and improve the water's oxidation state. Furthermore, the overall C/N/P interaction in water and sediment is necessary to detail the health status of the Rawa Pening waters.

Keywords: Rawa Pening; Nutrients; Sediment; Carbon

1. Introduction

A common problem in lakes/reservoirs lies in the ecological aspects, one of which is the chemical dynamics of nutrients. This impacts the sustainability of lakes like Rawa Pening, which are commonly used in various sectors.

Rawa Pening is a volcanic lake currently used for various purposes, such as agriculture, tourism, aquaculture and non-aquaculture, livelihoods, irrigation, and agriculture (Wulandari 2022; Mardiatno *et al*. 2023; Mujiburrohman & Andari 2023; Nada *et al*. 2023; Kintani *et al*. 2024; Putra *et al*. 2025). However, this high level of activity increases the potential for pollution, particularly nutrient pollution. Nutrient pollution can cause the lake to become fertile, allowing various autotrophic organisms to grow. If not managed sustainably, the lake will become anaerobic, negatively impacting fisheries.

Conversely, excessive fisheries aquaculture can contribute to the accumulation of organic matter. The decomposition of organic matter produces nutrients for the growth of autotrophic organisms. The bacterial decomposition process requires oxygen. If dissolved oxygen consumption is excessive and not balanced by aeration, it can potentially lead to hypoxia and reduction in the lake's water content. At this stage, the lake will produce toxic gases that harm heterotrophic organisms and even cause aesthetic pollution.

Pollution sources can be internal (autochthonous) or external (allochthonous). Floating cage activity is the dominant autochthonous source in the lake (Pratiwi *et al*. 2020). Leftover food, fish feces, and human domestic activities are sources of organic pollution in Rawa Pening. These wastes are buried and accumulated in the sediment as organic matter.

Sediment is the source of these nutrients. Nutrients originate from the breakdown and dissolution of organic matter. Organic matter is generally composed of carbon complexes that bind various inorganic elements, such as nitrogen and phosphorus. The molecular structure of organic matter by carbon allows analysis of organic matter based on its concentration, known as organic carbon or organic carbon. The availability of organic C is often linked to nutrient dynamics (Mbonda *et al*. 2025).

C from autochthonous sources originate from the decomposition of aquatic plant debris, phytoplankton, and fish food waste (Pratiwi *et al*. 2020; Yu *et al*. 2022; Zhou *et al*. 2022; Prasetyo *et al*. 2024; Quanliang *et al*. 2024). Allochthonous sources originate from soil erosion carried by river currents. Eroded soil can export organic matter and nutrients (Nada *et al*. 2023; Rantala *et al*. 2025; Wang *et al*. 2025).

Aquatic nutrients that influence fertility are usually represented by the elements nitrogen (N) and phosphorus (P). N has the subgroups NH_3 (ammonia), NO_2 (nitrite), and NO_3 (nitrate). The presence of N and P always coexists in the context of fertility and microalgae growth, so it is often expressed as a ratio called the N/P ratio or Redfield (Redfield 1934). This ratio is expressed as (N)16:1(P). If one of these two elements is dominant, it becomes a factor that needs to be limited or managed. Various lake management methods have been implemented to reduce/dilute/control nutrient concentrations (Mardiatno *et al.* 2023).

Various studies have been conducted to evaluate the condition of Rawa Pening from various aspects, including: biomarkers of trophic and nutrient status based on the growth of water hyacinth and diatoms (Prasetyo *et al.* 2021 & Prasetyo *et al.* 2024); the socio-economic and institutional impacts of community revitalization (Wulandari 2022; Mujiburrohman & Andari 2023; Kintani *et al*. 2024; Putra *et al.* 2025); evaluation of lake management methodology (Mardiatno *et al.* 2023); and the dynamics of allocthonous nutrient export (Nada *et al.* 2023). Furthermore, no recent research has been found regarding water quality data in the surface and bottom zones.

To date, no carbon stratigraphic profile of Lake Rawa Pening sediments has been reported. Stratigraphic profiles from the last five years have only been found related to diatom diversity (Prasetyo *et al.* 2024). Studies from more than five years prior have also not reported sedimentary carbon stratigraphy. Therefore, this study aims to explain the current condition of Lake Rawa Pening in terms of differences in nutrient concentrations in the surface and bottom zones, as well as sedimentary carbon stratigraphy.

2. Research Methods

Rawa Pening Lake is administratively located in Semarang Regency. This lake is part of the upstream part of the Tuntang River Basin (DAS). This research was conducted in June 2025, during the rainy season. Samples were collected during the day when it was not raining. All samples were transported and analyzed at the Laboratorium Lingkungan, Fakultas Geografi, Universitas Muhammadiyah Surakarta (UMS).

The lake's maximum depth during the rainy season is -15 m, based on bathymetric measurements (Figure 1). Bathymetric measurements were performed using a Garmin 545 Plus instrument, traversing the entire lake. The measurement data was then interpolated using the Inverse Distance Weighted (IDW) method and grouped into five depth classes. However, the maximum depth on the map (Figure 1) is -13.88 m. This is due to the nature of IDW interpolation, which eliminates outliers.

