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Vertical Distribution of Chl-a in Relation to Environmental Factors and Water Column Stratification in the Downstream Section of the Air Bengkulu River

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Abstract

The Bengkulu Watershed, which spans two administrative districts, plays a crucial role in supporting ecological and socio-economic functions in Bengkulu Province, Indonesia. Its main river, the Air Bengkulu, has experienced environmental pressures from land conversion, coal mining activities, domestic waste discharge, and industrial effluents, which may alter downstream water quality and disrupt estuarine ecological processes, including primary productivity. Historically, the adjacent coastal area was utilized by local fishers as a fishing ground in the early 2000s, but this function has since declined. However, studies on the ecological implications of these pressures on phytoplankton production in the Air Bengkulu estuary remain limited. This study aimed to assess phytoplankton productivity using Chl-a concentration as a proxy and examine its relationship with key environmental parameters. Fieldwork was conducted during the peak dry season from June to August 2025, with two sampling sessions per event in the morning and afternoon under spring tide conditions. Observations were carried out at three stations on three sampling events with measurements taken at three depth levels. Salinity, current velocity, dissolved oxygen, and nitrate concentration were measured at all depths, while temperature, pH, and water transparency were limited to surface levels. Chlorophyll-a (Chl-a) concentration was analyzed using spectrophotometric methods and its relationship with environmental parameters was evaluated using correlation analysis and quantile regression. The results showed that Chl-a concentrations were consistently very low across stations, ranging from 0.025 to 0.139 μg/L, indicating ultra-microtrophic to oligotrophic conditions. Among the measured parameters, nitrate concentration and current velocity exhibited the strongest relationships with Chl-a, suggesting their role as primary limiting factors, while other parameters showed comparatively weaker influences. These findings indicate that low nutrient availability and hydrodynamic conditions constrain phytoplankton biomass development and primary productivity in the Air Bengkulu River estuary, potentially limiting its capacity to sustainably support the food web.

1. Introduction

An estuary is a tidally brackish water body where riverine and marine waters interact (Nontji, 2008). Accordingly, the downstream section of a river is considered part of the estuarine system, as it remains under the combined influence of river discharge and marine dynamics. As dynamic and biogeochemically active environments, estuaries regulate primary productivity through coupled physical, chemical, and biological processes, along with substantial inputs of nutrients and organic matter (Cloern et al., 2014; Junior, 2025).

Phytoplankton, microscopic algae inhabiting aquatic systems, are highly responsive to environmental changes, making them a reliable indicator of water quality (EPA, 2023). Chlorophyll-a (Chl-a), a common photosynthetic pigment in all phytoplankton, is widely used as an indirect measure of algal carbon biomass and a proxy for primary productivity (Damar et al., 2020; Gall and Pinkerton, 2024), which underpins estuarine food webs and indicates ecosystem function and water quality.

Phytoplankton communities in estuaries typically consist of both freshwater and marine species due to continuously changing conditions driven by tidal dynamics. Their distribution depends on hydrodynamic processes and salinity tolerance (Nontji, 2008). The mixing of freshwater and seawater causes fluctuations in salinity, current velocity, and light availability, thereby influencing phytoplankton metabolism and photosynthesis, and shaping community abundance, distribution, and diversity (Cereja et al., 2021; Neun et al., 2022; Thrush et al., 2014; Xia et al., 2024; Ye et al., 2025).

Salinity regulates algal metabolism through osmotic stress and nutrient–sediment interactions, leading to spatial and temporal variability in nutrient availability (Orizar et al., 2024; Thrush et al., 2014). Differences in salinity tolerance affect metabolic performance, productivity, and survival, particularly in freshwater phytoplankton, with only a limited number of species able to persist across the full salinity gradient of estuarine environments (Cereja et al., 2021; Lancelot and Muylaert, 2011; Lionard et al., 2005; Steidle and Vennell, 2023).

Current velocity, governed by tidal dynamics, morphology, and upstream discharge (Purnaini and Purwono, 2018; Tendean, 2017), drives the transport of oxygen, nutrients, and organic matter while shaping Chl-a distribution (Reseck, 1988; Dahuri, 2003; Wang et al., 2024). Together with salinity, hydrodynamic variability enhances water mixing and turbidity, often constraining photosynthesis by reducing light penetration (Cloern et al., 2014). Interactions between current velocity and residence time can limit phytoplankton accumulation despite high nutrient availability (Zhong and Chien, 2024), whereas lower velocities promote retention within the optimal light zone and increase Chl-a concentrations (Zhang et al., 2015; Steidle and Vennell, 2023).

