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Natural and anthropogenic factor drives macronutrient distribution in the Bengkulu River, Indonesia

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ABSTRACT

The Bengkulu River, the largest river in Bengkulu Province, discharges into the Indian Ocean and drains a watershed increasingly influenced by agricultural, urban, and industrial activities. Despite its ecological and socio-economic importance, information on nutrient distribution and export along the river–estuary continuum remains limited. This study investigated the distribution, transport, and potential sources of macronutrients (nitrite, nitrate, phosphate, and silicate) and estimated their fluxes to adjacent coastal waters. Surface water samples were collected from 15 stations along the Bengkulu River–estuary system during the dry season (17–19 March 2023). Nutrient concentrations were analyzed using spectrophotometric methods. Concentrations ranged from 0.01–5.17 ppm for nitrite, 0.01–1.94 ppm for nitrate, 0.01–0.35 ppm for phosphate, and 0.79–35.21 ppm for silicate, with mean values of 0.54 ± 1.30, 0.38 ± 0.49, 0.04 ± 0.10, and 11.19 ± 9.92 ppm, respectively. Higher concentrations of nitrite, nitrate, and phosphate were generally observed near areas with intensive agriculture, industrial activities, and dense settlements, suggesting potential anthropogenic influence, although natural hydrodynamic processes may also contribute. In contrast, silicate showed higher concentrations in upstream areas and decreased toward the coast, a pattern that may be associated with dilution during mixing and biological uptake. Estimated nutrient fluxes to the Indian Ocean were ~9.9×10^9 mg day^{-1} for silicate, 1.9–6.1×10^7 mg day^{-1} for nitrate, 9.1–9.4×10^6 mg day^{-1} for nitrite, and 1.8–6.0×10^5 mg day^{-1} for phosphate. These results suggest that the Bengkulu River is an important pathway for nutrient transport to adjacent coastal waters. The findings provide baseline information on nutrient dynamics and land–sea nutrient connectivity in tropical river systems.

Keywords: macronutrients, biogeochemistry, Indian Ocean, Bengkulu River.

ABSTRAK

Sungai Bengkulu, sungai terbesar di Provinsi Bengkulu, bermuara ke Samudra Hindia dan mengalir melalui daerah aliran sungai yang semakin dipengaruhi oleh aktivitas pertanian, perkotaan, dan industri. Meskipun memiliki peran ekologis dan sosial-ekonomi yang penting, informasi mengenai distribusi dan dinamika nutrien di sepanjang sistem sungai–estuari masih terbatas. Penelitian ini bertujuan untuk mengkaji distribusi, transportasi, dan sumber potensial makronutrien (nitrit, nitrat, fosfat, dan silikat), serta mengestimasi fluksnya menuju perairan pesisir di sekitarnya. Sampel air permukaan dikumpulkan dari 15 stasiun di sepanjang sistem Sungai Bengkulu–estuari pada musim kemarau (17–19 Maret 2023). Konsentrasi nutrien dianalisis menggunakan metode spektrofotometri. Konsentrasi nutrien berkisar antara 0,01–5,17 ppm untuk nitrit, 0,01–1,94 ppm untuk nitrat, 0,01–0,35 ppm untuk fosfat, dan 0,79–35,21 ppm untuk silikat, dengan nilai rata-rata masing-masing sebesar 0,54 ± 1,30 ppm, 0,38 ±

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0,49 ppm, 0,04 ± 0,10 ppm, dan 11,19 ± 9,92 ppm. Konsentrasi nitrit, nitrat, dan fosfat di lokasi yang berdekatan dengan kawasan pertanian intensif, aktivitas industri, dan permukiman padat, umumnya lebih tinggi. Mengindikasikan adanya potensi pengaruh antropogenik, meskipun proses hidrodinamika alami juga dapat berkontribusi terhadap pola distribusinya. Sebaliknya, silikat menunjukkan konsentrasi yang lebih tinggi di daerah hulu dan menurun ke arah pesisir, pola yang mungkin berkaitan dengan proses pengenceran selama pencampuran massa air serta penggunaan oleh organisme biologis. Estimasi fluks nutrien ke Samudra Hindia mencapai 9,9 × 10^9 mg hari^{-1} untuk silikat, 1,9–6,1 × 10^7 mg hari^{-1} untuk nitrat, 9,1–9,4 × 10^6 mg hari^{-1} untuk nitrit, dan 1,8–6,0 × 10^5 mg hari^{-1} untuk fosfat. Hasil penelitian ini menunjukkan bahwa Sungai Bengkulu merupakan salah satu jalur penting transport nutrien menuju perairan pesisir di sekitarnya. Lebih lanjut, emuan ini menyediakan informasi dasar mengenai dinamika nutrien dan konektivitas nutrien darat–laut pada sistem sungai tropis.

Kata kunci: makronutrien, biogeokimia, Samudra Hindia, Sungai Bengkulu

1. Introduction

Rivers play an important role in transporting freshwater, sediments, and dissolved substances from terrestrial environments to coastal waters. Among these substances, macronutrients such as nitrogen, phosphorus, and silicon are essential elements that regulate aquatic productivity. However, excessive nutrient inputs from human activities can alter nutrient cycling and water quality in river systems. Increasing anthropogenic pressures within watersheds—including agriculture, urbanization, industry, and domestic wastewater discharge—have intensified nutrient loading in many rivers worldwide, leading to environmental problems such as eutrophication, harmful algal blooms (HABs), and hypoxia (Hayami et al., 2019; Maurya et al., 2020; Remondi et al., 2016).

Both natural processes and anthropogenic inputs control the distribution of macronutrients in river systems. Natural processes include rock weathering, soil leaching, and regeneration of organic matter, which release nutrients into river water (Bennekom & Salomons, 1980). At the same time, human activities such as agricultural runoff, industrial discharge, livestock farming, and domestic wastewater may significantly increase nutrient concentrations in rivers (Samanta & Dalai, 2018; Sidabutar et al., 2021). Nitrogen species (e.g., nitrate and nitrite), phosphate, and silicate are particularly important because they serve as key nutrients for phytoplankton growth (Reinl et al., 2022). While moderate nutrient availability supports primary productivity, excessive concentrations may lead to ecological disturbances such as eutrophication, oxygen depletion, and harmful algal blooms (Ikhsani et al., 2017; Prasetyo et al., 2020). Rivers therefore act not only as nutrient sources but also as transport pathways that deliver nutrients from land to coastal and marine environments.

The Bengkulu River is one of the major rivers in Bengkulu Province, Sumatra, Indonesia, and discharges directly into the Indian Ocean. The river drains a watershed characterized by diverse land uses, including urban areas, agriculture, fisheries, and industrial activities. Previous studies have reported that rivers in rapidly developing regions often experience increasing pollutant loads associated with anthropogenic activities (Belladona, 2017; Wiwit et al., 2025). However, information regarding the spatial distribution, transport processes, and relative contribution of macronutrients in the Bengkulu River system remains limited. In particular, there is still insufficient understanding of how nutrient concentrations vary along the river continuum from upstream areas to the estuary, and how both natural processes and human activities may influence their distribution.

