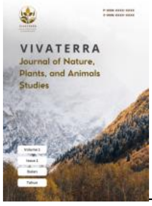

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Environmental Quality Assessment Based on Physical-Chemical Parameters and Organic Content of Substrates in the Estuarine Ecosystem of Lhokseumawe City

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Abstract

This study evaluates the environmental quality of the Krueng Cunda estuary in Lhokseumawe City by examining spatial variations in physical–chemical parameters and sedimentary organic content across five monitoring stations with distinct hydrodynamic and geomorphological characteristics. Temperature, salinity, dissolved oxygen, and pH were analyzed to characterize the water column, while C-organic and N-total measurements were used to assess substrate conditions that influence benthic habitat suitability. Results show that temperature ranged from 29–34°C and salinity from 15–30 ppt, reflecting a dynamic mixing regime typical of tropical estuaries influenced by tidal intrusion and freshwater discharge. Dissolved oxygen levels remained within 6.4–7.7 mg/L and pH between 7.3–7.9, indicating chemically stable and well-oxygenated waters capable of supporting diverse aquatic organisms. Sediment analysis revealed higher organic accumulation in fine-textured substrates, particularly at stations dominated by sandy-clay compositions, highlighting the strong relationship between grain size and organic retention. Overall, the integrated assessment confirms that the estuary maintains ecological functionality while exhibiting early indicators of environmental pressure that warrant continued monitoring to support sustainable coastal management efforts.

Keywords: *Estuarine ecology, water quality, organic matter, sediment characteristics, Lhokseumawe.*

INTRODUCTION

Estuaries are widely recognized as transitional ecosystems whose ecological character is shaped by tidal oscillations, freshwater inflow, and a broad spectrum of anthropogenic activities occurring within their watersheds, creating a dynamic environmental mosaic that constantly shifts in space and time (Sundoko et al., 2025). The interplay of these forces produces complex gradients of salinity, temperature, and turbidity, generating environmental conditions that are highly variable compared with either purely marine or freshwater systems. Such variability requires continuous scientific attention because the ecological functioning of estuaries depends heavily on the stability of their physicochemical components, particularly parameters that influence nutrient cycling and biological productivity. For this reason, estuaries serve as natural laboratories for understanding how environmental pressures shape aquatic ecosystems in rapidly changing coastal regions.

Among the key factors governing estuarine ecological balance are fundamental physicochemical attributes such as temperature, salinity, pH, and dissolved oxygen, each of which dictates metabolic performance, reproductive success, and survival thresholds of aquatic organisms (Caesar et al., 2025). These variables fluctuate across tidal phases and seasonal cycles, creating conditions that can either support diverse communities or impose physiological stress on sensitive taxa. Deviations from optimal ranges often signal disturbances stemming from watershed modifications, urban expansion, or contamination originating from human activities. Consequently, monitoring these physicochemical parameters provides an essential foundation for assessing the health and resilience of estuarine environments.

The estuarine region of Lhokseumawe City represents a strategic ecological corridor that functions as a transitional boundary between terrestrial discharge pathways and coastal marine systems, forming a habitat shaped by strong hydrodynamic and biogeochemical gradients (Saraswati et al., 202). Its distinctive environmental dynamics support a broad array of aquatic organisms that depend on the stability of the water column and sediment characteristics. Increasing anthropogenic pressures from residential settlements, industrial operations, and fisheries intensification have heightened concerns regarding potential alterations in water quality. This growing pressure underscores the need for comprehensive environmental assessments capable of revealing how human activities reshape ecological processes in this region.