Phytoplankton production is further influenced by water column stratification and mixing processes driven by freshwater inflow and tidal dynamics (Cloern et al., 2014). Stratification is defined as the development of vertically distinct water layers driven by density gradients, such as salinity (WetlandInfo, 2023). Strong stratification promotes phytoplankton growth by retaining cells within the euphotic zone, whereas intensified mixing redistributes cells below light-limited depths, reducing photosynthetic efficiency (Cloern et al., 2014; Gall et al., 2023). Environmental changes modify stratification intensity and mixed layer depth, influencing vertical gradients in primary productivity (Gall and Pinkerton, 2024; Xia et al., 2024; Zhong and Chien, 2024). This vertical variability is reflected in phytoplankton distribution across depths where phytoplankton productivity is typically higher near the surface, while in deeper layers, chlorophyll concentrations increase only when sufficient light penetrates (Domingues and Barbosa, 2023; Gall et al., 2023; Gonçalves-Araujo and Markager, 2020). However, this pattern is not always uniform due to mixing and stratification dynamics.

In addition to physical drivers, nutrient availability also regulates phytoplankton dynamics. Nitrate is an essential nutrient required for the synthesis of proteins, chlorophyll, and nucleic acids (Effendi, 2003; Nasution et al., 2019; Zakem et al., 2018). Elevated nitrate concentrations in estuarine systems often indicate anthropogenic inputs from river basins with intensive human activities, including wastewater discharge, agricultural runoff, septic leakage, and industrial effluents (EPA, 2000; González-Ramírez et al., 2023). This study uses nitrate as a nutrient parameter to establish baseline data for future research in the study area.

Land-based anthropogenic activities are a major source of nutrient inputs in estuarine systems. Land use conversion in the upstream area, intensive oil palm plantations, coal and river sand mining, and rubber processing activities in the middle reaches, as well as poorly planned coastal urban development in the downstream section, have contributed to the degradation of the Air Bengkulu River (Pareke and Putra, 2014). Belladona (2017) also reported substantial pollution from industrial effluents at multiple monitoring sites. The river water quality has been classified as moderately polluted by Dinas Lingkungan Hidup Bengkulu (2023) and has also been considered unsuitable as a raw water source due to pollution (Wijayanto et al., 2025). Consistent with these findings, the Bengkulu watershed has been categorized as being in poor condition and in need of restoration (BPDAS Ketahun, 2024). These cumulative pressures across the Air Bengkulu River watershed have the potential to alter downstream physicochemical conditions through riverine transport processes, leading to both deterioration of estuarine ecological functions and increased coastal vulnerability.

In the Air Bengkulu estuary, previous studies have predominantly focused on pollution status and surface-level physicochemical conditions, with limited attention to vertical variability and biological responses, particularly in relation to primary productivity. This may overlook important depth-related processes associated with stratification and mixing, resulting in an incomplete understanding of primary productivity in this area when assessed using Chl-a as a proxy.

Therefore, this study aims to assess phytoplankton dynamics represented by Chl-a concentration, with a focus on its vertical distribution and its relationship with key environmental parameters in the downstream section of the Air Bengkulu estuarine system. The study was conducted during the peak of the dry season, representing conditions of reduced freshwater discharge and stronger marine influence.

2. Materials and Methods

2.1. Study Area

The study area is characterized by a mixed, predominantly semidiurnal tidal regime, in which two high tides and two low tides may occur each day with unequal heights and periods (Hasibuan et al., 2020). Field measurements indicate that water depths in the river mouth zone range from approximately 1 to 4 meters (m), classifying the system as a shallow estuary. The study area encompasses approximately 1 kilometer (km) of the river channel extending upstream from the Air Bengkulu River mouth as presented in Figure 1.

Sampling was conducted during the peak of the dry season, as indicated by climatological records from BMKG Provinsi Bengkulu (2025). During this period, rainfall was relatively low, with total monthly precipitation ranging from 0 to 155 mm, with a mean of 9.4 mm, based on daily rainfall data obtained from the BMKG (2025) online database. Rainfall in the study area was recorded only once throughout the sampling period, occurring during the third sampling event at Station 2 at 17.00 local time. Details of the sampling schedule are provided in Table 1.