The depth data was then followed by the determination of lake morphometry as a supporting parameter to assess the influence of lake shape on nutrient dynamics. Morphometric parameters include shoreline length (S), volume (V), area (A), perimeter (C), Osgood index (1988), shoreline development index (SDF), mean depth (Z_{mean}), mean temperature (T_{mean}), maximum temperature (T_{max}), and maximum depth (Z_{max}) (Lakewatch 2003; Choinski and Zielisnki 2021; Dumpis and Lagzdins 2020). These supplementary data were processed in bathymetric data processing software. Shoreline length measurements were performed by digitizing the lake boundary. The lake circumference was calculated based on the square root of the relationship between four times the lake area (in km^2) multiplied by π (Bhardwaj & Thukral 2005).

$$Circumference\ (km) = \sqrt{4 \times \pi \times A} \tag{1}$$

Lake category determination refers to Osgood (1988), Lakewatch (2003), Bhardwaj & Thukral (2005), and Pi *et al.* (2022). The Osgood index is used to determine lake types based on depth and its influence on temperature distribution. The Osgood index is known to have lake classifications: dimictic (>9), intermediate (4 – 9), and polymictic (<4). The Osgood index is calculated based on the ratio of the average depth (m) and the square root of the lake surface area (km^2).

$$Osgood = \frac{Z_{mean}}{\sqrt{A}} \tag{2}$$

The shoreline development factor/index (SDF) is the ratio between the circumference (km) and the shoreline length (km). The minimum SDF value is 1 (a perfect circle); the higher the SDF, the more irregular the lake shape. Lake shape classification refers to Lakewatch (2003) and Bhardwaj & Thukral (2005). Lake area also determines other environmental parameters. Lake area classification refers to Pi *et al.* (2022).

$$SDF = \frac{C}{S} \tag{3}$$

Samples were taken from sediment and water. Water samples were selected at five points based on their association with the environment. Point 1 was selected based on a point not close to human activity (for example, a floating cage). Points 2 and 3 were selected based on their proximity to the flow input and the presence of water hyacinth. Points 4 and 5 were selected based on their proximity to the floating cage and the flow input.

Water samples were collected at two main depths: the surface and the bottom, using a Van Dorn Sampler. The samples were unpreserved and immediately analyzed using the APHA protocol (2023). Analysis was conducted on the nitrogen group parameters (NH_3, NO_2, NO_3), total phosphorus (TP), and dissolved organic carbon (DOC). Each nitrogen group was summed, resulting in a total nitrogen (TN) value.

Tests for ammonia (NH_3), nitrite (NO_2), and nitrate (NO_3) were carried out using the phenate, colorimetric, and second derivative spectrophotometric methods, respectively. The TP test uses the Ascorbic Acid Digestion method, with ascorbic acid acting as a reducing agent for the molybdenum complex. The DOC test uses the UV Absorption method with Potassium Hydrogen Phthalate (KHP) as the standard.

Sediment samples were selected at the shallowest point outside the seasonal tidal zone. Sediment collection was carried out using simple coring techniques, involving snorkeling, as the water depth was approximately 1.5 m. Core samples were collected using a 1-m-long PVC tube. The core tube was then split in half to reveal the sediment layers. The ends of each core (5 cm) were discarded.

The resulting samples were divided according to their analytical needs. The first section was used for water content measurement, while the second section was used for organic carbon analysis. The samples were then divided into subsamples, taken at 5 cm intervals. The sediment sample obtained was 50 cm long, so the sample sequence is 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, and 55 (Figure 4). Subsamples were then analyzed for organic carbon content using the Walkley-Black method (FAO, 2019). Water content testing was used as a variable for calculating organic carbon.

The water sample test results were conducted separately. The water samples were analyzed using matrix and hotspot correlations, while the sediment samples were graphed. The correlation and hotspot analyses were performed using R software. The sediment analysis was graphed using Microsoft Excel. Furthermore, the limiting factors for phytoplankton growth were determined using the N/P ratio, also known as the Redfield ratio (Redfield, 1934).

Nutrient concentrations were depicted using a hotspot model representing the surface (A) and bottom (B) zones (Figure 2). The color scale was applied based on gradation; the more intense the color, the higher the concentration. The correlation matrix illustrates the relationship between each nutrient parameter and the N/P ratio.

The N/P ratio is based on the stoichiometric ratio of phytoplankton biomass, which is 16:1. This means that the availability of N must be 16 times greater than P. If the ratio value is above 16, then the limiting factor for phytoplankton growth is P. If the ratio value is less than or equal to 16, then the limiting factor for growth is N. The N/P ratio has no units.

