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Original Research Article

Spatiotemporal Variation in Tropical Coastal Water Quality Driven by Shrimp Pond Effluents in Lombok and Sumbawa Islands, Indonesia

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Abstract

This study assessed spatiotemporal variability in coastal water quality associated with shrimp pond effluent discharge at four impacted sites and one reference site across Lombok and Sumbawa Islands, Indonesia, during wet and dry seasons from 2022 to 2024. Physicochemical conditions generally remained within acceptable ranges for marine biota; however, nutrient concentrations consistently exceeded national water quality standards, with phosphate reaching 3.089 mg L^{-1}, ammonia up to 2.202 mg L^{-1}, and NOx up to 1.848 mg L^{-1}. Chlorophyll-a (0.297–8.900 µg L^{-1}) indicated elevated phytoplankton biomass at impacted sites. Dry-season concentrations were substantially higher than wet-season values, consistent with reduced dilution under low-rainfall conditions, though physical mechanisms were not directly measured. An integrated PCA–ANOVA approach confirmed season as the dominant driver of nutrient variability (partial η^2 = 0.835) and site as the primary control on physical conditions (partial η^2 = 0.757). Spatial differences in nutrient accumulation were consistent with site morphology and pond operational characteristics, though these associations remain inferential given the absence of direct hydrodynamic measurements and limited access to pond-level data. These findings suggest that effluent management should prioritize phosphorus reduction, apply seasonally differentiated discharge standards, and strengthen monitoring at sites with restricted water exchange or proximity to conservation areas.

Keywords: Coastal water quality; eutrophication; nutrients; chlorophyll-a; shrimp pond effluent

1. Introduction

The management of waste generated from shrimp aquaculture has become a critical issue in coastal environmental studies. Numerous studies have demonstrated that estuarine and nearshore ecosystems are among the most heavily impacted by shrimp pond effluents (Bull et al., 2021), while recent review articles have highlighted advances in aquaculture wastewater management strategies aimed at reducing environmental pressure (Iber and Kasan, 2021). The type of waste produced and its implications for environmental sustainability remain key concerns, as the discharge of aquaculture effluents into the water column has been shown to significantly alter the physicochemical properties of intertidal waters (Oke, 2004). The magnitude of these changes is largely governed by the characteristics of the discharged waste as well as the carrying capacity and assimilative capacity of the receiving waters, resulting in spatially variable impacts across different coastal systems (Defra, 2008). Within this context, effluents derived from shrimp farming activities are among the most extensively studied sources of coastal pollution (Prihanta et al., 2020).

Lombok and Sumbawa Islands, located in West Nusa Tenggara (NTB) Province, Indonesia, represent one of the most significant shrimp aquaculture regions in the country, with pond operations distributed across nearly all coastal districts of Lombok and along the northern and western coasts of Sumbawa (DKP NTB, 2019). Together, these two islands encompass a diverse range of coastal morphologies from strait-facing open coastlines with strong tidal currents (e.g., the Lombok Strait, one of the primary pathways of the Indonesian Throughflow) to semi-enclosed bays and conservation-adjacent waters making them an ecologically and geographically representative system for investigating how aquaculture-derived nutrient inputs interact with contrasting coastal environments. Despite the scale of aquaculture activity and the ecological sensitivity of adjacent habitats, including coral reefs, mangroves, seagrass beds, and designated marine conservation areas, the water quality of intertidal zones receiving shrimp pond effluents in this region remains poorly characterized in the international scientific literature. Field observations indicate that organic waste from shrimp ponds is commonly discharged directly into intertidal waters through rivers or outlet channels without prior treatment (Islam et al., 2004), with the potential to disrupt the ecological balance of adjacent ecosystems (Prihanta et al., 2020; Jefri et al., 2025) through increased nutrient loading and organic matter inputs (Bui et al., 2012; de lacerda et al., 2021).

The physical and hydrodynamic characteristics of intertidal waters in Lombok and Sumbawa exhibit considerable spatial variability. Rocky intertidal zones generally possess more stable substrates and relatively higher current velocities, whereas sandy or muddy intertidal areas tend to accumulate greater amounts of sediment and experience more pronounced fluctuations in dissolved oxygen and nutrient concentrations (Susanto et al., 2021; Malik et al., 2023; Ghatpande, 2025). In addition, intertidal systems located within embayments typically exhibit limited water exchange, facilitating waste accumulation, in contrast to strait-associated intertidal zones that are characterized by strong currents and intensive water mass mixing (Bull et al., 2021). Consequently, intertidal areas within straits generally exhibit higher dilution capacities than those in bays or around small conservation islands where weak circulation and restricted hydrodynamics prevail (de Lacerda et al., 2021). Despite the recognized importance of these hydrodynamic contrasts, a specific research gap remains: it is not yet understood how the transition from open, current-driven coastal systems to semi-enclosed, low-flushing bay environments modulates the spatial extent, magnitude, and seasonal dynamics of aquaculture-derived nutrient enrichment in tropical intertidal zones. Without addressing this gap, it is not possible to develop differentiated, site-specific management strategies for coastal aquaculture in morphologically diverse regions.

The majority of shrimp pond waste originates from uneaten feed and metabolic by-products of cultured organisms (Djumanto et al., 2018). Metabolic wastes, including feces and excreta, result from the decomposition of organic feed materials, with protein content constituting a major contributor to the pollution load (Charlton et al., 2015). Shrimp pond effluents may occur in particulate form, containing

phosphorus, nitrogen, and organic carbon, as well as in dissolved form enriched with inorganic compounds such as ammonia (NH_3-N), nitrite (NO_2-N), nitrate (NO_3-N), and phosphate (PO_4^{3-}) (Verbyla et al., 2017; Sabilu et al., 2021). When discharged continuously without adequate management, pollution levels may exceed the environmental carrying capacity of receiving waters (Emeh and Igwe, 2018), ultimately exerting adverse effects on aquatic organisms, including intertidal biota (Voulvoulis and Burgman, 2019).

Previous studies have demonstrated that waste contamination can alter intertidal community structure, affecting both species composition and abundance (Murugesan et al., 2009; Jefri et al., 2025). Several investigations have also examined water quality conditions surrounding shrimp farming areas in Indonesia, including analyses of physicochemical parameters along the northern coast of Java (Mustofa and Mulyo, 2020), spatiotemporal assessments in intensive shrimp farming systems in Bulukumba, South Sulawesi (Mustafa et al., 2022), and pollution assessments in East Lombok (Aini and Parmi, 2022). However, these studies share important limitations: they are geographically restricted to single sites or administrative units, focus primarily on parameter compliance without examining the physical controls on nutrient distribution, and do not integrate pond-level attributes such as operational age and pond area as explanatory variables. Crucially, none of these studies explicitly examined how contrasting coastal hydrodynamic settings from high-energy strait environments to low-energy semi-enclosed bays mediate the spatial and seasonal patterns of effluent-driven nutrient enrichment. As a result, the interaction between anthropogenic nutrient inputs and coastal hydrodynamic processes in regulating nutrient retention and dilution remains poorly resolved in tropical intertidal systems, particularly across the geographically diverse coastal landscapes of eastern Indonesia.

Despite extensive research on shrimp pond effluents globally, most studies remain geographically localized and rarely integrate spatiotemporal variability with its key physical and operational controlling factors within a single comparative framework. Three specific knowledge gaps motivate the present study. First, the influence of coastal hydrodynamic regime particularly the contrast between open, strait-connected systems and semi-enclosed, low-circulation bays on nutrient enrichment patterns in tropical intertidal zones has not been systematically examined. Second, the role of pond-level characteristics, specifically operational age and pond area, in shaping the composition and magnitude of effluent nutrient loads across different receiving environments is not well understood. Third, no prior study has simultaneously assessed these interactions across multiple sites spanning two adjacent islands with distinct biogeographic and hydrodynamic contexts in Indonesia. This study addresses these gaps by adopting a multi-site, multi-season design across Lombok and Sumbawa Islands, which together provide a natural gradient of coastal morphologies and aquaculture intensities that is not available within any single island or administrative region. The approach enables a more integrated and geographically transferable understanding of how anthropogenic inputs interact with physical processes to shape coastal water quality dynamics in tropical intertidal environments.