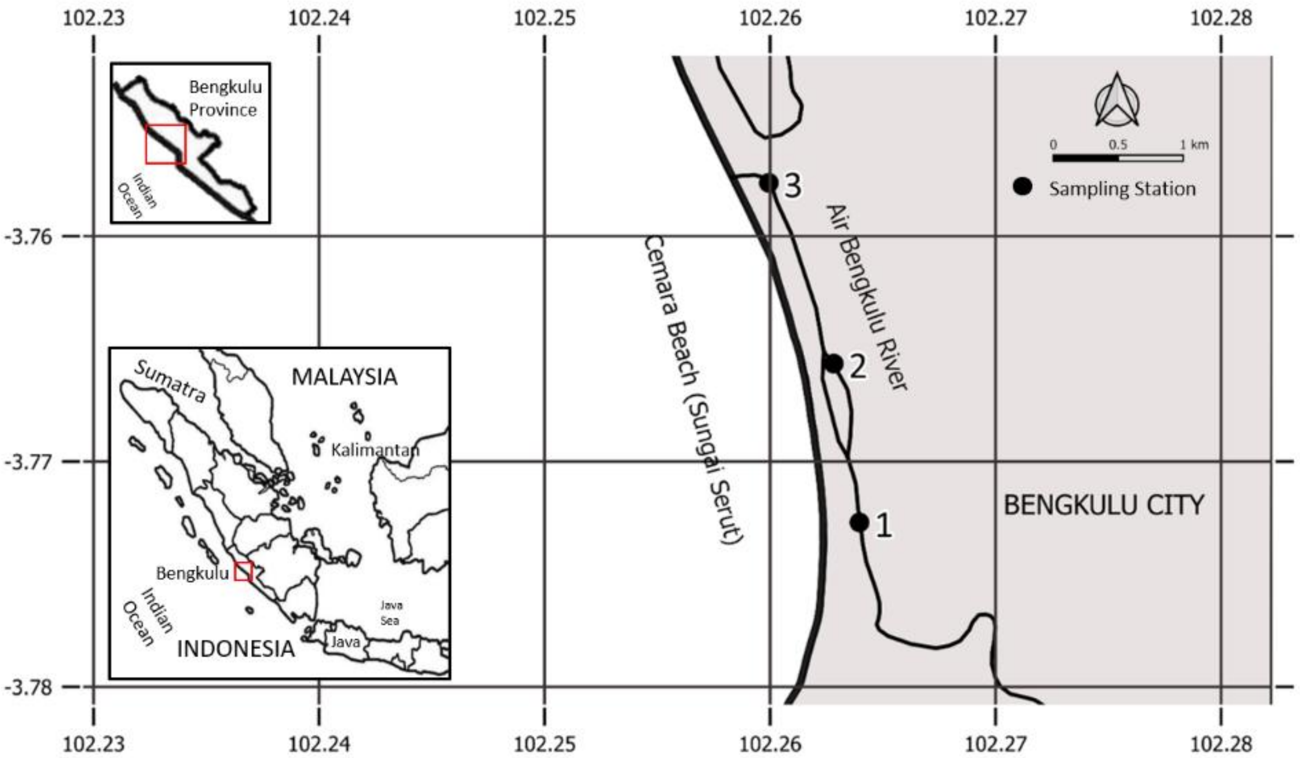


Figure 1. Location of the study area along the downstream of Air Bengkulu River, showing the sampling stations within approximately 1 km upstream from the river mouth.

Table 1. Geographic coordinates of sampling stations and schedule

Sampling Location	Coordinates	1st Sampling (June)		2nd Sampling (July)		3rd Sampling (August)	
		Morning	Afternoon	Morning	Afternoon	Morning	Afternoon
Station 1	102.26348 −3.77175	09.20	15.00	09.24	14.47	09.20	14.47
Station 2	102.26338 -3.76578	11.10	16.10	10.47	15.24	10.49	15.28
Station 3	102.25924 −3.75657	12.50	17.00	11.54	17.00	11.19	16.18

2.2. Field Sampling Design

Sampling was conducted at three stations at depths of 0, 1, and 2 m, twice daily, with collections performed in the morning during high tide and in the afternoon during low tide. Sampling was carried out on three occasions in June, July, and August 2025, timed to coincide with spring tide conditions associated with the new moon phase. Tidal information was obtained from the WXTide32 application.

Phytoplankton samples were collected by filtering 60 L of water through a plankton net. Nitrate (mg/L) samples were obtained from the filtrate collected during phytoplankton sampling. Both sample types were transported to the laboratory under chilled conditions. Phytoplankton subsamples (100 mL) were then filtered and stored frozen.

Environmental parameters were measured in situ, including current velocity (m/s) using a current meter, salinity (‰) using a refractometer, dissolved oxygen (mg/L) using a DO meter, temperature (°C) using a thermometer, pH (–) using a pH meter, and water transparency (%) determined using a Secchi disk. Salinity, current velocity, dissolved oxygen, and nitrate were measured at all depths, whereas temperature, pH, and water transparency were recorded only at the surface.

2.3. Laboratory and Statistical Analysis

Trichromatic spectrophotometric analysis was used to determine the concentration of Chl-a, referring to EPA Method 446.0 Revision 1.2 (EPA, 1997). Absorbance was measured at three primary wavelengths (A664, A647, and A630) and values were corrected using absorbance at A750, as specified in the method. Chl-a concentration (µg/L) was calculated using the equation proposed by Jeffrey and Humphrey (1975), as referenced in EPA (1997) and Rey and Aminot (2002). Nitrate concentration was determined spectrophotometrically using the brucine method, following the technical guidelines from Balai Penelitian Tanah (2005).