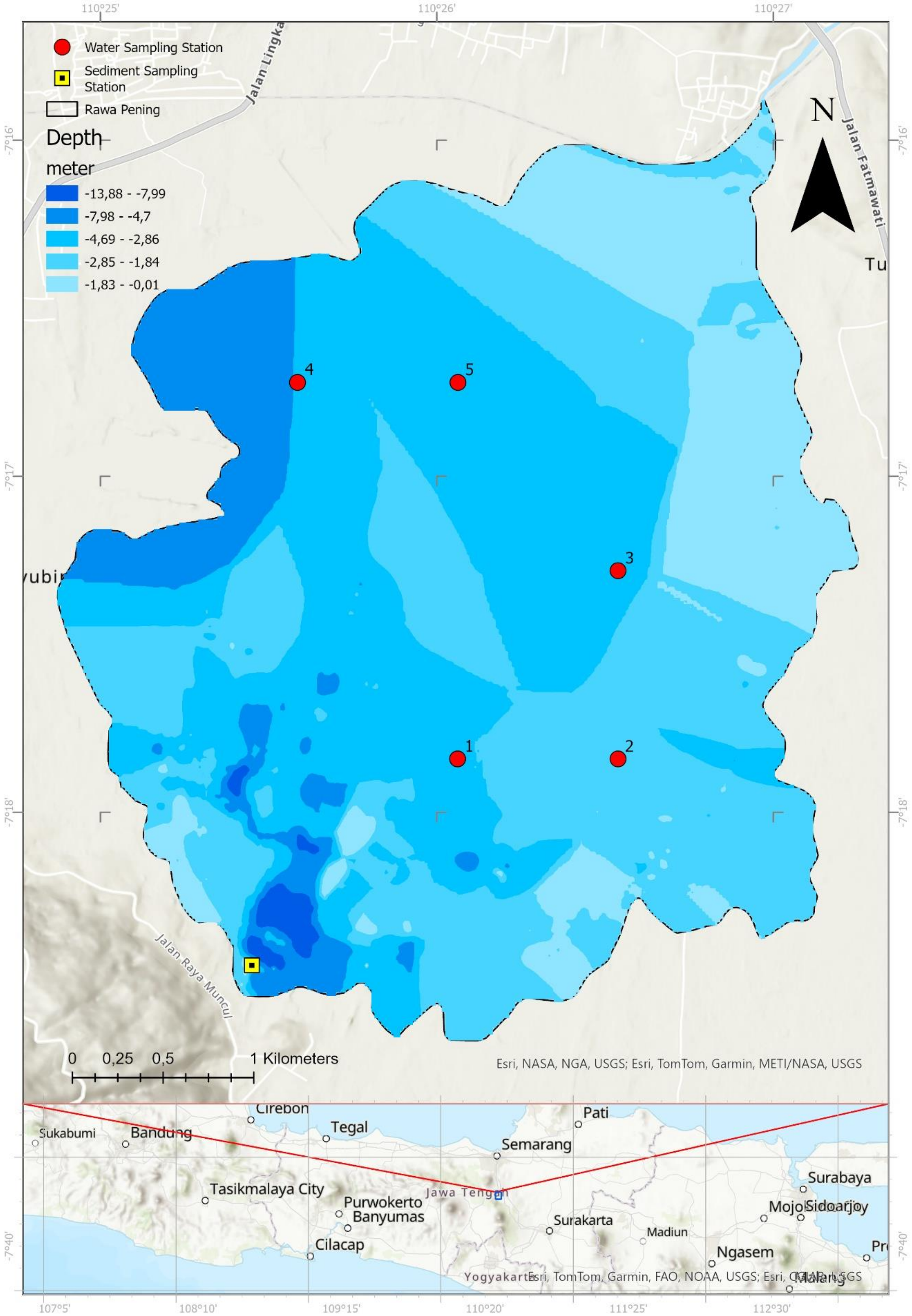

Figure 1. Research Location

3. Results and Discussion

3.1 Morphometric and Horizontal Nutrient Distribution

The morphometric data for Lake Rawa Pening shows: A = 15.17 km^2 or 1,517 ha, Z_{mean} = 3.44 m, C = 19.11 km, S = 15.11 km, SDF = 1.27, and Osgood Index = 0.88. In terms of area, this lake is classified as medium-sized. It is also classified as a polymictic lake based on the index (Osgood 1988) and as an asymmetrical circle based on the SDF category (Lakewatch 2003).

Lake area not only serves to describe its size but can also be used to assess the influence of wind on lake hydrodynamics. Wind plays a significant role in wave formation, which impacts mixing; therefore, the larger the lake area, the greater the wind's influence on wave formation. Mixing is important in ensuring an even distribution of dissolved oxygen concentrations in the water.

Furthermore, area also plays a role in the lake's dilution process; the larger the lake, the greater the volume, the greater the dilution process. The calculated volume of Rawa Pening in this study was 12,290,919 m^3. Combined with the area, it is expected that the lake has a high dilution capacity. Data related to retention (water discharge) and residence time are required to determine the lake's dilution capacity (Stefan 1989; Morillo *et al.* 2006). However, this study did not provide data on discharge, so further research on dilution capacity is needed. Dilution is a crucial measure in controlling the lake's pollution load.

However, Rawa Pening Lake only has one outlet, meaning the dilution process is uneven across the area. This is also supported by interviews with cage farmers and local boat tour providers who reported frequent mass fish deaths, particularly in the southern part of the lake. This suggests that Rawa Pening Lake has a high mixing capacity due to its size, but a low dilution capacity.

Although numerous inlets are found in Rawa Pening, which could aid the dilution process by increasing the lake's volume, a higher inlet-to-outlet ratio would increase the lake's pollution load. This is due to the numerous activities in Rawa Pening Lake that have the potential to cause a high pollution load (not included in this study). The pollution load in question is nutrients that impact aquatic productivity.