Understanding nutrient dynamics in the Bengkulu River is important because riverine inputs may influence water quality in the adjacent coastal environment. Assessing the distribution of macronutrients along the river–estuary continuum can help identify potential sources and transport patterns of nutrients within the watershed. Furthermore, estimating the flux of nutrients transported by the river can provide a preliminary indication of the magnitude of nutrient inputs delivered to coastal waters. Therefore, this study aims to: (1) examine the spatial distribution of macronutrients (nitrite, nitrate, phosphate, and silicate) along the Bengkulu River from upstream to the coastal area; (2) evaluate the potential influence of natural processes and anthropogenic activities on the observed nutrient patterns; and (3) estimate the flux of macronutrients transported from the Bengkulu River to the adjacent Indian Ocean.

2. Materials and methods

2.1 Samples collection

The Bengkulu River is the largest river system in Bengkulu Province, located on the western coast of Sumatra, Indonesia, and discharges directly into the eastern Indian Ocean. As a major river in the region, it plays an important ecological and socio-economic role, supporting fisheries, agriculture, transportation, and domestic water use for local communities. In recent years, the Bengkulu watershed has experienced increasing anthropogenic pressures associated with urban development, agricultural activities, tourism, and other land-based inputs (Belladona, 2017; Firdaus et al., 2015; Wiwit et al., 2025). Given its direct connection to the Indian Ocean, the Bengkulu River may act as an important pathway for the transport of macronutrients from land to the adjacent coastal waters. Therefore, investigating nutrient distribution in this river system is important for understanding land–ocean interactions and the potential impact of riverine inputs on coastal biogeochemistry in the eastern Indian Ocean.

Sampling was conducted during the dry season on 17 and 19 March 2023. Surface water samples were collected from a total of 15 stations along the Bengkulu River system. The detailed location for each station was provided in Supplementary Table 1. The sampling stations were selected using a purposive sampling approach to capture spatial variability along the river–estuary–coastal continuum as well as to represent differences in hydrological and environmental characteristics, including the main channel, minor tributaries, and adjacent coastal waters. Stations 1 – 7, 9, 12, 13, 14, and 15 were located along the main channel of the Bengkulu River, extending from the upstream section to the coastal–estuarine zone, including Kualo Estuary (station 14) that representing the river mouth area and Kualo Beach (station 15) which is directly connected to the Indian Ocean. In addition to the main river channel, samples were also collected from water bodies influenced by Bengkulu River tributaries, including Dendam Lake (station 8), Jenggalu Estuary (station 10), and Pasir Putih Beach (station 11). Similar to station 15, station 11 is located in coastal zone and directly connected to Indian Ocean. These sites also represent important aquatic systems in Bengkulu Province. The locations of all sampling stations are shown in Figure 1, while the coordinates and environmental characteristics of each station are provided in Supplementary Table 1.

The sampling campaign was conducted during the dry season to capture spatial variability in nutrient distribution under relatively stable hydrological conditions, when river discharge and dilution from rainfall are generally lower. Such conditions allow clearer observation of nutrient gradients along the river–estuary continuum. Nevertheless, it should be noted that the sampling represents a snapshot of environmental conditions during the dry season. Seasonal variations, particularly during the wet season when river discharge and runoff are typically higher, may influence nutrient concentrations and fluxes. Therefore, the results of this study should be interpreted as a preliminary assessment of macronutrient distribution in the Bengkulu River system.

In situ physical and chemical parameters, including salinity, pH, and temperature, were measured using a multiparameter water quality tester (EZ-9909SP). The instrument has a pH resolution of 0.01 with an accuracy of ±0.05 pH units, salinity resolution of 0.01% with an accuracy of ±0.1% within the 0.01–5.00% range, and temperature resolution of 0.1°C with an accuracy of ±0.5°C. The device is equipped with Automatic Temperature Compensation (ATC) to account for temperature variations during measurements. Prior to the survey, the pH sensor was calibrated using a three-point calibration with standard buffer solutions (pH 4.00, 6.86, and 9.18). To ensure data reliability, pH calibration was performed daily, while salinity calibration was conducted weekly using a 6.44 ppt NaCl standard solution. All measurements were carried out with the ATC function enabled to minimize the influence of temperature fluctuations (0.1–60.0°C) during field sampling.

Surface water samples (~500 mL) were collected using a pre-cleaned plastic beaker and immediately filtered through a 0.45 µm cellulose acetate membrane filter (Whatman) to remove suspended particles. The filtrate was transferred into pre-cleaned 500 mL high-density polyethylene (HDPE) bottles. To inhibit biological activity and prevent post-sampling alteration of nutrient concentrations, 1 mL of saturated $HgCl_2$ solution was added to each bottle as a preservative, following commonly applied protocols for nutrient preservation. This addition resulted in a final $HgCl_2$ concentration of approximately 0.02% (v/v) in the sample. The samples were stored in a cool and dark container during field transport and subsequently refrigerated at <4 °C until laboratory analysis.

2.2 Macronutrient analysis

Macronutrient analysis was conducted at the Biogeochemistry Integrated Laboratory, National Research and Innovation Agency (BRIN), Ancol, Jakarta, Indonesia. Concentrations of nitrate, nitrite, phosphate, and silicate in the water samples were determined using a UV–Vis spectrophotometer (UV-1201V) following the colorimetric methods described by Strickland and Parsons (1972). Briefly, concentrations of nitrite and nitrate were determined by the standard pink azo dye method (Strickland & Parsons, 1972). Moreover, the concentrations of silicate and phosphate were determined using the molybdenum blue method (Strickland & Parsons, 1972). The absorbance of samples was recorded in the wavelength 543 nm for nitrite and nitrate, 885 nm for phosphate, and 810 nm for silicate.

Analytical quality control for nutrient determination followed the procedures described by (Wiwit et al., 2025). Calibration curves were prepared using a series of standard solutions for each nutrient parameter. The calibration curves for each parameter are presented in Supplementary Figure 1. All calibration curves exhibited excellent linearity, with correlation coefficients (R) greater than 0.99. All samples were analyzed in duplicate, and the reported concentrations represent the average of duplicate measurements. The reagent blanks were analyzed to check for potential contamination. Milli-Q water (MQW), containing all reagents used in the analysis but without the sample, was used as a blank. All blank measurements were below the detection limit, indicating negligible background interference during analysis.

The limit of detection (LoD) was determined based on the standard deviation (σ) of the blank measurements: 0.005, 0.004, 0.041, and 0.001 ppm for nitrite, nitrate, silicate, and phosphate. The limit of detection (LoD) was estimated as 3.3σ, where σ represents the standard deviation of blank measurements. The calculated LoD values were 0.015 ppm for nitrite, 0.012 ppm for nitrate, 0.123 ppm for silicate, and 0.003 ppm for phosphate.

2.3 Data analysis

The study area covered a location with different characteristics. Therefore, for the convenience of the discussion, particularly the distribution of macronutrients, we used a statistical analysis to find patterns and similarities among the sampling stations to group them into clusters that are more similar to each other than to location in other clusters. Rstudio® and R software version 4.4.0 “Puppy Cup” were used to perform clustering analysis as well as to draw the dendrogram.