Therefore, this study examines the spatiotemporal variability of coastal water quality influenced by shrimp pond effluents across Lombok and Sumbawa Islands, Indonesia, by simultaneously incorporating pond characteristics (operational age and area) and contrasting coastal morphologies within a single comparative framework. The novelty of this study lies in three aspects: (i) it is the first to integrate multi-site water quality monitoring across Lombok and Sumbawa within a unified analytical framework, capturing a spectrum of coastal hydrodynamic conditions not available within any single study area; (ii) it explicitly links pond-level attributes (age and area) with observed water quality patterns across sites, an approach largely absent from previous Indonesian aquaculture studies; and (iii) it applies multivariate analysis to simultaneously resolve the contributions of seasonal forcing and site-specific hydrodynamic characteristics to nutrient variability, providing a more mechanistically informed basis for management recommendations than single-site or single-season investigations. Specifically, this study aims to (1) quantify spatial and seasonal variability in physicochemical parameters across impacted and reference sites, (2) identify dominant drivers of water quality variability using principal component

analysis, and (3) evaluate the role of coastal morphology and associated hydrodynamic conditions in regulating nutrient accumulation and ecosystem responses. Collectively, these objectives provide a more integrated basis for understanding coastal water quality dynamics and informing site-specific aquaculture management in tropical island environments.

2. Methods

2.1 Study Areas and Time

The study was conducted from 2022 to 2024, with water quality sampling carried out during the wet season (December–April) and the dry season (May–September) within the intertidal zone. Sampling was performed at four shrimp pond effluent discharge sites across Lombok and Sumbawa Islands, Indonesia: (1) Kayangan (KYN), North Lombok; (2) Sambelia (SBL), East Lombok; (3) Pemongkong (PMK), East Lombok; and (4) Poto Tano (PTN), West Sumbawa. In addition, one reference site, Sekotong (SKT) in West Lombok, was included to represent near-background intertidal conditions. SKT was selected because the site contains no shrimp aquaculture operations or other intensive mariculture facilities, is situated away from dense residential settlements, and is not subject to regular anthropogenic activities including commercial fishing, agricultural runoff, or tourism infrastructure that would constitute significant nutrient point or diffuse sources. These conditions collectively minimize the probability of effluent-driven or land-use-driven nutrient enrichment, making SKT a suitable relative reference for comparing water quality conditions at effluent-impacted sites (Figure 1). The reference site was sampled once during the study period. The selected sites represent contrasting hydrodynamic regimes, including open coastal systems with strong water exchange and semi-enclosed systems with restricted circulation (Table 1).

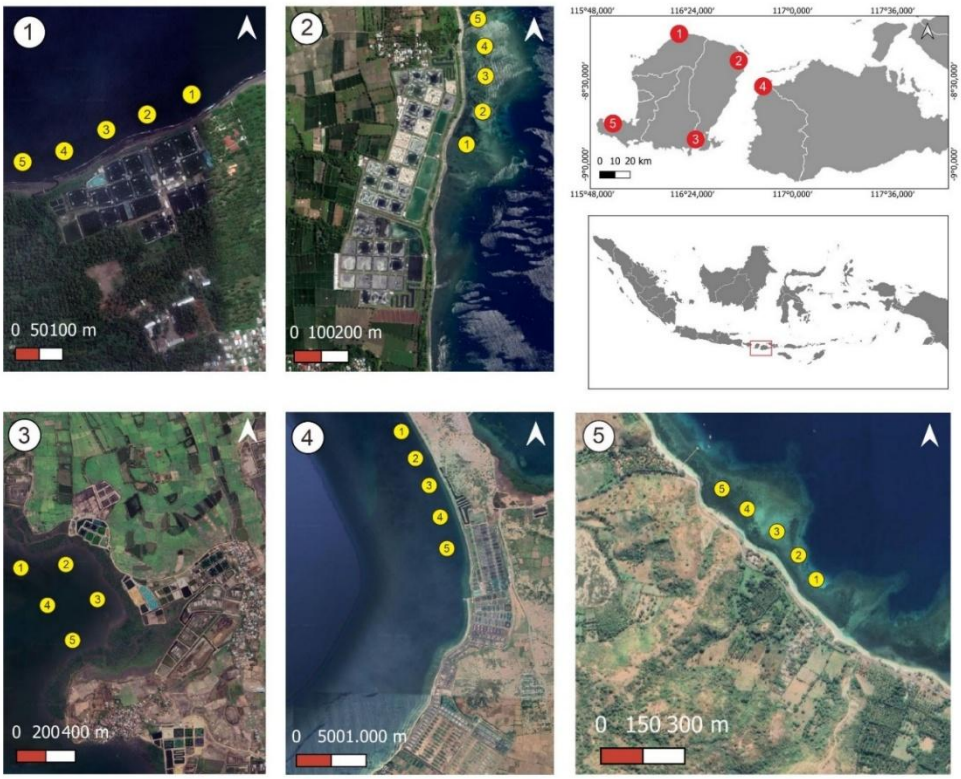


Figure 1. Study area and sampling locations in Lombok and Sumbawa Islands, Indonesia

2.2 Description of Research Location

Table 1. Coordinates and description of the sampling station

Station	Location	Coordinates	Site description
1	Kayangan, North Lombok (KYN)	8°13'15.93" S, 116°19'15.12" E 8°13'17.41" S, 116°19'12.09" E 8°13'18.54" S, 116°19'7.96" E 8°13'20.86" S, 116°19'5.37" E 8°13'22.04" S, 116°19'2.78" E	The sampling site is located along the North Lombok coast, directly facing the Lombok Strait within the Indonesian Throughflow (ITF) pathway. Shrimp ponds have been operating for <10 years.
2	Sambelia, East Lombok (SBL)	8°22'18.46" S, 116°43'30.50" E 8°22'13.99" S, 116°43'31.70" E 8°22'9.54" S, 116°43'31.62" E 8°22'4.11" S, 116°43'31.30" E 8°21'58.65" S, 116°43'30.69" E	The site is situated along a coastal area facing small islands within a Regional Marine Conservation Area and supports pearl oyster farming. Shrimp ponds have been operating for <10 years.
3	Pemongkong, East Lombok (PMK)	8°49'30.62" S, 116°28'12.32" E 8°49'27.77" S, 116°28'0.90" E 8°49'33.50" S, 116°28'4.00" E 8°49'41.06" S, 116°28'8.76" E 8°49'28.28" S, 116°27'45.49" E	This site is located in a semi-enclosed bay (Awang Bay), where effluent outlets face mangrove ecosystems, with surrounding waters used for lobster cage culture and seaweed farming. Shrimp ponds have been operating for <10 years.
4	Poto Tano, West Sumbawa (PTN)	8°31'54.28" S, 116°49'38.06" E 8°32'1.80" S, 116°49'42.10" E 8°32'9.55" S, 116°49'45.66" E 8°32'19.41" S, 116°49'51.08" E 8°32'25.72" S, 116°49'51.98" E	The site is located in front of long-established shrimp ponds (>25 years) covering >250 ha, with Belang and Pasaran Islands situated offshore of the effluent discharge area.
5	Sekotong, West Lombok (SKT)	8°44'13.00" S, 115°59'45.44" E 8°44'10.64" S, 115°59'43.58" E 8°44'7.47" S, 115°59'39.56" E 8°44'6.11" S, 115°59'38.64" E 8°44'2.67" S, 115°59'35.28" E	This site serves as a control location, with no direct influence from shrimp aquaculture, minimal human disturbance, and is primarily used for tourism.

**These sites represent a gradient of hydrodynamic conditions and aquaculture intensity, enabling comparative analysis of effluent impacts.*

2.3 Data Types and Sources

The data collected in this study consisted of primary data obtained through field surveys. Water samples were collected from the water column in front of shrimp pond effluent outlets during low tide conditions (Cereja et al., 2022). A detailed description of the measured parameters and data requirements is provided in Table 2. Hydrodynamic parameters including current velocity, water residence time, tidal flushing rate, and tidal prism volume were not included in the primary data collection, as their direct quantification would have required concurrent deployment of acoustic Doppler current profilers (ADCPs) or electromagnetic current meters at all five sites across multiple tidal cycles and seasons. This was not feasible given the logistical and resource constraints of a multi-site study spanning two islands, and is acknowledged as a recognized limitation of this investigation.