The SDF is useful in describing the homogeneity of a lake ecosystem; the higher the SDF value, the greater the heterogeneity of the associated ecosystems around the lake. Rawa Pening Lake has an asymmetrical circular shape, indicating a homogeneous ecosystem. This is supported by the dominant land use of agricultural activities (Mardiatno *et al.* 2022), resulting in allochthonous nutrient inputs from agricultural activities.

The current geometry of Rawa Pening represents an accumulation of changes over the past few years. Bashit *et al.* (2023) noted that changes in area occurred in Rawa Pening, with the water body expanding in 2021. This was caused by dredging of sediment on the lakeshore due to high sedimentation (Mardiatno *et al.* 2022; Bashit *et al.* 2023).

Nutrient concentrations in lakes generally vary with depth, with the deeper you go, the higher the concentration. Therefore, the average depth (Zmean) is useful in assessing aquatic productivity. Rawa Pening is classified as a shallow, polymictic lake. This means the lake lacks an epilimnion and hypolimnion zone, with an average surface temperature of 26.96°C at the time of measurement.

Temperature influences water density. Generally, the bottom layer of a lake has a higher density than the surface. In shallow lakes like Rawa Pening, the temperature difference between the top and bottom layers is only insignificant. Rawa Pening Lake had a maximum depth of 16.51 m during the rainy season (June 2025), meaning that some locations with deeper elevations may experience differences in density. However, Sasmito *et al.* (2022) found that TSS concentrations and turbidity (Amelia *et al.* 2022) remained within safe limits. This proves that sunlight, which affects temperature, can spread to the lower layers, so the difference is not significant. Density is related to mixing. The presence of wind and waves can upheave this density, allowing compounds or nutrients at the bottom of the water to be lifted. This can potentially cause toxicity to aquatic organisms at the surface if the bottom conditions are anaerobic.

Anaerobic conditions occur when dissolved oxygen is low, so reduction processes replace oxidation, resulting in compounds in the water that are hydrogen-bonded products such as NH_3, CH_4, and H_2S. Handoko & Sutrisno (2021) and Astuti *et al.* (2024) found that the average DO concentration in Lake Rawa Pening ranged from 3.04 to 8.3 mg/L. However, these studies only sampled the surface layer, so data on dissolved oxygen in the lower layers were not obtained.

Furthermore, the data presented in these studies varied from year to year within the same month. For example, the DO values of Rawa Pening in November 2020 and 2024 were 3.04 and 8.3 mg/L, respectively (Handoko & Sutrisno 2021; Astuti *et al*. 2024). This difference is due to differences in sampling time, location, and number of samples. Handoko & Sutrisno (2021) only sampled the edge area near the inlet, while Astuti *et al*. (2024) only sampled at three stations: the southern end, the central end, and the northern end (outlet). Nevertheless, these data can be used as a reference and demonstrate that lake size can influence aeration and mixing, especially in the surface layer (in this case, Rawa Pening).

This research was conducted at five stations, sampling based on the upper (A) and lower (B) layers. Data were adjusted to the lake water quality standards (PP No. 22-2021). In general, all parameters in Table 1 (except DOC) exceed the lake water quality standards. PP No.22 (2021) requires minimum TN and TP values for Class 1 of 0.65 and 0.03 mg/L, respectively. These values (Table 1) also generally exceed the quality standards in all classes. This indicates that the waters are already experiencing nutrient pollution in almost all locations. This condition is also supported by Astuti *et al*. (2024), who found TN and TP values exceeding the quality standards.

Table 1. Nutrient Data of Rawa Pening Lake

Sample	NH_3 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	TN (mg/L)	TP (mg/L)	DOC (mg/L)	N/P Ratio
1A	0.126	3.93	0.00895	4.06	0.0354	2.77	115
1B	0.126	8.91	0.00734	9.04	0.3566	3.01	25.4
2A	0.265	1.87	0.00951	2.14	0.0770	2.40	27.9
2B	0.0951	3.77	0.00752	3.87	0.0236	2.68	164
3A	0.124	3.85	0.00932	3.98	0.0329	2.56	121
3B	0.137	5.81	0.00779	5.96	0.179	2.44	33.3
4A	0.128	3.61	0.00725	3.75	0.0486	2.31	77.01
4B	0.127	4.04	0.00674	4.17	0.0369	2.46	113
5A	0.124	3.35	0.00719	3.48	0.0202	2.46	172
5B	0.117	3.84	0.00760	3.96	0.0825	2.69	48.1

Table 1 explains that the dominant TN value is contributed by NO3. The next dominant concentration is NH_3, while NO_2 does not have a significant impact on TN other than its very low value. The dominance of NO_3 indicates a high reduction-oxidation (redox) process in the lake. This is related to morphometric data, which shows a medium-sized lake. Mechanically, when sediments at the bottom of the lake contain a high amount of organic matter, if supported by high aeration, the decomposition products (in the form of nutrients) will undergo oxidation. At the same time, if oxygen is used up in decomposition, the compounds are reduced and bond with hydrogen. Thus, it can be assumed that the amount of dissolved oxygen is still sufficient for the lake area.