Furthermore, to assess the contribution of macronutrients from Bengkulu River to the Indian Ocean, we estimated the macronutrient flux using Equation 1.This flux was estimated using the commonly applied approach based on the product of river discharge and nutrient concentration (Howarth et al., 1996; Humborg et al., 1997).

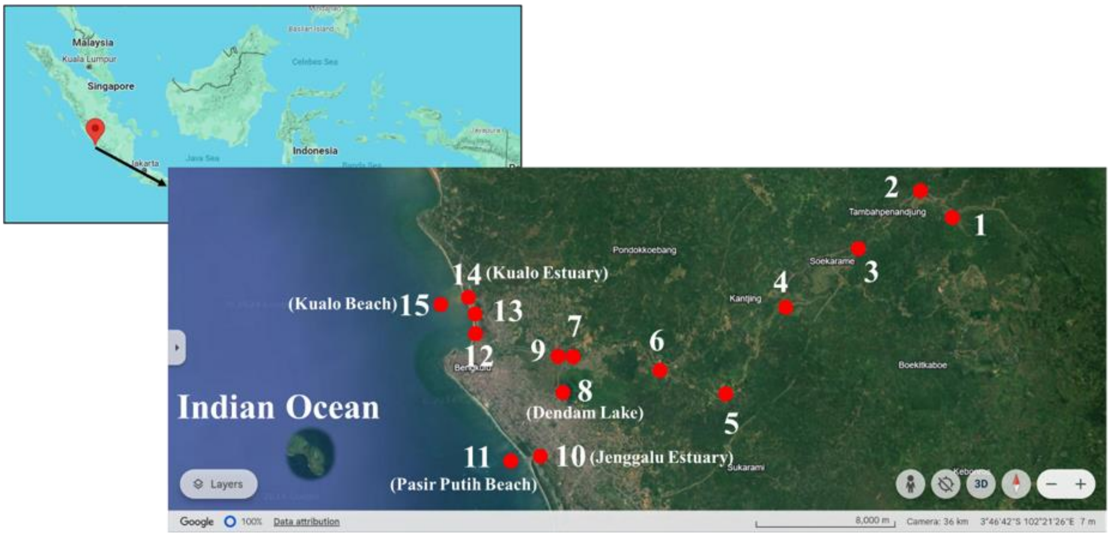

Figure 1. The study area. The upper map is the Bengkulu River located in Sumatera Island. The lower map showed the sampling points along the Bengkulu River from the upper stream to the coastal of Indian Ocean. Most stations (1–7, 9, 12–15) are located along the main channel of the Bengkulu River, including Kualo Estuary (station 14) which represents the river mouth area and Kualo Beach (station 15) which is directly connected to the Indian Ocean. Additional stations represent water bodies influenced by Bengkulu River tributaries, including Dendam Lake (station 8), Jenggalu Estuary (station 10), and Pasir Putih Beach (station 11). The maps are obtained and generated from Google Earth application.

$F_x = I_R C_x$……………………..Eq. 1

Where F_x is the macronutrient flux, I_R is the river inflow into the sea, C_x is the macronutrient concentration in the river water. In this study, the flux estimation represents the riverine export of nutrients from the Bengkulu River to the coastal ocean. Therefore, the macronutrient concentrations measured at station 14, located at the river mouth, were used to represent the riverine end-member prior to mixing with seawater. Stations located in the coastal area (stations 11 and 15) were excluded from the flux calculation because their nutrient concentrations may already be influenced by seawater mixing and coastal currents indicated by high salinity. In addition, the calculation assumes a unidirectional river discharge from land to the ocean and does not account for potential nutrient inputs from the marine environment.

For the flux estimation, river discharge data reported by Firdaus et al. (2015) were used, with a discharge of approximately ~8.3–8.5 × 10^7 m^3 day^{-1}. This value was applied because continuous discharge measurements for the Bengkulu River during the sampling period were not available. Consequently, the calculated nutrient fluxes should be interpreted as a preliminary estimation.

3. Results and Discussion

3.1. Hydrographic condition

The distribution of salinity, temperature, and pH of the water samples from 15 sampling stations along the Bengkulu River flowing toward the coastal Indian Ocean is shown in Figure 2, while the individual measurements for each station are presented in Table 1. Overall, salinity ranged from 0 to >32.7 ‰ with a mean value of 0.01 ± 0.028 ‰ for river-estuary stations (1-10, 12-14) and 32.45 ± 0.35 ‰ for coastal stations (11 and 15). pH ranged from 6.28 to 8.44 with a mean of 7.38 ± 0.59, and water temperature ranged from 25.7 to 29.8 °C with a mean of 27.97 ± 1.07 °C.

Salinity was 0 ‰ at most stations along the river, indicating strong freshwater dominance throughout the river system. Only stations 11 and 15, located in the coastal area and directly connected to the Indian Ocean (Fig. 2), exhibited salinity values typical of seawater (>32 ‰). In stations located near the vicinity estuary (stations 10, 12, 13, and 14), salinity values remained extremely low (0.1, 0, 0, and 0.02 ‰, respectively). The large difference between coastal stations (11 and 15) with other stations was statistically significant (ANOVA, $p < 0.05$). This pattern indicates that freshwater discharge strongly dominated the estuarine region during the sampling period, thereby limiting seawater intrusion into the river channel. The relatively strong river flow, combined with the river mouth being slightly elevated relative to the adjacent sea level, likely limited seawater intrusion into the river channel.

The pH values ranged from 6.28 to 8.25, with the mean value of 7.38 ± 0.59. The lowest pH was observed at station 8, located in Dendam Lake. Agricultural rice fields surround this lake and receives runoff containing agricultural waste (Firdaus et al., 2015). Agricultural runoff often contains high concentrations of macronutrients such as nitrate and phosphate, which may stimulate eutrophication. Nutrient enrichment can promote phytoplankton blooms followed by enhanced microbial respiration during the decomposition of organic matter, which consumes dissolved oxygen and produces CO_2, ultimately lowering pH in the water column (Ikhsani et al., 2017; J. Zhang & Gao, 2016). However, the observed pH range in Dendam Lake remains within the range previously reported for this lake, indicating that although localized acidification may occur, the overall pH condition is still consistent with existing literature (Khalik et al., 2023; Mersyah et al., 2021).

Water temperature ranged from 25.7 to 28.9 °C, with a mean value of 27.97 ± 1.07 °C. This range is consistent with typical tropical aquatic systems in Indonesia. Previous observations indicate that coastal waters in Indonesia generally exhibit sea surface temperatures ranging from approximately 27 to 31 °C, depending on location and season (e.g. Noprianda and Siregar 2024; Yunita and Zikra 2025). In our study area, the lowest temperature was recorded at station 1, located in the upstream section of the Bengkulu River. This station lies in a mountainous area at approximately 300 m above sea level, whereas the other stations are situated in lower elevation areas closer to the coastal plain. The relatively higher elevation likely contributes to the lower water temperature observed at station 1 due to cooler ambient air temperature and reduced solar heating. In contrast, slightly higher temperatures observed in downstream stations may reflect stronger solar radiation, slower water flow, and reduced shading in the lowland river sections.