As the confluence zone of freshwater from riverine systems and saline water from the open sea, the Lhokseumawe estuary accommodates biotic communities that are particularly sensitive to abrupt environmental change, especially those belonging to benthic assemblages whose physiology and distribution closely track substrate quality. The dynamic mixing of water masses intensifies fluctuations in salinity and nutrient concentration, producing conditions that may either enrich ecological functioning or trigger instability. Human-driven nutrient inputs, sediment reshaping, and chemical discharges aggravate these natural fluctuations, pushing the estuarine system toward states that may exceed its intrinsic buffering capacity. Understanding the extent of these impacts requires integrating water-column measurements with sediment-based indicators that reflect longer-term environmental trends.

Preliminary data from the Krueng Cunda Estuary provide an initial depiction of environmental variation, showing temperature ranges of 29–33 °C, salinity between 12–28 ppt, dissolved oxygen levels of 6.3–7.7 mg/L, and pH values spanning 7.3–7.9, values that align with typical estuarine fluctuation but warrant deeper interpretation regarding ecological thresholds (Ekamaida, 2017; Emersida, 2021). Such variability indicates that the system is influenced by both tidal mixing and riverine discharge, which jointly regulate oxygen availability and chemical composition. These conditions also influence nutrient transformation processes that determine the productivity and habitability of the system for aquatic organisms. A more detailed evaluation is needed to determine how these values interact with broader environmental pressures and what they reveal about long-term ecological stability.

Beyond the characteristics of the water column, the composition and quality of substrate materials play an equally important role in defining habitat suitability, especially for benthic communities whose ecological functioning is closely tied to sediment properties (Wijayanti, 2007). Fine-textured sediments tend to retain higher organic matter content compared with sandy substrates, thereby influencing microbial activity, nutrient regeneration, and redox conditions (Yudha et al., 2020). Variations in organic content can shape benthic community patterns, yet these biological responses are also mediated by the overarching physicochemical dynamics of the water. Understanding these coupled interactions is essential for interpreting the ecological implications of substrate variability within estuarine systems.

Previous research in estuarine environments, including studies conducted in Aceh, has frequently emphasized biological aspects or pollution indicators without fully integrating analyses of both water-column parameters and substrate organic content into a unified environmental assessment. This fragmented approach limits the ability to interpret how physical, chemical, and biological components jointly contribute to ecological shifts within the estuary. Moreover, the absence of comprehensive baseline data hinders efforts to compare temporal changes, evaluate environmental risk, or design effective management strategies. A scientifically robust evaluation requires a methodology that bridges these analytical gaps and presents a cohesive picture of ecosystem conditions.

The present study introduces conceptual and methodological novelty by combining spatial analysis of physicochemical parameters with measurements of organic carbon and total nitrogen content across multiple stations representing distinct environmental characteristics in the Krueng Cunda Estuary. This integrated design offers a more holistic understanding of how water-column attributes interact with sediment properties to structure ecological conditions within the system. Insights generated from this work are expected to advance environmental monitoring frameworks and strengthen management strategies for maintaining estuarine health in rapidly developing coastal regions. Through this approach, the study aims to (1) determine the spatial variability of key physicochemical factors and (2) assess the organic composition of estuarine substrates as indicators of habitat quality and environmental pressure.

RESEARCH METHOD

This study was conducted in the waters of the Krueng Cunda Estuary in Lhokseumawe City, Aceh, with data collection carried out over a period of one month in October 2025. This study is a descriptive-quantitative study conducted at five stations in the Krueng Cunda Estuary, which were selected based on the density of aquatic biota. Water samples were taken in situ to measure temperature, salinity, pH, and dissolved oxygen (DO) using a standard water quality probe. Sediment samples were obtained using an Ekman grab, then dried and analyzed in the laboratory to determine the organic C content using the Walkley–Black method and total N using the Kjeldahl method. The research population consisted of physical-chemical parameters and estuarine substrate characteristics, while the sampling points were measurement units at five observation stations based on anthropogenic activities of the community. Substrate types were classified based on sediment texture through simple granulometric observation. The data were analyzed descriptively based on Appendix VIII of Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Protection and Management of the Environment regarding marine biota, and compared with previously published ecological tolerance ranges.