Statistical analyses were conducted using the Kruskal–Wallis test, followed by a post hoc Mann–Whitney test, to evaluate spatial differences among parameters. Quantile regression was applied to assess the influence of environmental variables on the response variable. Chl-a data were log-transformed after adding a small constant to accommodate values below the detection limit. These non-detect values are reported as zero in the tables to reflect environmental conditions. Spearman's rank correlation was used to examine general relationships among the parameters. Statistical significance was determined at $p < 0.05$.

3. Results and Discussion

3.1. Environmental Parameter Heterogeneity

Environmental parameters were analyzed across stations at three depths at each station by comparing morning high-tide and afternoon low-tide conditions, as shown in Figure 2. Observed variations in current velocity suggest non-uniform vertical water mass movement, which influences key water-column processes such as nutrient transport, oxygen distribution, and salinity gradients. Higher dissolved oxygen concentrations observed during the afternoon are likely associated with enhanced photosynthetic activity under increased light availability. Depth-dependent differences in current velocity, however, may limit vertical mixing, leading to uneven oxygen distribution and increased heterogeneity. Similarly, increased nitrate heterogeneity during the afternoon reflects spatial variability in nutrient availability. Nitrate is transported by current from both marine and upstream river sources, while phytoplankton uptake occurs at different rates across depths, further amplifying concentration variability. In addition to river discharge, surface currents are influenced by diurnal tidal forcing and wind-driven circulation, whereas subsurface currents are largely influenced by riverbed morphology, which may contribute to vertical heterogeneity in environmental conditions.

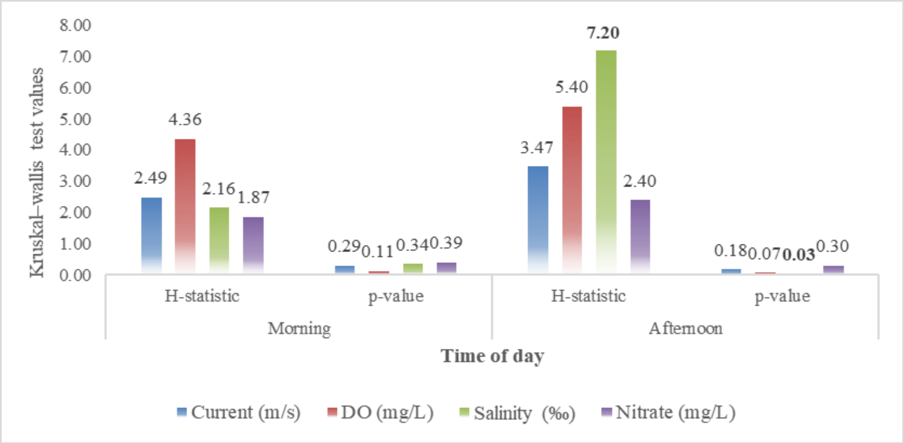


Figure 2. Depth-related variation of environmental parameters based on the Kruskal-Wallis test results, with a critical H value of 5.991 ($\alpha < 0.05$)

Although variability increased across depths during the afternoon, only salinity showed a statistically significant difference (H = 7.20, p = 0.03; Figure 2). With the exception of salinity, environmental conditions across the three water column layers were relatively homogeneous during the study period, suggesting that phytoplankton were exposed to broadly uniform physicochemical conditions both spatially and temporally. Post hoc Mann–Whitney tests revealed significant differences in afternoon salinity among all depths, whereas Chl-a concentrations remained consistently low and showed no significant variations across depths (Figure 3). These results indicate that salinity was not significantly associated with depth-related changes in Chl-a during the observation period.