Overall, the hydrographic conditions observed in the Bengkulu River indicate strong freshwater dominance. Such conditions suggest that the transport of land-derived nutrients and other dissolved substances from the watershed likely plays an important role in controlling the biogeochemical characteristics of the river–estuary–coastal continuum. The low salinity observed along most stations further implies that terrestrial inputs primarily drive hydrodynamics in the system.

Table 1. Obtained data on hydrographic parameters, macronutrient concentrations, and N/P ratio. The N/P ratio was calculated by dividing the sum of nitrate and nitrite concentrations by the phosphate concentration.

Station	pH	Salinity (‰)	Temperature (°C)	Nitrite (ppm)	Nitrate (ppm)	Phosphate (ppm)	Silicate (ppm)	N/P ratio
1	8.25	0	25.7	0.07 ± 0.014	0.125 ± 0.004	0.029 ± 0.000	28.39 ± 0.128	7
2	8.44	0	28.1	0.23 ± 0.014	N.D.	0.016 ± 0.000	26.12 ± 0.000	14
3	7.92	0	28	0.19 ± 0.014	0.002 ± 0.004	0.01 ± 0.000	24.22 ± 0.128	19
4	7.25	0	27.5	0.08 ± 0.000	0.136 ± 0.003	0.008 ± 0.000	22.23 ± 0.128	27
5	7.19	0	26.3	0.19 ± 0.043	0.102 ± 0.008	0.009 ± 0.001	17.79 ± 0.000	32
6	7.38	0.01	28.5	0.76 ± 0.014	0.113 ± 0.027	0.399 ± 0.002	4.93 ± 0.256	2
7	7	0	29	0.38 ± 0.000	0.592 ± 0.028	0.008 ± 0.000	7.83 ± 0.256	122
8	6.28	0	28.1	0.29 ± 0.014	0.001 ± 0.000	0.013 ± 0.000	2.04 ± 0.102	22
9	7.12	0	27.7	0.35 ± 0.014	0.597 ± 0.026	0.007 ± 0.000	7.73 ± 0.051	135
10	6.98	0.1	27.1	5.17 ± 0.043	1.729 ± 0.011	0.007 ± 0.000	2.43 ± 0.051	986
11	8.06	32.2	27.9	0.02 ± 0.014	N.D.	0.005 ± 0.001	0.19 ± 0.026	4
12	7.06	0	28.9	0.12 ± 0.000	0.772 ± 0.031	0.005 ± 0.001	6.42 ± 0.154	178
13	7.06	0	29.1	0.12 ± 0.000	0.743 ± 0.018	0.004 ± 0.000	5.28 ± 0.077	216
14	6.96	0.02	29.8	0.11 ± 0.014	0.713 ± 0.028	0.007 ± 0.000	11.99 ± 0.256	118
15	7.82	32.7	27.8	N.D.	0.018 ± 0.001	0.002 ± 0.000	0.23 ± 0.017	9

N.D. means below the detection limit

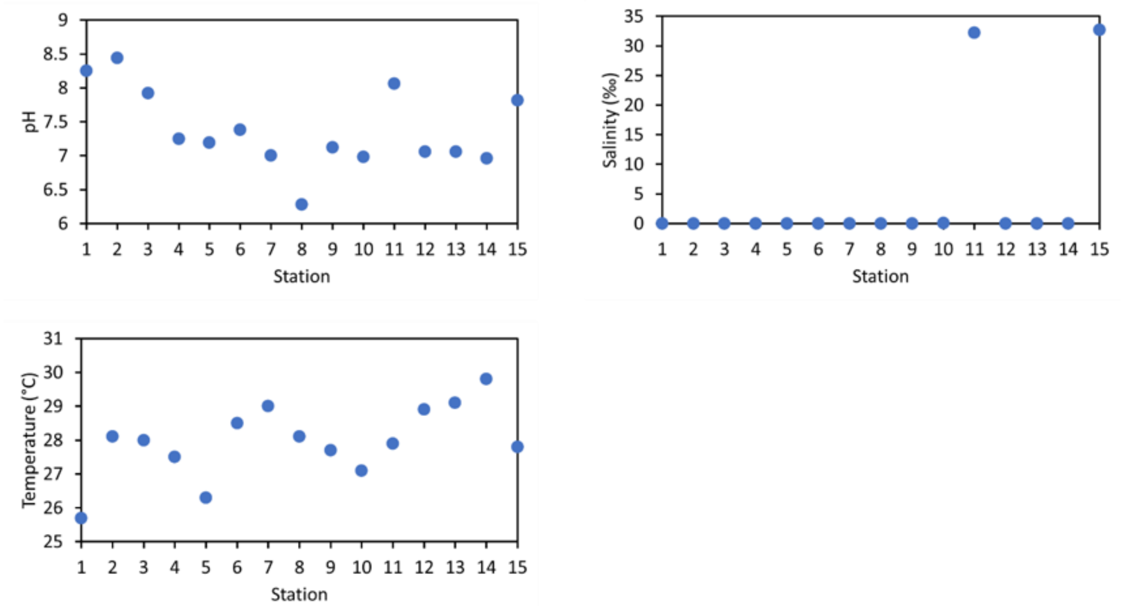

Figure 2. Distributions of salinity, temperature, and pH in all sampling stations. Please note the station number, which are written in order from 1 to 15.

3.2. Macronutrients in Bengkulu River: distribution, potential sources, and environmental status

The individual macronutrient concentrations for each station are presented in Table 1. Overall, nitrite concentrations ranged from 0.07 to 5.17 ppm, with an average of 0.54 ± 1.3 ppm, while nitrate varied between 0.001 and 1.79 ppm, with a mean of 0.375 ± 0.49 ppm. Silicate exhibited the highest concentrations among the measured nutrients (0.19–28.4 ppm; average 11.2 ± 9.92 ppm), whereas phosphate showed consistently low concentrations (0.002–0.4 ppm; mean 0.035 ± 0.1 ppm).

The spatial distribution of macronutrients reveals distinct patterns along the Bengkulu River–estuary–coastal continuum (Supplementary Fig. 2). Nitrite and nitrate generally increase from upstream to downstream, indicating possible nitrogen enrichment along the river system. In contrast, silicate shows a pronounced upstream dominance, with concentrations exceeding 20 ppm at upstream stations and decreasing to below ~10 ppm downstream. This pattern may be associated with dilution during freshwater–seawater mixing and reduced contributions from lithogenic sources. Phosphate remains relatively low across all stations (Supplementary Fig. 2).