RESULTS AND DISCUSSION

Physical Characteristics of the Estuarine Waters

The spatial variability of temperature across the estuarine stations reflects the combined influence of tidal mixing, freshwater inputs, and geomorphological constraints that shape the thermal profile of transitional waters. Temperature values ranging from 29 to 34°C exhibit patterns comparable to tropical estuarine systems where shallow morphology accelerates heat absorption, as described by Wisha et al. (2016). The upper range measured at Station 1 and Station 5 mirrors conditions reported in Segara Anakan, where estuarine openness and reduced shading contribute to elevated thermal loads driven by solar radiation cycles. Similar findings from Padang et al. (2024) show that thermal regimes in coastal waters may approach 33°C under strong atmospheric forcing, reinforcing that estuaries such as Krueng Cunda remain highly sensitive to climatic fluctuations and nearshore hydrodynamics:

Table 1. Water Quality Parameters in the Lhokseumawe Estuarine Stations

No	Parameter	Station 1	Station 2	Station 3	Station 4	Station 5
1	Temperature (°C)	34	32	29	32	34
2	Salinity (ppt)	30	25	15	28	30
3	DO (mg/L)	6.5	7.7	6.4	6.5	6.6
4	pH	7.2	7.6	7.3	7.9	7.6
5	C-Organic (%)	0.25–1.59	0.11–0.14	0.96–2.31	1.51–6.98	0.25–0.26
6	Substrate Type	Sandy clay	Sand	Sandy clay	Sandy clay	Sand

Temperature conditions measured in this study also align with biological tolerance thresholds documented for estuarine macrozoobenthos, which perform optimally at 25–31°C but exhibit physiological stress when temperatures exceed 30°C as noted by Purba et al. (2025). The elevated temperatures observed at certain stations suggest the presence of environmental pressure that may gradually reshape species distribution and community structure when maintained over extended periods. A similar ecological response was identified by Purnami et al. (2010), who demonstrated a decline in benthic richness under sustained thermal elevation in shallow coastal ecosystems. The close relationship between thermal gradients and faunal resilience underscores the need for continuous temperature monitoring to assess ecological stability.

Thermal patterns in the estuary are also influenced by sediment characteristics, where finer sediments with higher moisture retention may buffer rapid temperature shifts compared with sandy substrates. This association echoes the observations of Barus et al. (2010), who noted that compacted fine-grained sediments create microhabitats capable of mitigating abrupt thermal changes, although the broader water column remains influenced by tidal fluxes. The coexistence of sandy and sandy-clay substrates across the five stations indicates heterogeneity that fosters distinct thermal microconditions, potentially interacting with organic matter accumulation described by Yudha et al. (2020). This interplay emphasizes the multidimensional nature of thermal variability in dynamic estuarine zones.

Salinity distribution across the estuary ranged from 15 to 30 ppt, illustrating a classical estuarine mixing gradient often cited in studies such as Nugroho et al. (2017), who examined similar variability under tidal influence in the Bengawan Solo estuary. Stations closest to marine intrusion exhibited higher salinity due to reduced freshwater dilution, reflecting the hydrodynamic transitions described by Odum (1993). Such patterns reaffirm that estuarine stratification is shaped by the relative balance between riverine discharge and seawater encroachment, particularly during dry periods when freshwater contributions decrease. Comparable salinity intervals were identified by Simanjuntak and Rahardjo (2019) in the Cisadane estuary, highlighting the consistent behavior of transitional waters across Indonesian coastlines.

Moderate salinity fluctuation in the Krueng Cunda estuary suggests ecological conditions suitable for diverse estuarine fauna, including benthic communities documented by Bai'un et al. (2021) in mangrove-estuarine complexes. Salinity values observed fall within the ecological tolerance range recognized for many estuarine organisms, allowing them to maintain physiological performance under mixing-driven variability. These characteristics often play a decisive role in shaping species adaptations, including osmoregulatory strategies that govern survival across fluctuating salinity regimes. The environmental gradient identified here matches descriptions in Sundoko et al. (2025), who emphasized estuarine dynamism as a fundamental driver of habitat diversity.