Table 2. Data collected in the study along with seawater quality standards for marine biota

No.	Physicochemical parameters	Unit	Methods	Water quality standard*
1	Temperature	°C	In situ, multiparameter probe (WTW)	Coral reefs: 28–30 °C; Mangroves: 28–32 °C; Seagrass: 28–30 °C
2	Salinity	ppt	In situ, multiparameter probe (WTW)	Coral reefs: 33–34 ppt; Mangroves: ≤34 ppt; Seagrass: 33–34 ppt

No.	Physicochemical parameters	Unit	Methods	Water quality standard*
3	Total Dissolved Solids (TDS)	mg L^{-1}	In situ, multiparameter probe (WTW)	25–40 mg L^{-1}
4	Dissolved Oxygen (DO)	mg L^{-1}	In situ, multiparameter probe (WTW)	≥5–6 mg L^{-1} or ≥80–90% saturation
5	pH	N/A	In situ, multiparameter probe (WTW)	7.0–8.5; natural variation ≤0.2 units
6	Total Suspended Solids (TSS)	mg L^{-1}	Gravimetric method	Coral reefs: ≤20 mg L^{-1} (<10% seasonal variation); Mangroves: ≤80 mg L^{-1}; Seagrass: ≤20 mg L^{-1}
7	Ammonia (NH_3–N)	mg L^{-1}	Spectrophotometry	≤0.3 mg L^{-1}
8	NOx (NO_2^- + NO_3^-)	mg L^{-1}	Spectrophotometry	NO_2^- ≤0.06 mg L^{-1}; NO_3^- ≤0.008 mg L^{-1}
9	Phosphate	mg L^{-1}	Spectrophotometry	≤0.015 mg L^{-1}
10	Chlorophyll-a	µg L^{-1}	90% acetone extraction, spectrophotometry	Oligotrophic: <2 µg L^{-1}; Mesotrophic: 2–5 µg L^{-1}; Eutrophic: >5 µg L^{-1}

** Ministerial Decree of the Ministry of Environment No. 51 of 2004*

2.4 Data Collection Techniques

A total of two sampling campaigns were conducted across the study period between 2022 and 2024: one campaign during the wet season (December–April) and one campaign during the dry season (May–September). Each campaign involved a single visit to each of the five sites, yielding two seasonal data points per site (wet and dry), with the exception of the reference site (SKT), which was sampled once. This seasonal sampling design was adopted because inter-seasonal variation is known to be the dominant temporal driver of nutrient dynamics in tropical intertidal systems (Pello et al., 2014), and a single well-timed campaign per season is considered sufficient to characterize the contrasting hydrological conditions between the wet and dry periods. All measured and analyzed water quality variables followed the national marine water quality standards stipulated by the Ministerial Decree of the Ministry of Environment of the Republic of Indonesia No. 51 of 2004. Water samples were collected from the near bottom water column during low tide conditions between 08:30 and 12:00 Central Indonesia Time. Water samples were collected in triplicate at each station to ensure data reliability. Samples for laboratory analysis were stored in acid-washed polyethylene bottles and preserved in a cooled container at approximately 4°C prior to analysis.

In situ measurements included temperature (°C), salinity (ppt), pH, total dissolved solids (TDS; mg L^{-1}), and dissolved oxygen (DO; mg L^{-1}), which were recorded using a calibrated portable multiparameter water quality meter (WTW™ MultiLine™ 3310, Xylem Analytics, Germany). Additional water quality parameters, including ammonia (NH_3–N), NOx, and phosphate (PO_4^{3-}), were analyzed following manufacturer-standard colorimetric methods (WTW photoLab® 7100 VIS), which are consistent with APHA standard procedures (Federation, 2012), Total suspended solids (TSS) and chlorophyll-a were analyzed at the Sekotong Marine Aquaculture Fisheries Laboratory, Lombok. TSS was determined using the gravimetric method through filtration with glass fiber filters (GF/C), followed by oven drying and weighing with an analytical balance. Chlorophyll-a was quantified using the 90% acetone extraction method and measured spectrophotometrically (Parsons et al., 1984).

2.5 Data Analysis

Marine water quality parameters were analyzed using descriptive statistics to characterize physicochemical variability across all sampling stations (Bull et al., 2021). Spatial distribution patterns were visualized using contour interpolation generated in Surfer (version 29), with base maps derived from Google Satellite imagery and processed using QGIS (version 3.44.7).

Statistical analysis was conducted in two sequential stages. In the first stage, principal component analysis (PCA) was applied to identify the dominant physicochemical variables controlling water quality variability and to reduce multivariate data redundancy. The ten measured parameters dissolved oxygen (DO), pH, total dissolved solids (TDS), temperature, salinity, phosphate, ammonia, NOx, chlorophyll-a, and total suspended solids (TSS) were standardized prior to PCA using z-score transformation to remove the effect of differences in measurement units and scales (Bui et al., 2012). PCA was performed using XLSTAT by Addinsoft (version 2019.2.2). Principal components (PCs) with eigenvalues greater than 1.0 were retained following the Kaiser criterion, and variable loadings were used to interpret the contribution of each parameter to the resulting environmental gradients. In the second stage, PC factor scores for the two retained principal components were used as dependent variables in separate two-way analyses of variance (two-way ANOVA), with site (SBL, PMK, KYN, PTN) and season (wet, dry) as fixed factors. The ANOVA model included the main effects of site, season, and their interaction (site × season). Prior to ANOVA, the normality of model residuals was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene's test. Statistical significance was determined at $\alpha = 0.05$. The practical magnitude of each factor's effect was quantified using partial eta-squared (partial η^2), and overall model fit was assessed using R^2 and adjusted R^2. This integrated PCA–ANOVA approach enables pattern identification in multivariate water quality data while providing inferential tests of the statistical significance of spatial and seasonal differences among sites.

3. Result and Discussion

3.1 Physicochemical Parameters

Shrimp pond effluents can influence the physicochemical properties of tropical intertidal waters through inputs of organic matter and dissolved constituents (Yang et al., 2017; de lacerda et al., 2021). Across all sites, dissolved oxygen (DO) ranged from 6.96 to 15.71 mg L^{-1}, consistently exceeding the ecological threshold (>5 mg L^{-1}), indicating well-oxygenated conditions (Table 3). Higher DO values were generally observed during the wet season, while lower values occurred during the dry season, suggesting seasonal modulation linked to physical mixing and biological processes (Bull et al., 2021; Mustafa et al., 2022). Seawater pH remained within 7.45–8.91, with most values clustering around 7.9–8.2, indicating relatively stable carbonate conditions, although localized variation may reflect site-specific biogeochemical processes (Iber and Kasan, 2021).

Total dissolved solids (TDS), temperature, and salinity exhibited consistent seasonal patterns. TDS ranged from 45.5 to 52.2 mg L^{-1}, with higher values during the dry season and lower values during the wet season, reflecting the balance between evaporation and freshwater dilution (Cloern et al., 2014; Herbert et al., 2015; Chen et al., 2025). Temperature remained within a narrow tropical range (27.6–32.2 °C), while salinity varied between 29.8 and 34.7 ppt, with lower values during the wet season and higher values during the dry season. Spatial differences further indicate that semi-enclosed systems (e.g., PMK) exhibited greater variability in salinity and TDS compared to more open coastal sites (e.g., KYN and PTN), consistent with differences in water exchange and hydrodynamic conditions (Cerralbo et al., 2019; Senathirajah and Pattiaratchi, 2025).