In addition to the longitudinal gradient, several localized anomalies were observed. Elevated concentrations of nitrite and nitrate occurred at Station 10, reaching up to 5.17 ppm and ~1.7–1.8 ppm, respectively. Similarly, phosphate concentrations were relatively high at Station 6, reaching approximately 0.4 ppm. These elevated concentrations may indicate localized nutrient inputs and/or hydrodynamic conditions that favor nutrient accumulation, although the available data do not allow definitive identification of the underlying mechanisms (Belladona, 2017; Burson et al., 2016; Xiao et al., 2025). In contrast, coastal stations (Stations 11 and 15) generally exhibited lower concentrations of all measured macronutrients (nitrite and nitrate <0.1–0.5 ppm, silicate <2–3 ppm, and phosphate <0.05 ppm). This pattern may be associated with dilution during freshwater–seawater mixing. Likewise, the lentic system (Station 8) showed relatively low nutrient concentrations, which may reflect nutrient removal or transformation processes within the lake environment, including biological uptake and internal cycling (Khalik et al., 2023; Mersyah et al., 2021).

Taken together, the observed concentration ranges and spatial gradients suggest that nutrient dynamics in the Bengkulu River system may be influenced by a combination of longitudinal transport, localized tributary inputs, and coastal mixing processes. The upstream–downstream silicate gradient, the general increase in nitrate concentrations along the main channel, and the contrasting nutrient characteristics observed at the minor tributary indicate spatial variability in nutrient distribution that may be associated with differing hydrological and biogeochemical conditions across the system. These spatial heterogeneities suggest that stations with similar nutrient characteristics may form statistically distinguishable groups. To further examine these patterns and objectively identify similarities among sampling sites, a hierarchical cluster analysis was performed.

The results of the statistical analysis are presented in Figure 3, where the dendrogram shows that the sampling stations are grouped into seven distinct clusters. These clusters likely reflect differences in nutrient characteristics and environmental controls rather than simple spatial proximity. Station 10 forms an independent cluster, denoted as “J.E.”, indicating a distinct nutrient regime. This separation likely reflects its unique hydrographical setting, where inputs from a smaller tributary and its semi-enclosed coastal environment limit water exchange and promote nutrient accumulation (Horta et al., 2021; Statham, 2012). As a result, this station exhibits markedly different nutrient characteristics compared to the main river system.

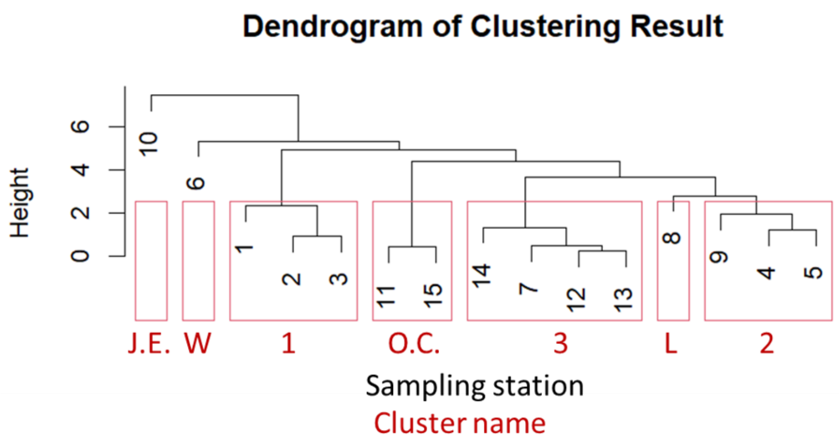

Figure 3. The dendrogram shows the result of the clustering analysis. The sampling stations (marked by the black alphabet) were grouped into 7 different clusters (marked by the red alphabet). The J.E. and W represent station 10 in the Jenggalu Estuary and station 6 which received wastewater from industries nearby (Belladona, 2017). While O.C. and L represent coastal and lake stations, respectively.

Similarly, Station 6 forms a separate cluster ("W"), which may suggest a localized deviation in water quality. This pattern is likely associated with point-source inputs, particularly wastewater discharge, which alters the nutrient composition relative to surrounding stations (Belladona, 2017). In contrast, stations along the main river are grouped into three clusters (Clusters 1, 2, and 3), representing a longitudinal gradient rather than discrete systems. Coastal stations (Stations 11 and 15) form a distinct cluster ("O.C."), characterized by relatively low nutrient concentrations due to seawater dilution, while the lentic system (Station 8) forms its own cluster ("L"). Dendam Lake receives the water from Bengkulu River but has quite stagnant water movement, thus the properties of this station are different from other zones.

To further interpret these clusters, the distribution of macronutrients is examined (Figure 4; Table 2). Nitrite and nitrate concentrations show a clear increasing trend from Cluster 1 to Cluster 3 along the river continuum. Cluster 1 represents upstream conditions with relatively low nitrogen concentrations, whereas Clusters 2 and 3 reflect progressively enriched conditions downstream. This pattern indicates suggests progresive nitrogen loading along the river system. The observed increase in nitrite and nitrate concentrations may be associated with increasing anthropogenic pressures along the watershed. Downstream areas are characterized by higher population density and diverse human activities, including agriculture, industry, tourism, transportation, and domestic discharge, all of which may contribute to nutrient inputs. This interpretation is consistent with the observed relationship between nutrient enrichment and land use patterns, as well as by previous studies in the same system (Belladona, 2017; Wiwit et al., 2025) as well as in other river systems regionally and globally (e.g. Vita Hidayati et al. 2025; X. Li et al. 2023). Moreover, studies employing stable isotope analysis have also demonstrated that elevated nitrate levels in river systems are often linked to anthropogenic sources such as agricultural runoff and domestic wastewater (Guo et al., 2023; C. Zhang et al., 2024).