Dissolved oxygen concentrations ranging from 6.4 to 7.7 mg/L indicate favorable oxygenation levels that support aquatic life, consistent with thresholds presented by Salmin (2005) who emphasized that DO above 5 mg/L enhances metabolic functioning of most aquatic organisms. Comparable DO values measured by Rahmawati et al. (2018) in the Donan estuary demonstrate that well-oxygenated waters often occur in areas with active hydrodynamic exchange, especially where mangrove vegetation enhances localized oxygen production. These conditions mirror the findings of Yustina et al. (2014) in the Siak estuary, though the latter exhibited lower DO due to anthropogenic stressors that were less evident in the present study. The DO values in Krueng Cunda also align with quality standards described in national regulations (Indonesia, 2021), indicating that oxygenation remains supportive of ecological integrity.

Spatial variations in pH displayed a narrow range between 7.3 and 7.9, reflecting chemical stability that characterizes many healthy estuarine systems. This stability is comparable to the ranges reported in Demak and Porong estuaries by Hartati et al. (2019) and Wicaksono et al. (2020), where pH neutrality helps maintain nutrient balance and biogeochemical processes. Such conditions also reduce the risk of acidification-driven stress, an issue often intensified in estuaries exposed to heavy organic inputs that modify carbonate equilibrium. The relatively balanced pH levels correspond with descriptions by Handayani et al. (2001) regarding the role of pH as a fundamental indicator of aquatic well-being.

The organic carbon content of sediments revealed noticeable discrepancies among stations, with the highest concentration recorded at Station 4 where sandy-clay textures prevailed. This outcome matches observations by Fadhillah et al. (2021), who reported elevated TOC levels in fine-textured sediments due to their capacity to retain organic particulates. The relationship between sediment texture and organic accumulation is also supported by Tanjung et al. (2019), who demonstrated stronger organic enrichment in estuarine areas receiving high deposition rates of suspended material. These findings align with classifications introduced by Barus et al. (2020), placing several stations within medium to very high organic categories that contribute to benthic habitat potential.

Organic enrichment in estuarine sediments plays a vital role in sustaining benthic communities, as described by Bai'un et al. (2021) in mangrove-associated habitats where organic inputs bolster microhabitat suitability. Stations characterized by intermediate to high organic matter may favor deposit-feeding invertebrates capable of exploiting nutrient-rich sediments. This ecological benefit, however, must be balanced with the risk of organic overloading, which may alter oxygen diffusion and sediment chemistry when accompanied by excessive anthropogenic discharge. ANZECC and ARMCANZ (2000) emphasize that organic content combined with sediment grain size serves as a diagnostic factor for evaluating contaminant retention potential in transitional ecosystems.

The overall patterns observed in temperature, salinity, oxygenation, pH, and sediment organic content illustrate a dynamic estuarine system influenced by hydrodynamic processes, sediment characteristics, and external environmental inputs. Variability among stations reflects the diverse ecological niches shaped by tidal movements, freshwater inflow, and textural changes in sediment deposits as recognized in estuarine ecological literature such as Fynnisa et al. (2024). The interplay of these abiotic parameters forms the basis for understanding spatial heterogeneity that governs organism distribution and ecosystem functioning. Such insights support ongoing assessments of environmental condition, providing foundational evidence for coastal resource management strategies advocated by Ekamaida (2017) and Emersida (2021) in coastal Aceh.