Table 3. Physicochemical water quality parameters at intertidal sites influenced by shrimp farming effluents

Location	Season	Station	Parameters					
			DO (mg L^{-1})	pH	TDS (mg L^{-1})	Temp. (°C)	Salinity (ppt)	Seawater quality standards*
SBL	Dry	1	8.14	8.13	49.3	29.8	32.5	DO; >5 mg L^{-1}
		2	8.57	8.42	49.5	29.8	32.6	pH; 7.0–8.5
		3	8.10	7.86	45.7	29.9	29.8	TDS; 80 mg L^{-1}
		4	8.10	8.91	49.1	30.4	32.3	Temperature; natural
		5	7.68	8.16	46.4	30.0	30.4	Salinity; 33–34 ppt
	Wet	1	10.44	8.12	46.2	30.1	30.2	
		2	15.34	8.15	46.9	29.4	30.7	
		3	7.46	8.16	47.8	28.8	31.3	
		4	15.71	8.16	48.1	28.7	31.5	
		5	11.79	8.12	48.0	28.4	31.5	
PMK	Dry	1	8.78	8.03	52.2	31.2	34.7	
		2	8.68	8.07	51.9	31.1	34.3	
		3	8.11	8.04	51.9	30.6	34.4	
		4	9.21	8.10	51.9	31.1	34.4	
		5	8.55	8.09	51.9	30.1	34.3	
	Wet	1	6.96	7.95	46.5	30.9	30.4	
		2	7.14	7.91	45.5	31.2	29.8	
		3	7.60	8.06	46.8	30.8	30.7	
		4	7.64	8.04	46.8	31.1	30.7	
		5	7.39	8.08	46.9	30.5	30.6	
KYN	Dry	1	7.47	8.10	46.5	29.1	30.3	
		2	8.06	8.13	46.6	29.9	30.5	
		3	7.74	8.11	46.7	29.8	30.5	
		4	7.64	8.12	47.0	29.7	30.7	
		5	7.58	8.11	46.7	29.7	30.5	
	Wet	1	8.60	8.15	49.3	28.0	32.2	
		2	8.74	8.15	49.3	27.6	32.4	
		3	8.58	8.16	49.4	28.3	32.2	
		4	8.96	8.16	49.3	28.2	32.2	
		5	8.50	8.14	49.2	28.1	32.2	
PTN	Dry	1	7.52	8.15	48.7	28.1	32.0	
		2	7.85	8.15	48.7	28.4	32.0	
		3	8.03	8.15	48.7	28.4	32.0	
		4	8.56	8.17	48.7	28.6	31.9	
		5	8.86	8.23	48.7	29.2	31.7	
	Wet	1	9.24	8.10	49.2	31.2	32.4	
		2	8.50	8.06	48.9	29.9	32.2	
		3	8.24	8.11	47.1	30.9	31.1	
		4	9.75	8.07	49.4	29.6	32.5	
		5	8.80	8.08	49.2	29.3	32.4	
SKT	Control	1	10.08	7.45	46.4	32.2	31.9	
		2	11.13	7.96	46.6	30.4	33.8	
		3	15.18	8.18	46.5	31.0	32.7	
		4	12.21	8.13	46.6	31.1	32.6	
		5	11.69	8.23	46.6	31.1	32.6	

** Ministerial Decree of the Ministry of Environment No. 51 of 2004*

Overall, although all physicochemical parameters remained within acceptable ranges for marine ecosystems, the observed spatiotemporal variability is consistent with the influence of seasonal forcing and site-specific coastal morphology on water quality dynamics (Voulvoulis and Burgman, 2019; De Lacerda et al., 2021). The greater salinity and TDS variability at PMK compared to KYN and PTN is consistent with the reduced water exchange expected in a semi-enclosed bay setting, though this

inference is based on site morphology rather than direct hydrodynamic measurements, and should be interpreted with appropriate caution.

3.2 Nutrient Parameters

Spatial and seasonal variability in phosphate, ammonia, and NOx concentrations across intertidal waters receiving shrimp pond effluents indicates measurable nutrient inputs and associated variation in coastal water quality (Table 4). Across all impacted sites (SBL, PMK, KYN, and PTN), phosphate concentrations consistently exceeded the marine water quality standard for biota (<0.015 mg L^{-1}), with observed values ranging from 0.330 to 3.089 mg L^{-1}. The highest concentrations were recorded at PMK during the dry season (up to 3.089 mg L^{-1}) and at SBL (up to 2.951 mg L^{-1}), while comparatively lower values were observed during the wet season, although still above the threshold.

The spatial and seasonal pattern of phosphate accumulation reflects an interplay of source loading, hydrological dilution, and sediment biogeochemistry. At PMK, which recorded the highest dry-season phosphate (3.089 mg L^{-1}), three concurrent processes are mechanistically consistent with the observed concentrations: (i) reduced freshwater input during the dry season curtails dilution, effectively concentrating dissolved phosphorus discharged through pond outlet channels; (ii) elevated temperature and salinity both higher at PMK during the dry season (31.2°C, 34.7 ppt) promote desorption of sediment-bound phosphorus from organically enriched pond and intertidal sediments, releasing bioavailable orthophosphate into the overlying water column, a mechanism well documented in shallow tropical coastal systems receiving high organic matter inputs (Qiu et al., 2024); and (iii) the semi-enclosed morphology of Awang Bay restricts tidal export of dissolved phosphorus, extending residence time and allowing phosphate to accumulate to concentrations far exceeding those at open-coast sites. The wet-season reduction in phosphate at all impacted sites though still above threshold is consistent with freshwater dilution and increased tidal energy during the wet monsoon attenuating the nearshore concentration gradient (Bull et al., 2021). At SBL, the high dry-season phosphate (up to 2.951 mg L^{-1}) despite its more open coastal setting suggests that direct effluent loading from pond outlets is sufficient to sustain elevated concentrations even where dilution capacity is comparatively greater, indicating a high source flux relative to the assimilative capacity of the receiving waters. It should be noted that shrimp pond effluents may not be the sole phosphorus source at all sites: terrestrial runoff carrying fertilizer-derived phosphorus, internal loading from sediment remineralization, and contributions from adjacent aquaculture operations including pearl oyster farming at SBL and seaweed cultivation at PMK cannot be fully excluded. However, the substantially lower phosphate at SKT (0.172–0.343 mg L^{-1}) compared with all four impacted sites (0.330–3.089 mg L^{-1}) supports effluent discharge as the dominant driver, and the spatial co-occurrence of peak concentrations with active pond outlets is consistent with this inference. Formal source partitioning would require isotopic tracing or nutrient mass balance approaches beyond the scope of this study.

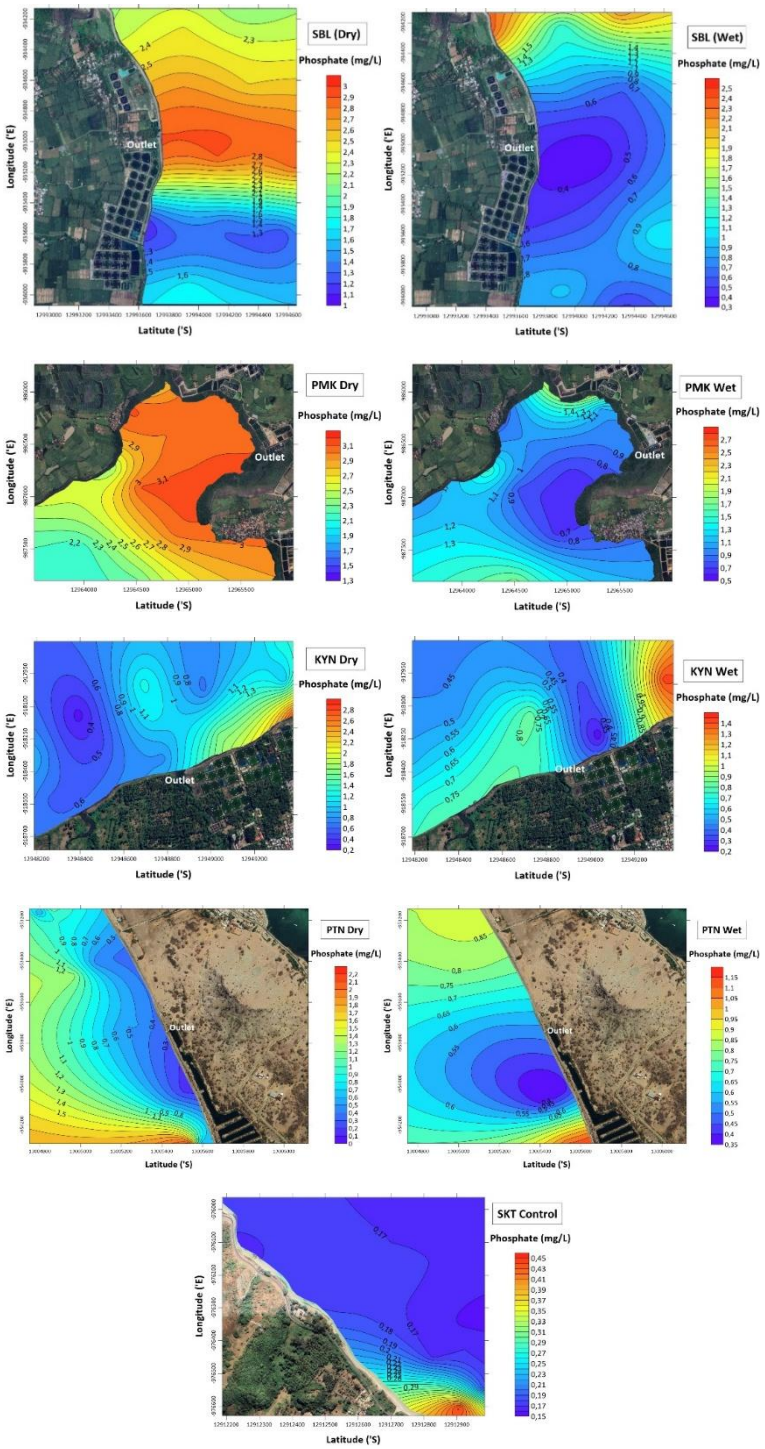


Figure 2. Spatial distribution of phosphate (PO_4^{3-}, mg L^{-1}) concentrations in intertidal waters influenced by shrimp pond effluent discharge at four coastal sites (left; dry season and right; wet season)