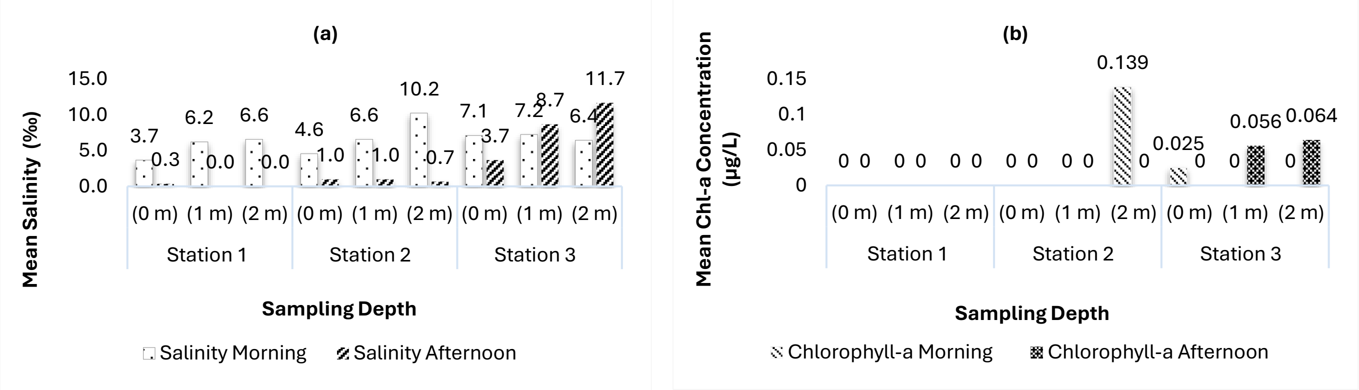


Figure 3. Comparison of average salinity (a) and Chl-a concentrations (b) between morning and afternoon observations across three depths at three stations.

Table 2. Overall mean nitrate concentrations and current velocities compared to Chl-a concentration* at three river depths across stations

Sampling Location	Depth (meter)	Morning			Afternoon		
		Nitrate (mg/L)	Current Velocity (m/sec)	Chl-a (µg/L)	Nitrate (mg/L)	Current Velocity (m/sec)	Chl-a (µg/L)
Station 1	0	0.359	0.147	0.000	0.245	0.143	0.000
	1	0.396	0.064	0.000	0.430	0.237	0.000
	2	0.677	0.166	0.000	0.248	0.209	0.000
Station 2	0	0.429	0.379	0.000	0.265	0.114	0.000
	1	0.419	0.316	0.000	0.266	0.232	0.000
	2	0.488	0.099	0.139	0.261	0.232	0.000
Station 3	0	0.420	0.164	0.025	0.294	0.120	0.000
	1	0.375	0.167	0.000	0.285	0.120	0.056
	2	0.381	0.396	0.000	0.284	0.086	0.064

*Values reported as zero indicate Chl-a concentration below the spectrophotometric detection limit

3.2. Diurnal Patterns of Nitrate and Current Velocity

During the study period, neither nitrate levels nor current velocity exhibited consistent patterns across the three depths, and the mean value range of both parameters was lower in the afternoon than in the morning (Figure 4). The highest nitrate concentration was recorded at a depth of 2 m at Station 1 on the first sampling (1.142 mg/L), while the lowest was at the surface of the same station on the third sampling (0.039 mg/L). The maximum and minimum current velocities were recorded at the surface of Station 2 on the second sampling (0.900 and 0.012 m/s, respectively). Both parameters generally exhibited lower values on the third sampling than on preceding sampling events.

Progressive decline occurred in current velocity from the first (0.170–0.422 m/s) and second (0.096–0.244 m/s) sampling to a weak and stable flow condition on the third sampling (0.060 m/s). This pattern indicates increased water column stability and a longer residence time following water inflow from the nearby Air Hitam River into the Air Bengkulu River via a small canal one day prior to the third sampling. Under low-current conditions, water masses from both rivers are likely to persist longer within the water column, allowing phytoplankton and organic materials to remain available for biological processes. These conditions coincided with the highest detection of Chl-a across all sampling points, consistent with findings that zones characterized by longer residence time tend to support greater phytoplankton accumulation (Zhang et al., 2015; Stumpner et al., 2020; Steidle and Vennell, 2023). Such conditions may also facilitate the mixing of phytoplankton and light organic matter from the Air Hitam River into the Air Bengkulu River, potentially contributing to the slightly elevated productivity observed at Station 3. While Figure 4 depicts the diurnal fluctuations in nitrate and current velocity, Table 2 presents their overall mean values over the study period. During the morning and afternoon sampling, nitrate concentrations and current velocities did not exhibit consistent patterns at the three depths. Nitrate concentrations ranged from 0.359 to 0.677 mg/L in the morning and from 0.245 to 0.430 mg/L in the afternoon, while current velocities ranged from 0.064 to 0.396 m/s and from 0.086 to 0.237 m/s, respectively. Chl-a concentrations generally remained stable even at higher nitrate levels, indicating that lower current velocities had a slightly greater influence on phytoplankton growth than nitrate, and that the overall phytoplankton response was limited despite variations in these parameters.