Salinity Dynamics, Dissolved Oxygen Variations, and pH Stability Across Estuarine Stations

Salinity values across the estuary displayed a strong gradient that reflected the balance between freshwater discharge and marine intrusion, creating spatial patterns typical of transitional coastal ecosystems influenced by tidal exchange as noted by Odum (1993) and widely observed in estuarine literature. The distribution from 15 to 30 ppt aligned with the ecological requirements of benthic organisms documented by Nugroho et al. (2017), where the interplay of tidal cycles and watershed inflows determines the degree of stratification and mixing. Stations located closer to the riverine influence exhibited diluted conditions, while stations receiving greater exposure to seawater displayed elevated salinity levels that suggest persistent tidal penetration. Such gradients represent an important ecological axis because they structure species composition, regulate nutrient solubility, and guide habitat suitability as observed in various tropical estuaries reported by Simanjuntak and Rahardjo (2019).

The observed salinity range indicates a stable mixing regime where the relative contribution of marine waters is higher during low-fluvial periods, consistent with conditions described by Wisha et al. (2016) in the Segara Anakan estuary. This pattern demonstrates how geomorphology, tidal amplitude, and seasonal flow collectively influence estuarine hydrodynamics by altering transport pathways and segregation zones. The values at stations near the inlet, which reached up to 30 ppt, highlight the dominance of oceanic signatures that are often associated with reduced terrigenous sedimentation and stronger current flushing. Such characteristics create ecological compartments within the estuary that affect physiological performance of benthic fauna, as indicated by Purba et al. (2025) and reinforced by benthic distribution principles presented by Wijayanti (2007).

Lower salinity recorded at Station 3, reaching 15 ppt, signifies freshwater-driven dilution zones where catchment inflows may rise due to rainfall variability or upstream retention releases, aligning with descriptions provided by Handayani et al. (2001). These zones often promote stratification during neap tides, resulting in layered water masses with distinct chemical properties that influence nutrient regeneration rates and particle sedimentation. Such conditions increase turbidity and enhance fine sediment deposition that may accumulate organic matter as suggested by Fadhillah et al. (2021). This backdrop simultaneously shapes habitat complexity and modifies the spatial distribution of macrozoobenthos, consistent with the ecological role of salinity emphasized by Bai'un et al. (2021).

Dissolved oxygen (DO) levels ranging from 6.4 to 7.7 mg/L illustrate a well-oxygenated environment that supports healthy metabolic functioning of estuarine biota, aligning with early interpretations presented by Salmin (2005). Values surpassing the minimum threshold for aquatic life indicate strong reaeration and limited organic loading, features commonly associated with tidal renewal documented by Susiana (2015). Stations with slightly higher DO such as Station 2 may benefit from enhanced mixing and potentially elevated primary productivity, which contribute to oxygen replenishment through photosynthetic pathways as proposed by Hartati et al. (2019). These oxygen conditions signify a system that has not experienced depletion episodes typically linked to excessive nutrient enrichment or stagnant hydrodynamics.

Variations in DO were also influenced by temperature regimes, where warmer waters near Stations 1 and 5 may slightly reduce solubility yet remain within the ecological tolerance range described by Padang et al. (2024). Such thermal–oxygen interactions are central to estuarine physiology because they control aerobic respiration and determine stress responses among sensitive taxa, especially benthic organisms confined to substrate–water interfaces. Conditions recorded in this study resemble those of the Donan estuary reported by Rahmawati et al. (2018), where DO values remained stable due to tidal oscillation that prevents stagnation in shallow basins. This interplay between hydrodynamics and oxygen concentration reinforces the concept that estuaries with continuous seawater exchange maintain greater ecological resilience.

Comparisons with results documented by Yustina et al. (2014) reveal that DO values in Lhokseumawe are substantially higher than those in anthropogenically stressed systems, providing early indication that organic inputs may be moderate rather than excessive. The elevated oxygen levels also reflect the limited presence of decomposable pollutants, suggesting that the assimilation capacity of the estuary remains adequate to maintain bio-stability in the water column. Stations with consistent DO near 6.5 mg/L demonstrate how moderate biological demand is balanced by strong aeration and microbial turnover processes that prevent oxygen sag. Such equilibrium mirrors patterns observed in mangrove-associated estuaries, where vegetation enhances DO through canopy-driven microclimate regulation as described by Purba et al. (2025).