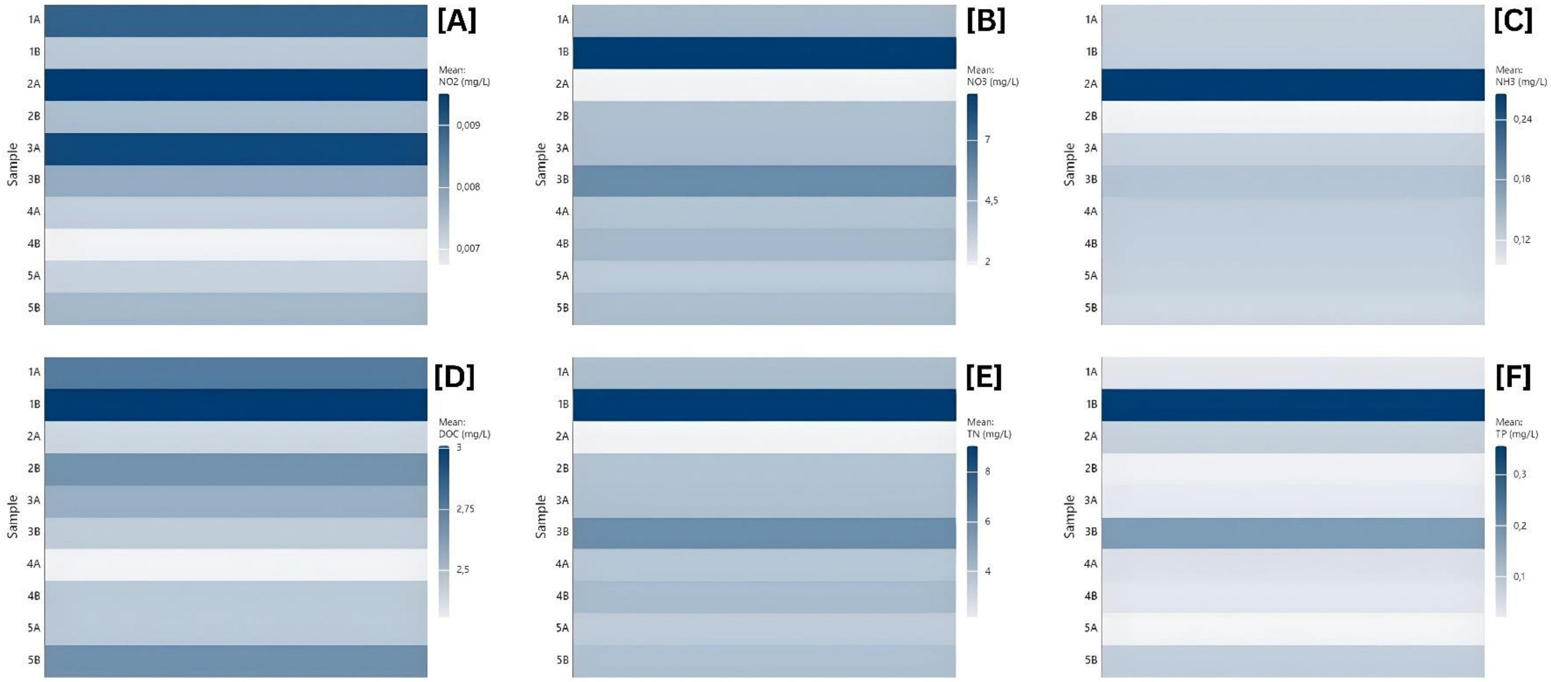

Figure 2. Nutrient concentration in the Upper/Surface (1-5A) and Lower/Base (1-5B) zones of water. The[A] graph represents NO_2; [B] graph represents NO_3; [C] represents NH_3; [D] represents DOC; [E] represents TN; [F] represents TP.

The even distribution of nutrients due to mixing and aeration can be seen in Figure 2. In general, Zone B has a higher concentration than Zone A. Contrary to this, NO_2 and NH_3 have high concentrations in Zone A. In retrospect, NH_3 should be dominant in Zone B. This can occur if the lake experiences continuous mixing. Furthermore, these two parameters are also related. Figure 3 shows a low positive relationship between NH_3 and NO_2, which is a toxic parameter for aquatic heterotrophic organisms. This means that an increase in ammonia concentration is accompanied by an increase in nitrite concentration at a less significant rate. The mechanism of this relationship can be seen from the enzymatic process of denitrification by bacteria that converts NH_3 compounds into NO2 (Bernhard 2010).

NH_3 concentrations are high in zones 1A, 2A, and 3A. This is supported by the high abundance of water hyacinth in these areas (Muna *et al*. 2025). NH_3 is known to act not only as a toxic agent but also as a nutrient source for plants/phytoplankton when ionized (NH_4^+), thereby increasing water hyacinth growth. Conversely, NH_3 values are slightly higher in zone 5B, an area with fewer water hyacinths and near the outlet, suggesting a high dilution rate.

The highest nutrient concentration zones are in 1A and 1B. These locations are areas where water hyacinth growth is high. However, there is no human activity in these locations. Morphometrically, this could be caused by sediment movement if the sediment is predominantly fine-grained (Lakewatch 2003; Ariseno 2025). This movement is caused by high wave activity, which can move the sediment. This is also evidenced by Prabandini *et al*. (2021) and Kusumastuti *et al*. (2021) found that the sediment texture of Rawa Pening is clayey, with a dominant clay fraction.