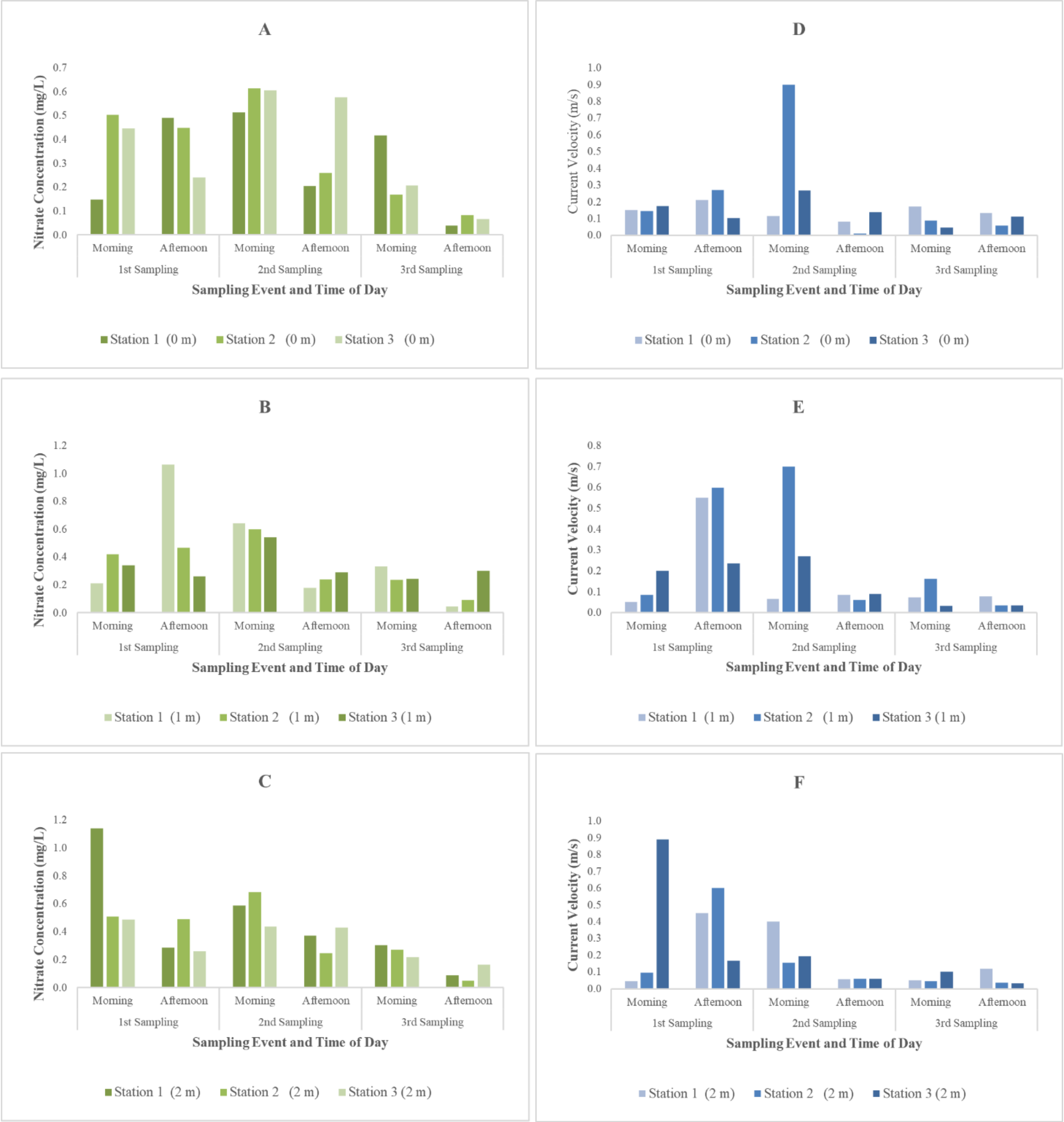
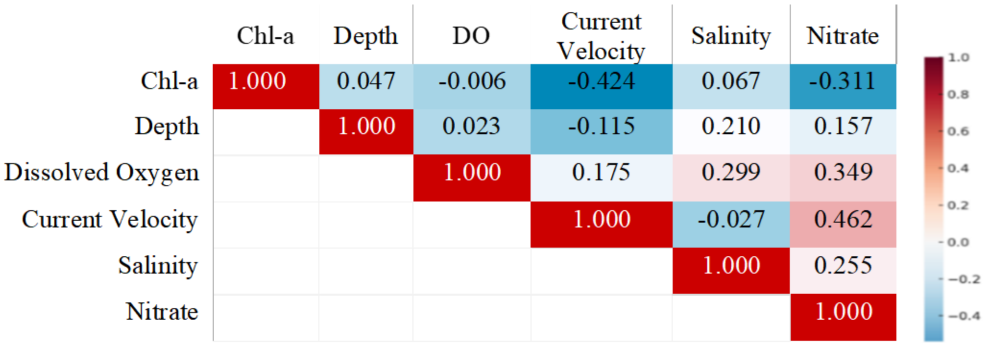


Figure 4. Dynamics of nitrate concentrations (A, B, C) and current velocity (D, E, F) at depths of 0 m (A, D), 1 m (B, E), and 2 m (C, F) which were collected twice daily (morning and afternoon) on three stations, over three sampling events

3.3. Chl-a Concentration

Spectrophotometric analysis revealed that the concentrations of Chl-a on all depth layers at the three stations were mostly below the detection limit and were therefore recorded as zero, as shown in Table 2. This low variation persisted under both high- and low-tide conditions. Only slight increases were observed at Station 2 at a depth of 2 m (0.139 µg/L) and at the surface of Station 3 (0.025 µg/L) during morning measurements. Similarly, slight increases were also observed at Station 3 at depths of 1 and 2 m (0.056–0.064 µg/L) during afternoon measurements. No significant increase was observed at any of the sampling points at Station 1. These limited variations suggest that Chl-a concentrations were generally constrained across stations and depths, likely associated with the influence of current velocity and nitrate, as indicated by the statistical analyses.