The pH values ranging from 7.3 to 7.9 represent a neutral–alkaline spectrum consistent with well-buffered systems dominated by carbonate-rich seawater contributions, consistent with observations from Wicaksono et al. (2020). This range promotes favorable physiological processes for benthic invertebrates and finfish since extreme acidity or alkalinity can impede enzymatic reactions crucial for survival and growth. Stability across all stations suggests that freshwater inflows did not carry excessive acidifying agents such as high dissolved organic carbon or anthropogenic effluents capable of lowering pH, as has been observed in more degraded waters by Yustina et al. (2014). Conditions of this nature typify estuaries with balanced alkalinity dynamics, especially where marine intrusion governs chemical buffering.

The continuing presence of pH values above 7.2 also indicates that the decomposition of organic matter within the sediment has not reached rates capable of lowering pH significantly, as noted in the sediment–water interaction processes discussed by Barus et al. (2010). Where acidic conditions occur in estuaries, they are typically linked to anaerobic mineralization or sulfide oxidation, neither of which appears dominant in the assessed stations. Instead, the pH stability aligns with the moderate organic concentrations in sediments reported in Tanjung et al. (2019), which prevent acidification shocks in bottom waters. Such chemical consistency also supports the maintenance of ionic equilibrium crucial for osmoregulation, a critical factor in estuarine transitions described by Fynnisa et al. (2024).

Comparison with national regulations as detailed in PP No. 22/2021 indicates that the observed pH range falls safely within acceptable ecological boundaries for estuarine waters. Compliance with such standards reinforces the interpretation that anthropogenic disturbances have not yet exerted significant acid–base alterations that could compromise habitat suitability. Ecological assessments based on ANZECC & ARMCANZ (2000) further highlight that pH stability is a key indicator of early system health because it reflects the buffering capacity of the estuary against fluctuations driven by organic loading and hydrological change. These aligned insights strengthen the conclusion that the chemical balance of the estuary remains functional under natural variability.

The combined interpretation of salinity, DO, and pH underscores the intricate interactions controlling estuarine water quality across spatial gradients shaped by tidal influences, substrate composition, and the strength of freshwater input. Such synergy guides the distribution of benthic organisms whose adaptive thresholds depend on hydrodynamic stability and physico-chemical predictability as illustrated by Bai'un et al. (2021). Patterns documented across the stations depict an estuary that retains ecological functionality, exhibiting environmental signatures similar to tropical estuaries with moderate anthropogenic pressure described by Susiana (2015). These findings contribute essential environmental baselines that serve as comparative references for longer-term monitoring and estuarine resource management strategies.

CONCLUSION

The overall patterns of temperature, salinity, dissolved oxygen, pH, and sedimentary organic content across the Krueng Cunda estuary demonstrate a hydrodynamically active and ecologically functional system where tidal exchange, freshwater discharge, and sediment heterogeneity jointly shape spatial variability in water quality. The alignment of measured parameters with previously documented tropical estuarine conditions suggests that the system remains within ecologically tolerable thresholds for most benthic and pelagic organisms, although elevated temperatures at several stations indicate emerging thermal stress that may influence future community structure if intensified. The consistency of DO and pH levels, coupled with moderate to high organic matter in fine-textured sediments, further signifies an estuary with stable biogeochemical processes capable of supporting diverse habitats, while simultaneously underscoring the need for adaptive monitoring as anthropogenic pressures and climatedriven fluctuations continue to evolve. Collectively, these insights provide a robust scientific basis for ongoing environmental assessment and offer essential reference points for coastal management strategies aimed at preserving the ecological resilience of the Lhokseumawe estuarine region.

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