Ammonia (NH_3–N) concentrations exceeded the marine water quality guideline (≤0.3 mg L^{-1}) at several impacted sites, particularly during the dry season, with values ranging from 0.069 to 2.202 mg L^{-1}. The highest dry-season concentrations were recorded at PTN (2.202 mg L^{-1}) and SBL (2.142 mg L^{-1}), while wet-season concentrations at most stations were substantially lower (0.069–0.087 mg L^{-1}), consistent with a freshwater dilution effect. In shrimp aquaculture systems, dissolved ammonia in receiving waters is generally attributed to two pathways: direct excretion of ammonium (NH_4^+) by shrimp as a metabolic

end-product of protein catabolism (Charlton et al., 2015; Sabilu et al., 2021), and microbial ammonification of uneaten feed and fecal matter accumulating in pond sediments, through which heterotrophic bacteria remineralize organic nitrogen to inorganic ammonium that may reach the water column via diffusion or resuspension (Mustafa et al., 2022). The comparatively high ammonia at PTN relative to other sites is consistent with its pond characteristics an operational history exceeding 25 years and a total area exceeding 250 ha which are associated with greater cumulative organic matter deposition in pond sediments and a proportionally larger total effluent volume per discharge event compared with the younger, smaller complexes at the other sites. However, as direct measurements of pond water quality and effluent discharge were not obtained, this interpretation remains inferential. Additionally, the ecological significance of the observed ammonia concentrations may be modulated by pH and temperature, as higher values of both increase the proportion of the more toxic un-ionized form (NH_3); the dry-season conditions recorded at PTN (pH 8.15–8.23, temperature 28–29°C) suggest that un-ionized ammonia fractions may have been elevated relative to wet-season conditions, though formal calculation of NH_3 speciation was not performed in this study (Sabilu et al., 2021).

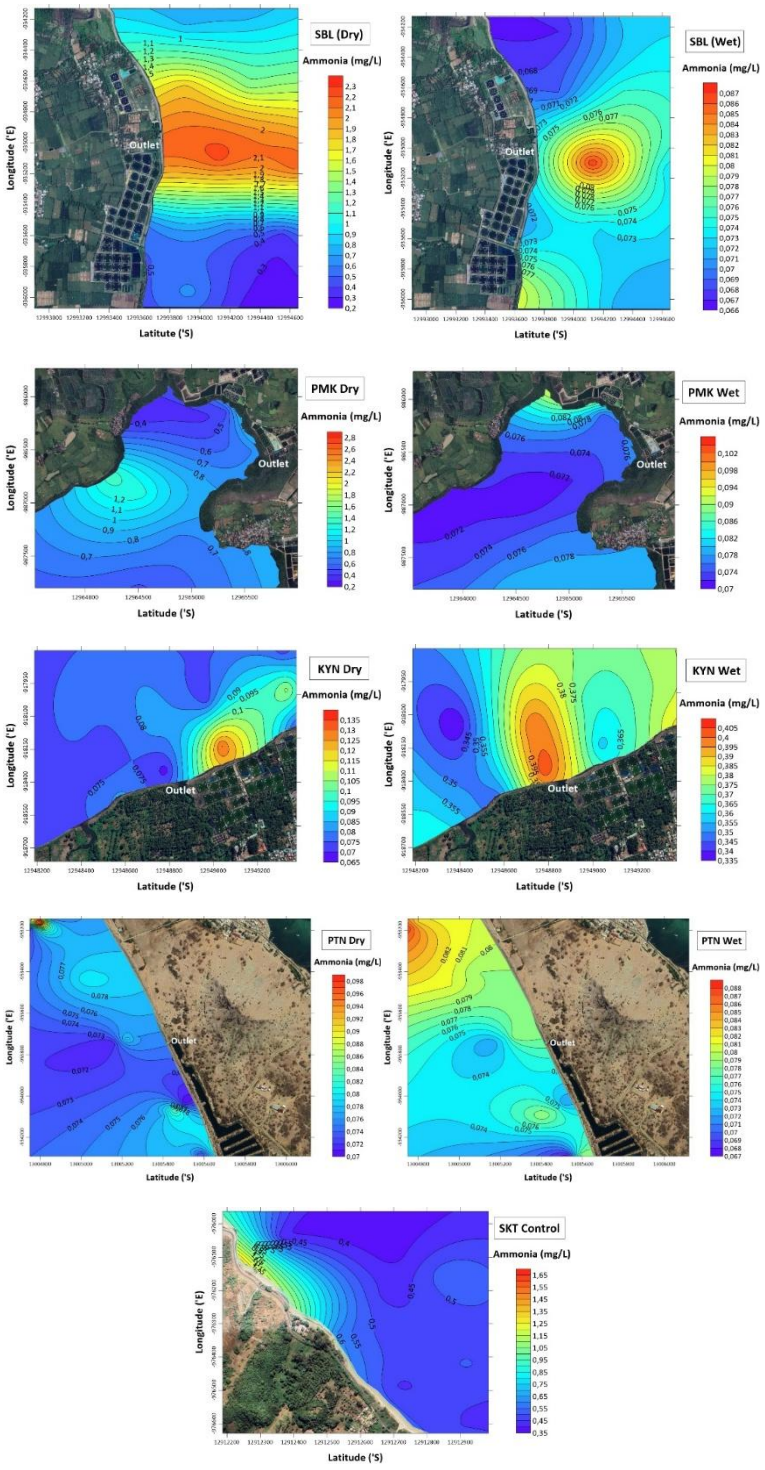


Figure 3. Spatial distribution of ammonia (NH_3–N, mg L^{-1}) concentrations in intertidal waters influenced by shrimp pond effluent discharge at four coastal sites (left; dry season and right; wet season)

Similarly, NOx (nitrate + nitrite) concentrations at all sites exceeded the marine water quality standard (<0.008 mg L^{-1}), with values ranging from 0.221 to 1.848 mg L^{-1}. Higher concentrations were generally observed during the dry season, particularly at SBL (up to 1.848 mg L^{-1}) and PTN (up to 1.396 mg L^{-1}), while wet-season values were comparatively lower but remained above the threshold (Figure 4). This pattern is consistent with ongoing nitrogen transformation processes, including nitrification of dissolved ammonia, under varying hydrological conditions (de Lacerda et al., 2021).