Quantile regression was performed using river depth, dissolved oxygen, current velocity, salinity, and nitrate as predictors of Chl-a at three quantiles ($\tau = 0.25$, 0.50, and 0.75) representing low, median, and high concentrations, respectively. All collected data were included. The intercept coefficient remained stable across quantiles ($\beta = 0.544$, 0.543, and 0.568), indicating that the model predicted baseline concentrations within a narrow range across all levels of distribution. River depth, dissolved oxygen, and salinity showed limited effects on Chl-a concentrations across the water column. Significant effects were observed only for current velocity at two quantiles and nitrate at one quantile: current velocity shifted from positive at the lower quantile to negative at the median and upper quantiles ($\beta = 0.170$, -0.213, and -0.212), suggesting that it limits Chl-a at moderate-to-high concentrations; nitrate shifted from negative to positive ($\beta = -0.546$, 0.000, 0.290), indicating that nitrate limits Chl-a only at low concentrations.



	Chl-a	Depth	DO	Current Velocity	Salinity	Nitrate
Chl-a	1.000	0.047	-0.006	-0.424	0.067	-0.311
Depth		1.000	0.023	-0.115	0.210	0.157
Dissolved Oxygen			1.000	0.175	0.299	0.349
Current Velocity				1.000	-0.027	0.462
Salinity					1.000	0.255
Nitrate						1.000

Figure 5. Spearman correlation among parameters; blue indicates negative correlations, red indicates positive correlations, and color intensity reflects the strength of the correlation.

Spearman's correlation analysis was conducted to assess the relationships between the parameters and the concentration of Chl-a, as well as the influence of river depth on all parameters (Figure 5). Chl-a exhibited moderate negative correlations with current velocity ($\rho = -0.424$) and nitrate ($\rho = -0.311$), which is consistent with the quantile regression results. Water column depth exhibited weak correlations with all other parameters, including Chl-a ($\rho = 0.047$), dissolved oxygen ($\rho = 0.023$), current velocity ($\rho = -0.115$), salinity ($\rho = 0.210$), and nitrate ($\rho = 0.157$), indicating that variations in depth had an insignificant effect on these parameters' conditions.

Observations indicate that most Chl-a concentrations at all depths across the three stations were below the detection limit under both high tide and low tide conditions. These results suggest that the area around the mouth of the Air Bengkulu River has very low primary productivity. Detected concentrations ranged from 0.025 to 0.139 µg/L (see Table 2), corresponding to the ultra-microtrophic to oligotrophic trophic classes, according to Gall and Pinkerton (2024). Nitrate and current velocity appear to be the main limiting factors for Chl-a concentrations across the three depths in the water column. This finding aligns with the study by González-Ramírez et al. (2023), who reported that riverine nitrate supply and hydrodynamic factors are the primary drivers of chlorophyll variation in estuarine ecosystems. However, nitrate effectiveness is found to depend on current dynamics, and its high concentrations do not always result in enhanced Chl-a concentrations in estuaries, a pattern also observed by Mallin et al. (1993).

The negative correlation between nitrate and Chl-a at low concentrations likely reflects rapid phytoplankton uptake, as phytoplankton can remove nitrate and other dissolved nitrogen species from the water column at substantial rates during periods of high productivity, as reported by Torres-Valdes and Purdie (2006). This results in rapid nitrate assimilation and limited accumulation in the water column, indicating that nitrate may act as a limiting factor when the utilization of phytoplankton exceeds the available supply. Our observations of relatively low Chl-a concentrations are consistent with this pattern and likely reflect a limited phytoplankton population. Kennish, as cited by Rasyid et al. (2018), reported that the optimal nitrate range for phytoplankton growth is 0.9–3.5 mg/L, while concentrations below 0.44

mg/L may constrain growth. Furthermore, Rasyid et al. (2018) demonstrated that low nitrate concentrations in estuarine waters were associated with reduced phytoplankton abundance. Consistent with these findings, the observed nitrate concentrations in the Air Bengkulu River fall below this range and are insufficient to adequately support phytoplankton productivity, thereby contributing to low primary production.