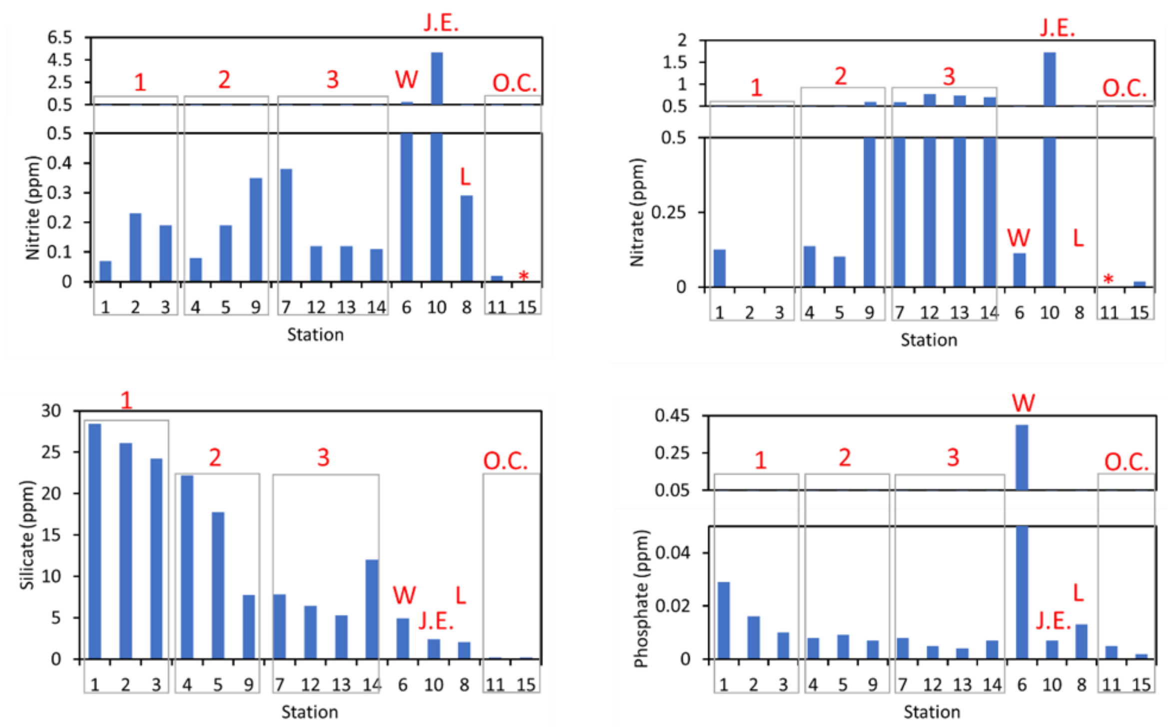

Figure 4. Distributions of macronutrients including nitrite, nitrate, silicate, and phosphate in all sampling stations. Based on the statistical analysis, the sampling stations are divided into 7 clusters namely clusters 1, 2, 3, W, J.E., L, and O.C. The J.E. and W represent station 10 in the Jenggalu Estuary and station 6 which received wastewater from industries nearby. While O.C. and L represent coastal and lake stations. Please note the order of station numbers that are grouped based on the clusters. Red stars (*) in graphs indicate that the values were below the detection limit. Note the break in the x-axis for nitrite, nitrate, and phosphate.

Table 2. Comparison of macronutrient concentration in different locations in Indonesia

Location	Nitrite (ppm)	Nitrate (ppm)	Silicate (ppm)	Phosphate (ppm)	Location	References
Rivers						
Bengkulu River	R: 0.07 – 5.17 A: 0.54 ± 1.3	R: 0.001– 1.79 A: 0.375 ± 0.49	R: 0.19 – 28.4 A: 11.2 ± 9.92	R: 0.002 – 0.4 A: 0.035 ± 0.1	Bengkulu Province, Sumatera Island	This study
Bengkulu River	R: 0.001 – 0.014	R: 0.005 – 0.058	R: 0.163 – 9.314	R: 0.011 – 0.085	Bengkulu Province, Sumatera Island	(Wiwit et al., 2025)
Bengkulu River	-	R: 8.12 – 16.27	-	-	Bengkulu Province, Sumatera Island	Belladona (2017)
Hitam River	A: 0.014	A: 0.029	-	A: 0.042	Bengkulu Province, Sumatera Island	Rasyid, Purnama, and Kusuma (2018)
Banyuasin River	R: 0.002 – 0.093	R: 0.025 – 3.21		R: 0.011 – 0.231	South of Sumatera Province	Putri et al. (2019)
Ciliwung River	-	R: 2.28 – 5.66	-	R: 1.03 – 10.87	Jakarta, Java Island	Patricia, Astono, and Hendrawan (2018)
Mekong River	-	R: 0.01 – 2.21	-	R: 0.01 – 0.35	Mekond River in Cambodia	(Sok et al., 2022)
Lake						
Dendam Lake	0.29	0.001	2.04	0.013	Bengkulu Province, Sumatera Island	This study
Dendan Lake	R: 0.002 – 0.004	R: 0.006 – 0.027	R: 1.378 – 1.831	R: 0.011 – 0.019	Bengkulu Province, Sumatera Island	(Wiwit et al., 2025)
Dendam Lake	-	0.63	-	< 0.01	Bengkulu Province, Sumatera Island	Mersyah et al. (2021)
Dendam Lake	-	-	-	0.1 – 1.15	Bengkulu Province, Sumatera Island	Khalik et al. (2023)
Maninjau	-	R: 0.37 – 7.43	-	R: 0.02 – 0.65	West Sumatera Province	Lukman, Sutrsno, and Hamdani (2013)
Jatibarang	-	R: 0.45 – 9.64	-	R: 1.26 – 4.81	Semarang, Java Island	Ikhsan, Rudiyanti, and Ain (2020)
Tonle Sap Lake		R: 0.02 – 3.40 A: 0.81 ± 0.77	-	R: 0.01 – 0.33 A: 0.11 ± 0.07	Cambodia	(Sok et al., 2022)
Coastal stations						
Bengkulu	R: N.D. – 0.02	R: N.D. – 0.02	R: 0.19 – 0.23	R: 0.002 – 0.005	Bengkulu Province, Sumatera Island	This study
Pulau Tikus	N.D.	0.005	0.616	0.079	Bengkulu Province,	(Wiwit et al., 2025)

Location	Nitrite (ppm)	Nitrate (ppm)	Silicate (ppm)	Phosphate (ppm)	Location	References
					Sumatera Island	
Matasiri	A: 0.0002	A: 0.032	A: 0.144	A: 0.006	South of Kalimantan	Risamasu and Prayitno (2011) Data from surface
Ambon Bay	-	R: N.D. – 0.097	-	R: 0.05 – 0.07	Ambon Island, Maluku Province	Ikhsani, Abdul, and Lekalette (2016) Data from surface
Jakarta Bay	-	R: 0.030 - 0.608	R: 0.079 - 5.416	R: 0.004 - 0.383	Jakarta, The Capital City of Indonesia	(Prayitno & Afdal, 2019) data from surface
Chao Praya River estuary	-	R: 2.10 – 2.82	-	R: 0.013 – 0.117	Chao Praya River, Thailand	(Khongmanont et al., 2024)

Note: R: Ranged, A: Average, N.D.: below the detection limit

Within this framework, Station 10 (Cluster "J.E.") represents an extreme case of nitrogen enrichment, with nitrite and nitrate concentrations reaching up to 5.17 and 1.72 ppm, respectively. Station 10 is located in the tourism and mangrove area. Therefore, local biogeochemical processes associated with mangrove ecosystems may also contribute to elevated nitrogen concentrations in this area (Widiardja et al., 2021).

This interpretation is further supported by the comparison between the two estuarine systems in the study area. Despite both estuaries being influenced by dense surrounding populations and anthropogenic inputs, nitrite and nitrate concentrations in Jenggalu Estuary (Station 10) are notably higher than those observed in Kualo Estuary (Station 14). While both systems are connected to the Indian Ocean, their hydrographic settings are different. Kualo Estuary is directly connected to the open ocean, allowing more effective seawater intrusion and flushing, whereas Jenggalu Estuary is partially enclosed by a small bay, which likely restricts water exchange. This limited flushing may promote nutrient retention and accumulation, which could partly explain the elevated nitrogen concentrations observed in Jenggalu Estuary, in addition to the anthropogenic local input and internal biogeochemical processes within the system (Wiwit et al., 2025). This pattern is consistent with estuarine mixing theory where restricted exchange promotes non-conservative nutrient behavior (Horta et al., 2021; Officer, 1979; Statham, 2012). The observed relationship between salinity and nutrient concentrations is consistent with the influence of estuarine mixing. Coastal stations with high salinity (Cluster O.C.; Stations 11 and 15; salinity ~32‰) consistently exhibit low concentrations of nitrite, nitrate, and phosphate, suggesting dilution through seawater mixing. In contrast, riverine and estuarine stations with low salinity (0–0.1‰) show substantially higher and more variable nutrient concentrations. This inverse relationship is consistent with observations in other estuarine systems, where dissolved inorganic nutrients decrease with increasing salinity due to mixing and dilution processes (Ikhsani et al., 2021; Tao et al., 2021).