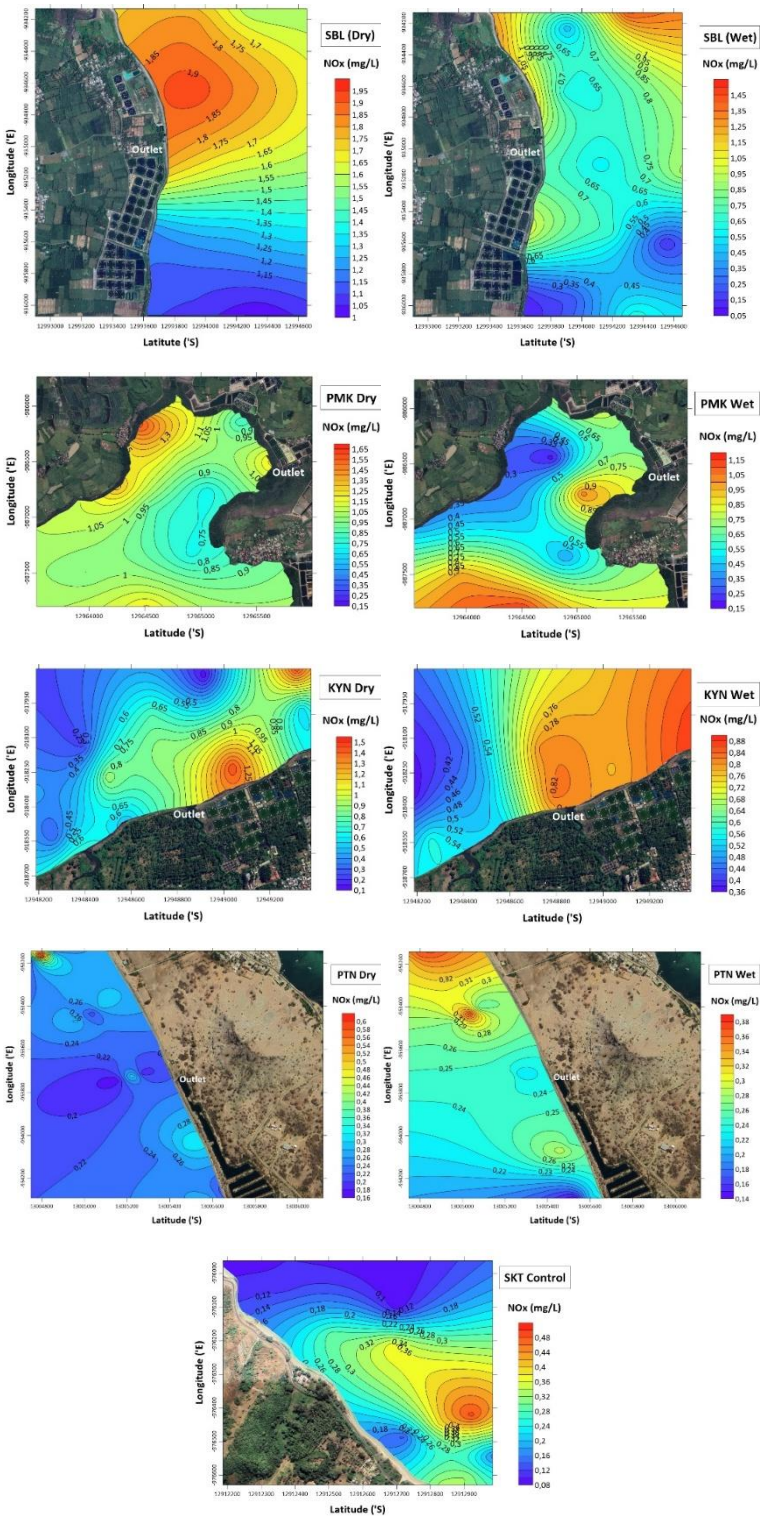


Figure 4. Spatial distribution of NOx (mg L^{-1}) concentrations in intertidal waters influenced by shrimp pond effluent discharge at four coastal sites (left; dry season and right; wet season)

Although sampling sites were selected based on proximity to shrimp pond effluent outlets, elevated nutrient concentrations cannot be attributed exclusively to aquaculture-derived inputs, as multiple pathways operate simultaneously in tropical coastal systems. Four supplementary sources warrant consideration: (i) terrestrial runoff from adjacent agricultural and peri-urban land mobilizes fertilizer residues and domestic wastewater during the wet season (Herbeck et al., 2021), consistent with

wet-season nutrient concentrations at KYN, SBL, and PTN that remain above threshold despite seasonal reduction; (ii) internal loading from organically enriched intertidal sediments, where microbial remineralization releases DIN and DRP into the water column via diffusion or resuspension, a process most active during the dry season when external dilution is lowest and sediment temperatures are highest (de Lacerda et al., 2021; Qiu et al., 2024); (iii) co-located aquaculture at specific sites, including pearl oyster farming at SBL and seaweed and lobster cage culture at PMK, which contribute organic waste through biodeposition and uneaten feed; and (iv) atmospheric deposition of reactive nitrogen as a background input affecting all sites (Zhao et al., 2021). An important limitation is that direct data from within the pond systems including pond water nutrient concentrations, effluent discharge volumes, and drainage schedules were not obtainable due to restricted access to several facilities, precluding a formal mass balance linking effluent characteristics to receiving water nutrient loads. The inference that shrimp pond effluents are the dominant enrichment driver therefore rests on three indirect lines of evidence: the spatial correspondence between peak concentrations and effluent outlet positions; substantially lower nutrient levels particularly phosphate at the effluent-free reference site (SKT); and a wet-season nutrient reduction pattern consistent with dilution of a continuous point source. These lines of evidence are indicative rather than conclusive; future studies incorporating stable isotope ratios ($\delta^{15}N$, $\delta^{18}O$-NO_3^-) or nutrient mass balance approaches would substantially strengthen this attribution. Overall, nutrient concentrations at all impacted sites consistently exceeded national marine water quality standards across both seasons. The persistence of elevated phosphate, ammonia, and NOx suggests conditions that may sustain chronic nutrient enrichment, with potential consequences for primary productivity and biogeochemical cycling in adjacent ecosystems (Akinnawo, 2023). The elevated ammonia at SKT (0.459–0.840 mg L^{-1}) despite the absence of shrimp pond influence is most likely attributable to organic matter mineralization in intertidal sediments a natural process common in tropical intertidal zones with macroalgal and seagrass detritus and minor diffuse inputs from low-intensity tourism. Critically, SKT phosphate (0.172–0.343 mg L^{-1}) was consistently and substantially lower than at all impacted sites (0.330–3.089 mg L^{-1}), confirming that the phosphorus enrichment signal associated with shrimp pond effluents is absent at the reference site and supporting its use as an appropriate comparative baseline, with the caveat that ammonia data across all sites should be interpreted in light of potential natural background contributions.

Table 4. Spatial and seasonal variation of phosphate, ammonia, and NOx concentrations in intertidal waters influenced by shrimp pond effluents

Location	Season	Station	Variables			Seawater quality standards*
			Phosphate (mg L^{-1})	Ammonia (mg L^{-1})	NOx (mg L^{-1})	
SBL	Dry	1	1.786	0.642	1.101	Phosphate; ≤ 0.015
		2	1.328	0.651	1.280	mg L^{-1}
		3	2.951	2.142	1.656	Ammonia; ≤ 0.3 mg
		4	2.695	1.335	1.843	L^{-1}
		5	2.393	0.773	1.848	NOx; ≤ 0.008 mg L^{-1}
	Wet	1	0.747	0.076	0.312	
		2	0.728	0.072	0.634	
		3	0.518	0.077	0.738	
		4	0.719	0.071	0.942	
		5	1.943	0.069	1.069	
PMK	Dry	1	3.080	1.329	0.938	
		2	2.510	0.498	0.985	
		3	2.785	0.833	1.046	
		4	3.089	0.913	0.780	
		5	2.335	0.634	1.076	
	Wet	1	1.037	0.079	0.616	

Location	Season	Station	Variables			Seawater quality standards*
			Phosphate (mg L^{-1})	Ammonia (mg L^{-1})	NOx (mg L^{-1})	
		2	1.389	0.087	0.631	
		3	1.056	0.074	0.282	
		4	0.707	0.073	0.617	
		5	1.351	0.075	0.815	
KYN	Dry	1	1.703	0.084	0.735	
		2	1.009	0.093	1.074	
		3	1.062	0.077	0.765	
		4	0.487	0.077	0.931	
		5	0.715	0.072	0.911	
	Wet	1	1.424	0.377	0.878	
		2	0.330	0.358	0.782	
		3	0.842	0.405	0.825	
		4	0.820	0.346	0.535	
		5	0.831	0.367	0.568	
PTN	Dry	1	2.134	1.671	1.157	
		2	2.332	2.202	1.361	
		3	2.550	1.198	1.354	
		4	2.913	0.673	1.396	
		5	2.519	0.440	1.147	
	Wet	1	0.899	0.083	0.373	
		2	0.806	0.079	0.260	
		3	0.540	0.075	0.221	
		4	0.386	0.077	0.287	
		5	1.123	0.078	0.239	
SKT	Control	1	0.343	0.459	0.273	
		2	0.190	0.479	0.337	
		3	0.176	0.524	0.290	
		4	0.173	0.780	0.191	
		5	0.172	0.840	0.112	

3.3 Chlorophyll-a and Total Suspended Solids (TSS)

The spatial and seasonal variability of chlorophyll-a and total suspended solids (TSS) in intertidal waters influenced by shrimp pond effluents indicates measurable responses to nutrient inputs and suspended particulate matter (Table 5). Chlorophyll-a concentrations at all impacted sites (SBL, PMK, KYN, and PTN) consistently exceeded the seawater quality standard for marine biota (<0.2 µg L^{-1}), with values ranging from 0.297 to 8.900 µg L^{-1} across seasons (Figure 5). The highest concentrations were observed at KYN during the wet season (up to 8.900 µg L^{-1}), followed by elevated values at PMK (up to 4.153 µg L^{-1}) and PTN (up to 5.142 µg L^{-1}). These patterns indicate increased phytoplankton biomass relative to background conditions and are consistent with nutrient enrichment in intertidal waters influenced by aquaculture activities (Burford et al., 2020; Herbeck et al., 2021).