NO_3 and TP are essential nutrient parameters for the growth of phytoplankton and water hyacinth (Pratiwi *et al*. 2020). Therefore, the lake often experiences high water hyacinth growth rates (Syarif *et al*. 2021). This condition is also supported by the growth of phytoplankton/microalgae, as indicated by high chlorophyll-a content. Karla *et al*. (2022) and Astuti *et al*. (2024) found high concentrations of chlorophyll-a in Lake Rawa Pening.

Reducing concentrations is necessary to control nutrient enrichment in Rawa Pening. One approach is to create buffer zones in the river basin, which are considered effective in controlling allochthonous N and P export (Mardiatno *et al*. 2023; Nada *et al*. 2023). The N/P ratio in Rawa Pening is known to be above 16, meaning that overall, P is a limiting factor for plant/phytoplankton growth.

This is also supported by the negative correlation between the N/P ratio and nutrient parameters (Figure 3). The highest negative correlation is found in TP and the N/P ratio, meaning that the higher the N/P ratio, the lower the P value. Therefore, P is a limiting factor for the growth of autotrophic organisms. Reducing P concentrations can reduce the rapid growth rate of autotrophic organisms.

P sources can come from both autochthonous (within the lake) and allochthonous (outside the lake), similar to N. However, Nada *et al*. (2023) briefly suggested that P export is lower on land around Rawa Pening. This means that the primary P source comes from within the lake (autochthonous). Autochthonous P predominantly comes from uncontrolled fisheries cultivation activities, namely floating cages (Pratiwi *et al*. 2020). Furthermore, Pratiwi *et al*. (2020) stated that excess P can also be seen from the dominance of Cyanophyceae. This condition can be seen in zones 3B and 5B, in addition to 1B, which have high concentrations of TP. This is due to their proximity to floating cages. Station 4 has the lowest concentration, which is thought to be due to wave movement distributing P to Station 5.

P is also closely related to N, which forms the basis for the N/P ratio. This is evidenced by the correlation matrix (Figure 3), which shows a very high positive correlation between TP, TN, and NO_3. Evidence of NO_3's dominance over TN is seen in the correlation value of $R^2 = 1$, indicating that TN values are influenced by high NO_3 levels. TP and TN have a correlation of $R^2 = 0.90$, indicating that an increase in TP coincides with an increase in TN. In conclusion, NO_3 and TP are interrelated and serve as growth nutrients for autotrophic organisms. In contrast, NO_2 has a negative correlation with all other parameters except NH_3, meaning that the higher the TN value, the lower the NO_2 and NH_3 levels.