Compared to the guidelines for the macronutrient concentration in river water by Indonesia Government Regulation 2021 No. 22 (Government of Indonesia, 2021), the nitrite concentration in the river stations was higher than the threshold safety level for the biota. The maximum nitrite concentration in freshwater based on this regulation is 0.06 ppm. Nitrite concentrations at the river stations ranged from 0.07 to 5.17 ppm, exceeding the recommended guideline values. On the other hand, nitrate concentration that ranged from 0.02 – 1.73 ppm showed lower values compared to the threshold from the guideline for nitrate concentration in river water, a maximum of 10 ppm (Government of Indonesia, 2021). Similarly, the concentration of total dissolved inorganic nitrogen (nitrite plus nitrate, ~0.3 ppm) in Dendam Lake was lower than the threshold for the lake water 0.65 ppm (Government of Indonesia, 2021). This relatively low concentration suggests that nitrogen levels in the lake were still within acceptable limits and may indicate moderate nutrient input without excessive enrichment.

The concentration of nitrite and nitrate in the coastal stations (station 11 and 15) were consistently depleted, <0.02 ppm for both nitrite and nitrate. Such low concentrations likely reflect rapid biological uptake by phytoplankton or dilution processes in the coastal waters. These values were lower than the guidelines for nitrite and nitrate concentration in seawater (Government of Indonesia, 2021), indicating that nitrogen enrichment was not evident in these coastal stations during the sampling period.

The silicate concentration showed an opposite pattern compared to those of nitrite and nitrate. Along the Bengkulu River flow, the highest silicate concentration was detected in cluster 1 up to 28.4 ppm, and decreased gradually (Fig. 4). Rock weathering is the main source of the silicate in the natural water (Liu et al., 2019). The higher topography and stronger water flow may intensify weathering processes, enhancing the dissolution of silicate-bearing minerals and increasing dissolved silicate concentrations in river waters (Gaillardet et al., 1999; Meybeck, 1987) as seen in cluster 1. The gradual decrease in silicate concentration may reflect biological uptake by phytoplankton, particularly diatoms, since this class of phytoplankton was found to be dominant in a previous study (Rasyid et al., 2018). In the coastal stations, the concentration of silicate, 0.19 ppm in station 11 and 0.23 ppm in station 15, consistently showed lower values compared to those in river stations that ranged from 2.04 – 28.4 ppm. The low silicate concentration in ocean stations may also suggest the phytoplankton utilization (Twining et al., 2019).

The concentration of phosphate showed an unclear pattern in the study area (Fig. 4). The highest phosphate concentration was observed in cluster W (station 6), up to 0.4 ppm. This value was >10 times higher than phosphate concentrations in other stations. The lowest phosphate concentration was observed in the coastal stations. Interestingly, cluster W also showed a relatively high nitrite concentration. The exceptionally high phosphate and nitrite concentrations at this station may indicate localized nutrient inputs. This station is located close to the residential area and a location for wastewater disposal from industries near the river bank. Therefore, domestic and industrial wastewater may represent potential sources of phosphate and nitrite at this station (Belladona, 2017). Overall, except for a datum from station 6, the concentration of phosphate in the river (0.004 – 0.029 ppm), lake (0.001 ppm), and coastal (0.002 – 0.005 ppm) stations showed lower values than the guideline for phosphate concentration in the water bodies. The threshold level for phosphate concentration was 0.2 ppm in rivers, 0.01 ppm in lakes, and 0.015 in oceans, respectively (Government of Indonesia, 2021).

Based on the observed nutrient concentrations and comparison with regulatory thresholds, several locations within the Bengkulu River system exhibited nutrient levels that exceeded guideline values, particularly for nitrite (Government of Indonesia, 2021). However, the generally low nitrate, phosphate (except at station 6), and dissolved inorganic nitrogen (nitrite + nitrate) levels suggest that widespread nutrient enrichment or eutrophication is not evident across the system. The lake and coastal waters remain within acceptable water quality standards, indicating relatively good environmental conditions for aquatic biota.

To further assess nutrient dynamics, the molar ratio of dissolved inorganic nitrogen to phosphate (N:P) was evaluated. The N:P ratio is widely used to assess nutrient limitation, with the Redfield ratio (16:1) serving as a reference for balanced phytoplankton growth (Redfield, 1958). The calculated N:P ratios in this study shown considerable variability across the system as seen in Table 1. Upstream stations (e.g., Stations 1 and 2) generally exhibit N:P ratios below or close to the Redfield value (7–14), suggesting relatively balanced nutrient conditions or potential nitrogen limitation (Howarth & Marino, 2006). Similarly, very low N:P ratios observed at several stations (e.g., Station 6 = 2; Station 11 = 4) may indicate relatively lower nitrogen availability compared to phosphate. This condition may be influenced by localized inputs, particularly at Station 6. In contrast, several midstream and downstream stations (e.g., Stations 7, 9, 12, 13, and 14) display markedly elevated N:P ratios (≥100), indicating strong phosphorus shortage and excess nitrogen relative to phosphate. The most extreme case is observed at Station 10, where the N:P ratio reaches 986, indicating a strong imbalance between dissolved inorganic nitrogen and phosphate. Such extreme ratios have been reported in systems influenced by anthropogenic nitrogen inputs and/or restricted water exchange (Chen et al., 2023).

Furthermore, the nutrient concentrations observed in the Bengkulu River system show substantial variability and generally fall within the range reported for both local and regional aquatic systems, although several distinct features highlight the uniqueness of this study.

The comparison of macronutrients concentration in our study area with others is provided in Table 2. Nitrite concentrations in the Bengkulu River are notably higher and more variable than those reported in previous studies from the same region, such as the Bengkulu River reported by Wiwit et al. (2025) and the Hitam River (Rasyid et al., 2018). This elevated nitrite level likely reflects localized inputs, as well as temporal variability associated with differences in sampling seasons and slight spatial mismatches in sampling locations between studies. In contrast, nitrate concentrations in this study are generally lower than those reported in earlier studies in the Bengkulu River by Belladona, (2017), suggesting either temporal variability or differences in sampling locations and hydrological conditions. When compared to other Indonesian rivers, such as the Banyuasin River (Putri et al., 2019) and the highly urbanized Ciliwung River (Patricia et al., 2018), nitrate levels in the Bengkulu River are relatively moderate, indicating a lower degree of anthropogenic nitrogen enrichment. Phosphate concentrations in the Bengkulu River are also relatively low compared to heavily impacted systems such as the Ciliwung River (Patricia et al., 2018), but remain comparable to values observed in less disturbed rivers such as the Banyuasin River (Putri etl al., 2019). Silicate concentrations are relatively high compared to many riverine and coastal systems, reflecting strong lithogenic control and weathering inputs typical of tropical catchments. These values are generally consistent with previous observations in the Bengkulu region (Wiwit et al., 2025); however, the wider range observed in this study is likely influenced by temporal variability associated with differences in sampling periods, which can affect runoff intensity and silicate supply.