Table 5. Spatial and seasonal variation of chlorophyll-a and total suspended solids (TSS) in intertidal waters influenced by shrimp pond effluents

Location	Season	Station	Variables		Seawater quality standards*
			Chlorophyll-a (µg/L^{-1})	TSS (mg L^{-1})	
SBL	Dry	1	2.967	8.0	Chlorophyll-a; <0.2
		2	2.967	15.8	(µg/L^{-1})
		3	1.187	6.8	TSS; <20 mg L^{-1}

Location	Season	Station	Variables		Seawater quality standards*
			Chlorophyll-a (µg/L^{-1})	TSS (mg L^{-1})	
		4	2.373	7.8	
		5	3.263	21.4	
	Wet	1	2.769	2.9	
		2	1.978	5.2	
		3	2.176	7.6	
		4	2.373	7.5	
		5	2.175	9.1	
PMK	Dry	1	1.978	17.4	
		2	2.373	5.0	
		3	0.791	31.8	
		4	2.571	35.0	
		5	1.779	13.8	
	Wet	1	2.571	8.1	
		2	2.967	22.6	
		3	4.153	7.2	
		4	1.187	6.3	
		5	0.791	7.1	
KYN	Dry	1	3.362	11.9	
		2	2.967	13.4	
		3	4.747	13.1	
		4	3.164	13.6	
		5	5.340	13.1	
	Wet	1	8.900	4.1	
		2	1.187	6.2	
		3	7.120	5.8	
		4	8.307	6.9	
		5	2.373	7.7	
PTN	Dry	1	2.289	8.5	
		2	2.571	5.9	
		3	0.989	6.1	
		4	1.780	11.4	
		5	5.142	12.1	
	Wet	1	0.297	6.6	
		2	1.780	9.2	
		3	3.263	6.8	
		4	4.153	7.4	
		5	3.263	9.2	
SKT	Control	1	2.275	1.2	
		2	3.362	1.7	
		3	3.263	2.1	
		4	2.472	2.3	
		5	3.066	1.9	

In contrast, TSS concentrations exhibited more heterogeneous spatial and seasonal patterns, ranging from 2.9 to 35.0 mg L^{-1} across all sites. Most observations remained below the regulatory threshold (<20 mg L^{-1}); however, elevated values were recorded at several stations, particularly at PMK during the dry season (up to 35.0 mg L^{-1}) and wet season (up to 22.6 mg L^{-1}). These higher concentrations

suggest increased suspended particulate loads, which may be associated with sediment resuspension and the release of organic matter from shrimp pond effluents. Increased TSS can reduce light penetration and influence primary production dynamics in intertidal waters (Alongi, 2018; Wijayanto et al., 2025).

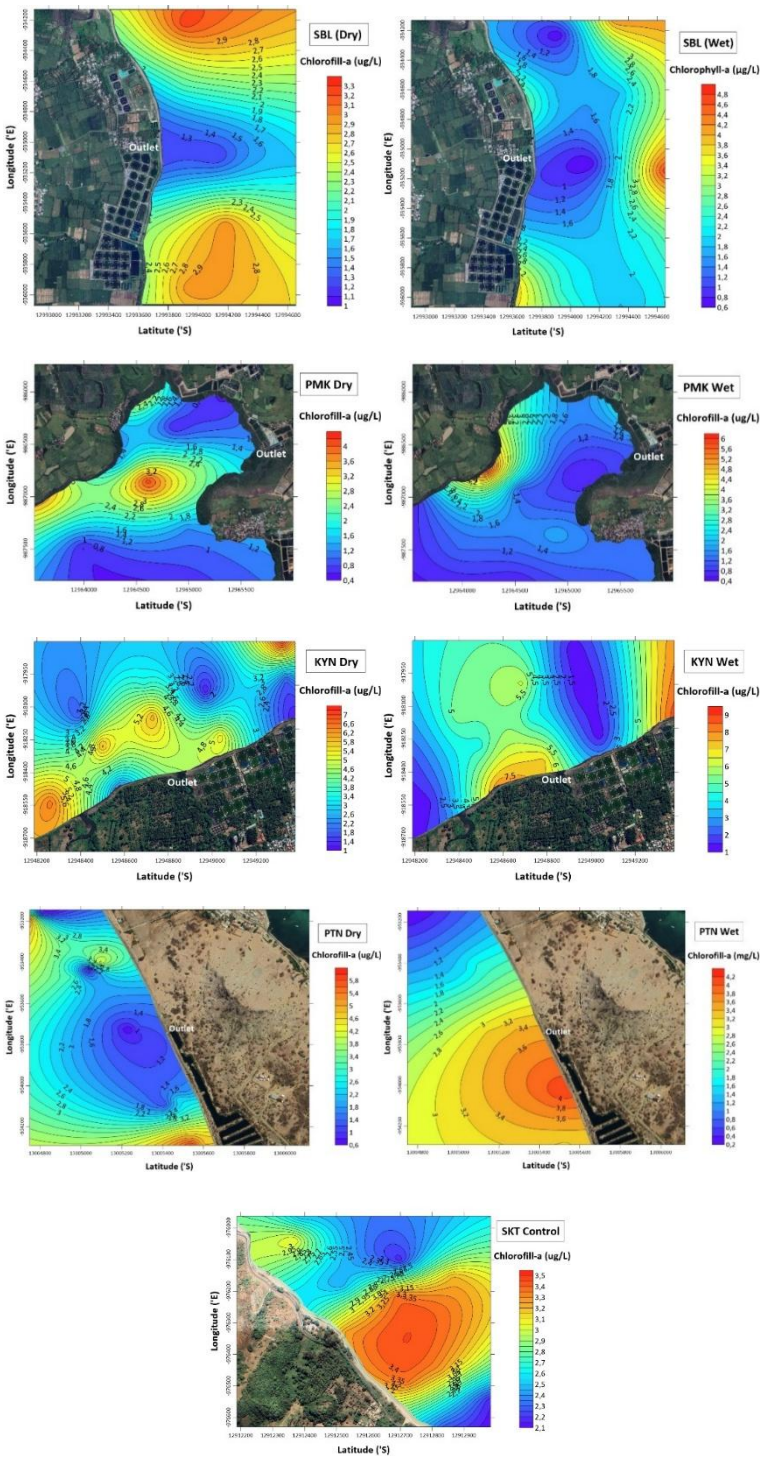


Figure 5. Spatial distribution of chlorophyll-a (µg L^{-1}) concentrations in intertidal waters influenced by shrimp pond effluent discharge at four coastal sites

The control site (SKT) exhibited relatively lower and more stable TSS values (1.2–2.3 mg L^{-1}), while chlorophyll-a concentrations remained within a narrower range (2.275–3.362 µg L^{-1}), indicating comparatively stable conditions in the absence of direct aquaculture inputs (Figure 6). Overall, the observed patterns suggest that shrimp aquaculture activities are associated with elevated chlorophyll-a

concentrations and variable suspended particulate conditions in intertidal waters. These conditions may influence trophic dynamics and light availability, which are important factors regulating coastal ecosystem processes (Hargan et al., 2020; Zhou et al., 2024).