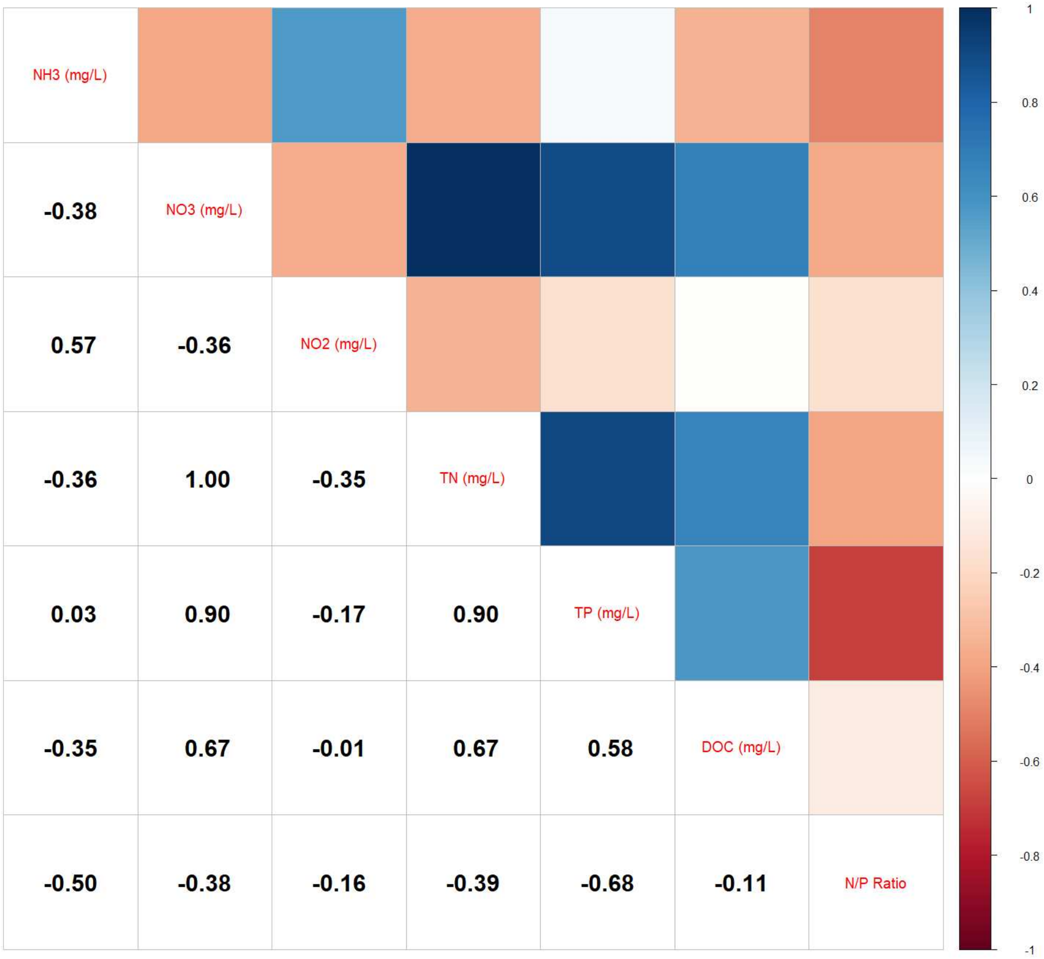

Figure 3. Correlation Matrix between Nutrients and N/P Ratio

Trophically, Rawa Pening Lake is eutrophic (Astuti *et al*. 2024). This means the waters are already in a state of high fertility. This condition is also reflected in the high growth dynamics of water hyacinth, a macro bioindicator of water quality. In 2021, water hyacinth growth experienced its highest rate, especially in the outlet area and floating cages, within 28 days (Syarif *et al*. 2021). This certainly impacted changes in water hyacinth area due to the high doubling time (DT).

Conversely, in 2024, water hyacinth distribution decreased by approximately 250 ha in 3 months (Muna *et al*. 2025). This is due to lake revitalization within the reservoir, for example, through nutrient management, dredging of sediment deposits, improving and demarcating lake boundaries, and harvesting water hyacinth for processing into products such as crafts and fertilizer (Wulandari 2022; Mardiatno *et al.* 2023; Mujiburrohman & Andari 2023; Nada *et al.* 2023; Kintani *et al.* 2024; Putra *et al.* 2025).

These differences in growth are caused by factors such as the type of research, location, and number of replications. Syarif *et al.* (2021) used an in-situ experimental study, while Muna *et al.* (2025) used a spatio-temporal GIS-based study. The results of these experiments appear to indicate that nutrient concentration levels do not affect water hyacinth growth rates (Syarif *et al.* 2021). This is evident in the stations with the lowest TP and TN values, but the highest growth rates. Furthermore, TP and TN concentrations were measured in a single measurement, making it impossible to monitor the rate of nutrient consumption (Syarif *et al*. 2021). In general, nutrient concentration distribution has a significant impact on the growth of autotrophic organisms.

3.2 Vertical Organic Carbon Distribution

The concentration of organic carbon decreases with increasing sediment depth. Figure 4 shows the difference in sediment color in core samples at the surface (0 cm) and the lower (55 cm) boundary. Sediment color reflects the color of the soil; darker sediment indicates higher organic matter content, while lighter sediment indicates lower organic matter content.

Soil/sediment with high organic matter content is blackish-brown or black. Over time, organic matter is continuously decomposed by bacteria and fungi, converting it into nutrients. The reduction in organic matter causes the color to become lighter, such as yellow or bright brown.

The bottom of lakes constantly experiences sediment accumulation due to hydrodynamics. This accumulation creates layers, allowing the sediment to serve as a marker of the lake's age (Soeprobowati 2025). Furthermore, low organic carbon concentrations in the bottom layers of sediment can indicate that the decomposition and deposition of the sediment have occurred over a long period of time.

The qualitative appearance of organic material layers is supported by organic carbon values expressed as percentages (%) and g/kg (Figure 5). Figure 5 shows a graphical trend of decreasing organic C concentration at each depth. The highest organic C concentration was found to be approximately 400.88 gC/kg, or 9.91%, in the 10 cm layer. The lowest concentration was 44.95 gC/kg, or 0.886%, in the 55 cm layer.

A significant downward trend occurred in the 10 to 15 cm layers. Furthermore, the 10 cm layer had a higher organic C concentration than the 5 cm layer. This indicates that the 5 cm layer represents recent sediment accumulation, while the 10 cm layer represents a layer from an earlier period. In terms of concentration values, the 40, 50, and 55 cm layers are classified as low concentrations (Tan 2005). Furthermore, the layers above them are still categorized as moderate to very high (Tan 2005).

The distribution of organic C values (except in the 10 cm layer) also shows a gradual decline. This means that organic carbon, from the top to the bottom, is generally considered high. This contradicts Prabandini *et al.* (2021), who stated that the sediment in Rawa Pening is classified as low. There are two possible discrepancies: the reference categorization of organic carbon values and the sampling location.

The value given by Prabandini *et al.* (2021), which is around 1-2%, indicates that organic carbon is still considered moderate (Tan 2005). The sampling location was identified as being in the floating cage area in the northern part of the lake, while in this study, it was located near the Bukit Cinta tourist site (South). This value clearly contradicts the condition of water cover.

The presence of organic matter is beneficial as a food source for heterotrophic organisms, such as benthic macroinvertebrates, or benthos. However, the number of benthos found showed low diversity, indicating high levels of pollution (Prabandini *et al.* 2021). These conditions indicate an anaerobic environment at the bottom of the lake. No benthos were also found during coring.

This means that the lower water column contains low levels of dissolved oxygen and high levels of reduced compounds. Other studies also support this condition, for example in the Cengklik Reservoir (Ariseno 2025). In that study, sediments were found to smell like rotten eggs. This odor could originate from the production of sulfur (sulfur-S) or methane (CH_4).