3.4. Influence of Other Environmental Factors

We observed higher salinity heterogeneity in the afternoon samples, indicating that freshwater and seawater do not mix uniformly in the estuary of the Air Bengkulu River. Despite the estuarine waters being relatively shallow and lacking permanent stratification, interactions between seawater intrusion and freshwater flow can still generate salinity variations across depths. The intensity of tides, current velocity, and wind at specific times may enhance or weaken mixing in the estuary, particularly during low tide (Lupiola et al., 2025). This combination of factors likely explains why salinity variability was most pronounced among the measured parameters at different depths in the afternoon. Current velocities were higher during the morning high tide than during the afternoon low tide, resulting in reduced mixing and greater heterogeneity in the measured variables. Consequently, salinity differences across depths became more pronounced.

Salinity strongly influences algal metabolism, requiring cells to adapt to osmotic pressure while affecting the availability of nutrients, as well as the structure, distribution, and diversity of phytoplankton communities in freshwater and brackish estuaries (Orizar et al., 2024; Xia et al., 2024). Changes in salinity can limit the activity or induce the mortality of non-tolerant phytoplankton species (Cereja et al., 2021), enabling only tolerant species to survive. The low phytoplankton productivity observed in this study is likely the result of their small population in the Air Bengkulu River and selection by salinity. The highest tides in the morning bring higher salinity from the sea into the river, likely reducing the number of freshwater phytoplankton that could otherwise survive. Conversely, the lowest tides in the afternoon increase salinity dilution, further increasing salinity variability across the estuarine water column.

In addition to salinity-driven processes, other environmental parameters were also evaluated. Temperature, water transparency, and pH were measured at the surface layer. The pH values (6.7–7.7) indicated near-neutral to slightly alkaline conditions, which are generally favorable for most aquatic organisms, including phytoplankton, as they fall within the optimal range of 6.5 to 8.0 (EPA, 2026). Similarly, water temperature (26–32°C) was within or slightly above the optimal range for aquatic organisms in tropical waters (20–30°C; Effendi, 2003). However, statistical analysis revealed that none of these parameters had a significant relationship with Chl-a concentration, indicating that they were not the primary factors controlling phytoplankton dynamics in the study area, particularly based on the surface measurements. Among these parameters, water transparency is further discussed due to its direct role in regulating light availability.

Water transparency is an important factor controlling primary productivity in estuarine systems, as limited light availability constrains phytoplankton physiology and growth in estuaries despite elevated nutrient levels (Xia et al., 2024). In this study, surface water transparency (0.8–45.4%) indicates heterogeneous light conditions, with lower values indicating potential light limitation in more turbid waters (Kirk, 2011). The waters appeared visually turbid throughout the study period, except at Station 3 near the estuary mouth during a rainfall event, when the highest water transparency value (45.4%) was recorded. This event coincided with a slight increase in afternoon Chl-a concentrations at 1 and 2 m (0.056 and 0.064 µg/L; Table 2). However, overall were dominated by low transparency values, suggesting restricted light availability for phytoplankton photosynthesis and consequently reduced primary productivity. Such conditions may be associated with salinity gradients and concurrent changes in light availability, as higher salinity in estuarine waters is often associated with increased turbidity and reduced light penetration, which together can limit phytoplankton photosynthetic activity, alter community dynamics, and render phytoplankton presence difficult to detect in estuarine environments (Cereja et al., 2021; Ye et al., 2025). A similar pattern was reported by Utami et al. (2025), where low Chl-a concentrations were associated with limited light availability. These conditions may also be further influenced by anthropogenic inputs from land-based activities, which can increase turbidity and reduce light penetration, potentially limiting phytoplankton productivity in the estuarine system.

4. Conclusion

The estuarine ecosystem of the Air Bengkulu River is shaped by complex spatial and temporal interactions among environmental factors. This study indicates that physical mixing processes and nutrient availability, particularly current velocity and nitrate concentration, are the important drivers of Chl-a variability, whereas the general water quality parameters are not the dominant limiting factors. The consistently low Chl-a concentrations indicate ultra-microtrophic to oligotrophic conditions and limited primary productivity, with implications for food web support and local capture fisheries. Anthropogenic influences affecting turbidity and nutrient dynamics may further constrain productivity. This study contributes to a better understanding of environmental controls on phytoplankton dynamics, in particular in the downstream section of the Air Bengkulu River and provides a basis for future investigations on river-sea interactions and water quality management. Future studies should include observations during rainy and transitional seasons and broaden the temporal scope of the study to better capture seasonal variability, while also incorporating additional parameters not included in this study, such as turbidity, suspended solids, and other nutrients.

5. Data Availability Statement

All data included and used in the study are open and contain no confidential and ethical private information.

6. Funding Institutions

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7. Conflict of Interest

Each author has declared that there is no conflict of interest in the writing or submission of this manuscript.

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