At the regional scale, nutrient concentrations in the Bengkulu River are generally comparable to those reported in Southeast Asian systems. For example, nitrate concentrations overlap with those observed in the Mekong River (Sok et al., 2022), while phosphate levels fall within the lower range of those reported for the Chao Phraya estuary (Khongmanont et al., 2024). In lacustrine environments, nutrient concentrations in Dendam Lake measured in this study are generally consistent with previous reports from the same system, although some studies have documented higher phosphate levels (Khalik et al., 2023), indicating episodic or localized nutrient enrichment. Compared to other Indonesian lakes such as Lake Maninjau (Lukman et al., 2013) and Jatibarang Reservoir (Ikhsan et al., 2020), Dendam Lake appears to be less nutrient-enriched, suggesting relatively lower anthropogenic pressure. In coastal waters, macronutrient concentrations off Bengkulu are markedly lower than those reported in more urbanized coastal systems such as Jakarta Bay (Prayitno and Afdal, 2019). Similar low concentrations have been reported in relatively less impacted coastal areas such as Matasiri waters (Risamasu and Prayitno, 2011), suggesting that Bengkulu coastal waters may currently exhibit relatively low to moderate nutrient levels.

Overall, the comparison with previous studies across Indonesia and Southeast Asia suggests that the Bengkulu River system is characterized by moderate nutrient levels with localized enrichment, particularly for nitrogen species. The relatively lower nitrate and phosphate concentrations compared to heavily urbanized systems indicate that the watershed is not yet severely impacted; however, elevated nitrite levels and spatial variability may reflect anthropogenic influences, although natural hydrological and biogeochemical processes may also contribute. These findings highlight the importance of early management interventions to prevent further nutrient loading and potential eutrophication in the Bengkulu River and its adjacent coastal waters.

3.3. Potential contribution of macronutrient flux to the Indian Ocean

Given the higher macronutrient concentrations in the river stations compared to those in the coastal stations, this indicates that the Bengkulu River transports macronutrients to the Indian Ocean. Using the maximum discharge of Bengkulu River of 8.3 – 8.5 × 10^7 m^3/day (Firdaus et al., 2015) and macronutrient concentration in the Bengkulu River plume (station 14), the fluxes of macronutrients into the Indian Ocean were estimated. Bengkulu River transported the largest silicate flux of 0.99 – 1.02 × 10^9 mg/day followed by nitrate flux of 5.91 – 6.09 × 10^7 mg/day, nitrite flux of 9.12 – 9.39 × 10^6 mg/day, and phosphate flux of 5.81 – 5.98 × 10^5 mg/day. It is worth noting that our data serves as a snapshot for a short time period since the sampling was conducted once per dry season.

Based on the reported data by Subramanian (2008), the northeastern Indian Ocean basin (Bay of Bengal) received a large nitrogen flux up to ~ 0.025 Tg/day (1 Tg = 10^{15} mg) through major Indian rivers including the

Ganga, the Padma, the Meghna, and other tributaries of the Ganga Rivers. While the northwestern Indian Ocean basin (Arabian Sea) received slightly lower nitrogen flux (~ 0.13 Tg/day) from the Indus, the Narmada, and the Netravati Rivers (Subramanian, 2008). Compared to the fluxes from gigantic rivers that drain to the northern Indian Ocean, the contribution from the Bengkulu River to the eastern tropical Indian Ocean was less significant. The eastern tropical Indian Ocean is a nitrogen-limited system, and the major sources of nitrogen were atmospheric deposition and vertical diffusion (Ikhsani et al., 2023; Krishnamurthy et al., 2009; Twining et al., 2019). The riverine-sourced nutrients potentially affect the coastal area rather than the open ocean (Cotrim Da Cunha et al., 2007). Given the excess nitrogen (and other micronutrients) in the coastal stations (stations 11 and 15), fluvial input from the Bengkulu River probably supports nitrogen availability for phytoplankton in the coastal waters of the Indian Ocean. Furthermore, this contribution is probably larger during the rainy season when freshwater discharge reaches its maximum. Nonetheless, more data are required to verify the influence of fluvial input on macronutrient availability in the eastern tropical Indian Ocean.

4. Conclusion

This study examined the spatial distribution of macronutrients (nitrite, nitrate, phosphate, and silicate) along the Bengkulu River continuum from upstream to coastal waters during the dry season of 2023, evaluated potential natural and anthropogenic influences on nutrient distribution, and estimated nutrient fluxes to the adjacent Indian Ocean. The results demonstrated considerable spatial variability in nutrient concentrations across the river–estuary–coastal system. Nitrite and nitrate concentrations were generally higher in areas characterized by intensive human activities, suggesting potential anthropogenic influences on nutrient distribution within the Bengkulu River system. Notably, nitrite concentrations at several stations exceeded the permissible threshold for aquatic biota established by Government Regulation No. 22 of 2021, indicating localized water quality concerns. The elevated nitrite and nitrate concentrations observed in Jenggalu Estuary (Station 10) may be associated with a combination of local anthropogenic inputs and hydrographic conditions that potentially restrict water exchange and nutrient flushing.

In contrast, silicate concentrations generally decreased from upstream to coastal waters, a pattern consistent with dilution during estuarine mixing. Rock weathering in the upstream mountainous area (Cluster 1) is considered a likely natural source of dissolved silicate. Phosphate exhibited a less distinct spatial pattern; however, elevated concentrations at Station 6 may indicate localized nutrient inputs associated with nearby human activities. Overall, while most parts of the Bengkulu River system remained within acceptable water quality conditions and showed no clear evidence of widespread eutrophication during the sampling period, localized nutrient enrichment at several stations highlights the need for continued monitoring and management of nutrient inputs.

Based on the flux estimates, the Bengkulu River delivers substantial amounts of macronutrients to the Indian Ocean, dominated by silicate ($0.99–1.02 \times 10^9$ mg day^{-1}), followed by nitrate ($5.91–6.09 \times 10^7$ mg day^{-1}), nitrite ($9.12–9.39 \times 10^6$ mg day^{-1}), and phosphate ($5.81–5.98 \times 10^5$ mg day^{-1}). These findings suggest that the Bengkulu River represents an important pathway for nutrient transport from land to coastal waters. However, the flux estimates should be interpreted with caution because they are based on observations collected during a single dry-season survey and river discharge data obtained from previous studies rather than direct in situ measurements. Consequently, the estimates may not fully capture seasonal variability, particularly during periods of higher discharge in the wet season, and therefore remain subject to uncertainty.

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