Reduced organic carbon can produce CH_4 rather than CO_2. Sulfur is naturally present in sediments. Under aerobic conditions, S is oxidized to SO_4 (sulfate). Conversely, if S is reduced, it produces H_2S (hydrogen sulfide). SO_4 is generally utilized by phytoplankton as a minor growth compound (Wang *et al*. 2022). Mass fish mortality events generally occur due to high levels of reduced S (H_2S) (Wang *et al*. 2022; Ariseno 2025).

In fact, during field measurements, the weather was windy, but when passing through the southern fish cage area, the weather was calm. This condition indicates an area where mixing rarely occurs, so that when upwelling occurs, H_2S will rise and poison farmed fish.

Figure 4. Sedimentary layering structure representing organic C, which is qualitatively visible by color differences. The red line indicates the upper/surface boundary (0 cm), while the green line indicates the lower boundary (50 cm).

Rawa Pening Lake morphometrically experiences high aeration, resulting in even oxygen distribution down to the bottom. However, field interviews revealed frequent mass fish kills in several areas, particularly near floating cages. Further interviews also revealed the water smelling like rotten eggs, both near and away from the cages.

The high levels of organic carbon accumulation are also related to the level of DOC dissolution (Mbonda *et al*. 2025). This is evidenced by the high DOC values in the bottom waters (Figure 2). DOC is useful for monitoring carbon storage and emissions, as well as serving as a growth medium for autotrophic organisms. DOC is also linked to N and P (Figure 3), so higher DOC levels also increase N and P production.

The dynamics of carbon storage in the sedimentary stratigraphy of Rawa Pening have not been reported to date. Furthermore, the data presented is only available from a single station. Therefore, further research on carbon storage stratigraphy is needed, especially in locations with high nutrient concentrations. This is done to evaluate pollution variables that need to be prioritized for management.

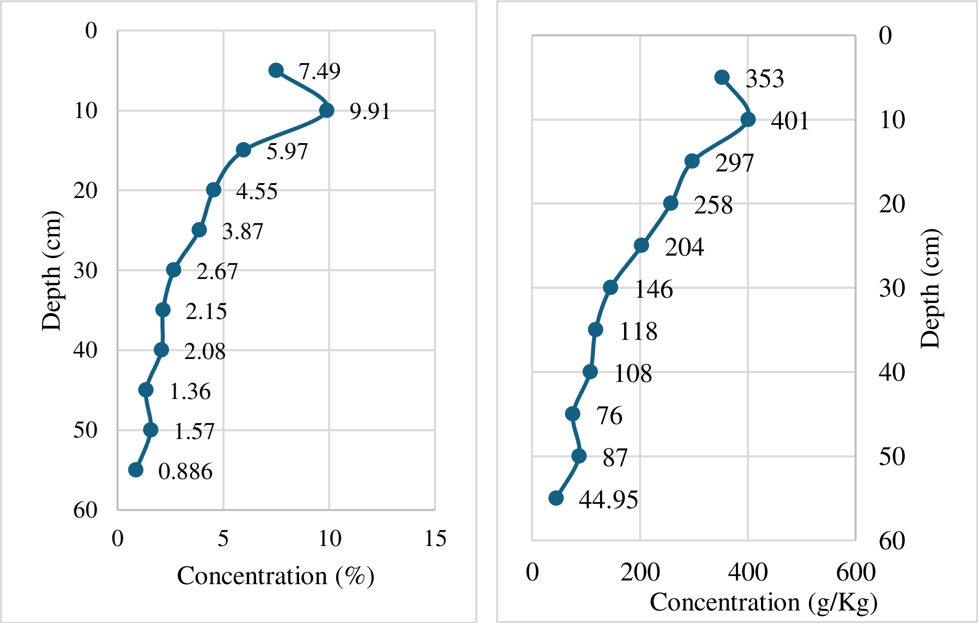

Figure 5. Vertical profile of C-Organic at different concentration units

4. Conclusion

Rawa Pening Lake is morphometrically classified as a polymictic lake with a medium area and an asymmetrical circular shape. This condition indicates high aeration down to the bottom, with a maximum depth of -15 m. Therefore, the current dissolved oxygen concentration is suspected to be high. Correspondingly, the lake's nutrient concentrations, namely TN and TP, are also in the high range, exceeding the specified quality standards.

Available nutrients are dominant and concentrated in the lower zone of Rawa Pening's waters. The nutrients most responsible for eutrophication are NO_3-N and TP. Meanwhile, NO_2 and NH_3 dominate in the upper zone. This condition indicates mixing accompanied by high nutrient production from sediment.

The N/P ratio indicates that P is the limiting factor for microalgae growth. This is also evidenced by the high negative correlation between TP and the N/P ratio, with $R^2 = -0.68$. Therefore, P is a priority in pollution control. TN, TP, and DOC have a positive relationship, so an increase in DOC is naturally accompanied by an increase in TN and TP. DOC originates from sedimentary organic carbon. Sedimentary organic carbon concentrations were found to be high from the 40-5 cm layer, with a range of 2.08–9.91%, or 108–401 gC/kg.

The study lacked the number of sampling stations, both in water and sediment. Data variability is essential for sustainable lake management. Further research is expected to complement the vertical organic carbon structure at several stations in Rawa Pening and demonstrate the presence of sulfur in the waters below.

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Conflict of interest

I declare that I have no conflicts of interest.

Data availability

Data is available upon Request.

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