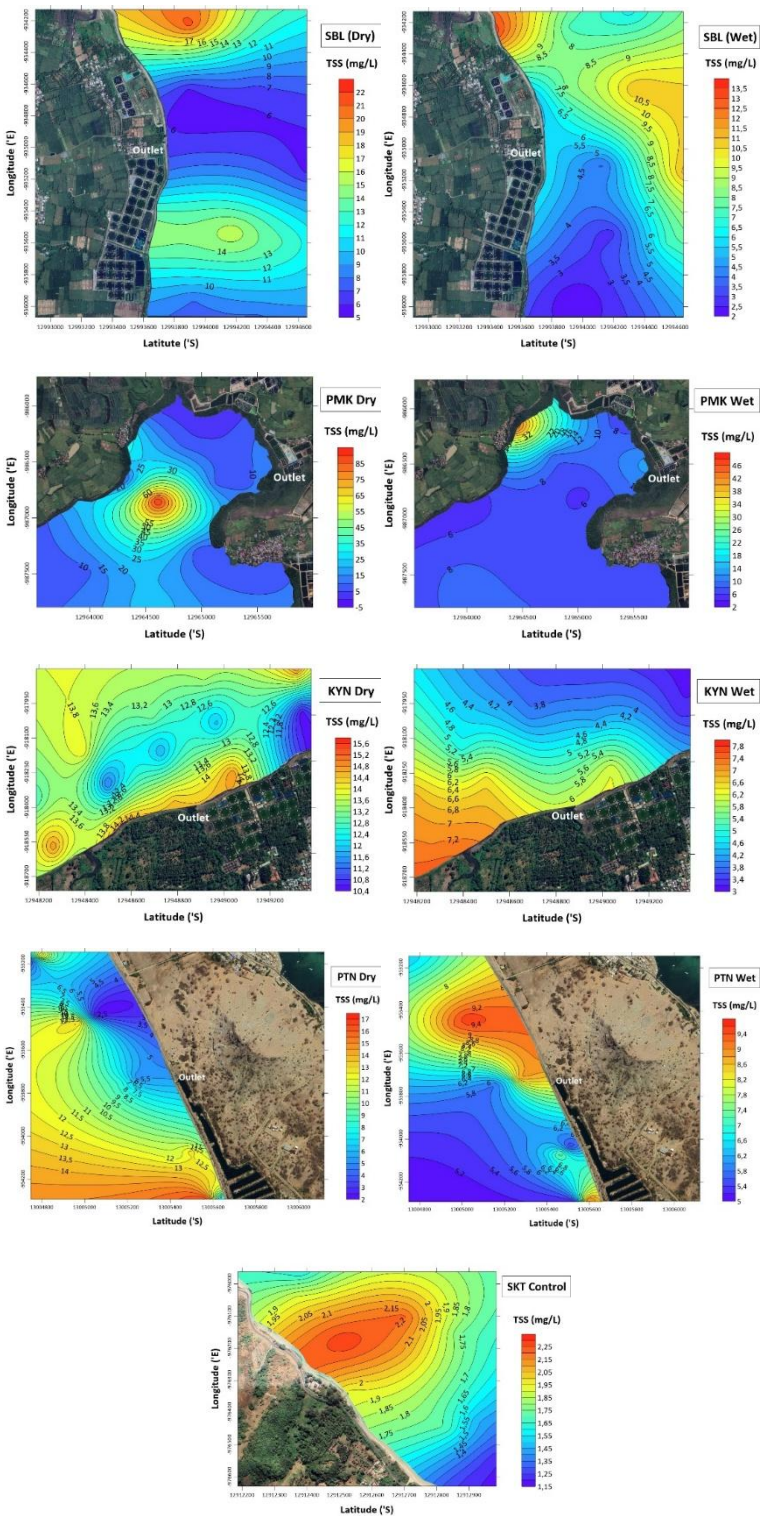


Figure 6. Spatial distribution of total suspended solid (mg L^{-1}) concentrations in intertidal waters influenced by shrimp pond effluent discharge at four coastal sites

3.4 Multivariate Analysis of Physicochemical Parameters and Spatio-Temporal Variability

The PCA biplot (F1: 32.02%; F2: 17.59%) explains 49.61% of the total variance and reveals structured relationships among physicochemical variables and sampling conditions. The first principal component (F1) is primarily associated with nutrient-related variables, including phosphate, ammonia, and NOx, which are aligned along the positive axis together with salinity and TSS. The similar orientation of these vectors indicates positive associations among these variables, representing a gradient of nutrient enrichment and dissolved or suspended material accumulation (Figure 7). Such coupling between nutrient concentrations and salinity is frequently observed in coastal environments influenced by anthropogenic inputs and limited water exchange (Bui et al., 2012; Bull et al., 2021; de Lacerda et al., 2021). In contrast, dissolved oxygen (DO) and chlorophyll-a are oriented toward the negative side of F1, suggesting an inverse association with the nutrient-related variables. This pattern is consistent with processes in nutrient-enriched systems, where increased organic matter production and subsequent microbial decomposition can influence oxygen dynamics (Ehrnsten et al., 2020; Zhao et al., 2021; Duque et al., 2022), while variations in phytoplankton biomass reflect responses to changing nutrient availability and environmental conditions (Burford et al., 2020; Zhou et al., 2024).

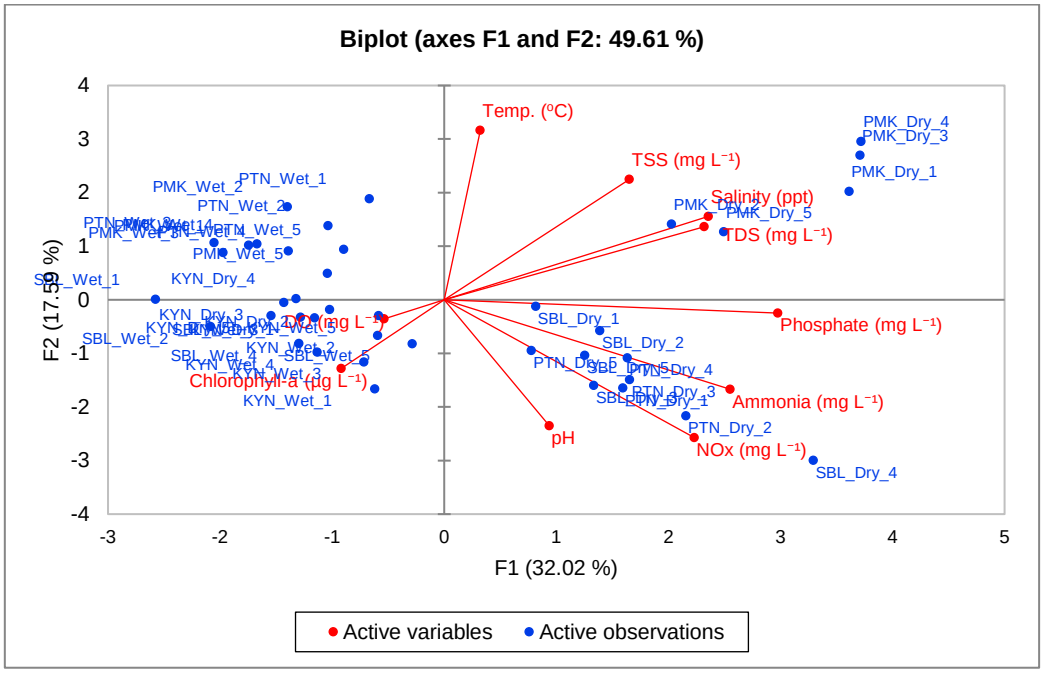


Figure 7. Principal component analysis (PCA) biplot showing relationships among physicochemical parameters and spatiotemporal sampling sites

From a spatial perspective, PMK and part of SBL cluster on the positive side of F1, indicating conditions characterized by elevated nutrient concentrations consistent with eutrophic status. These sites are situated in semi-enclosed or island-sheltered coastal settings where reduced water exchange is expected based on their geomorphology, which may promote nutrient retention and accumulation (Bull et al., 2021; de Lacerda et al., 2021; Duque et al., 2022). Conversely, KYN and several wet-season samples are positioned on the negative side of F1, representing comparatively lower nutrient concentrations. The strait-facing location of KYN is consistent with greater tidal energy and water exchange capacity relative to PMK, which may contribute to the lower nutrient levels observed there; however, as direct hydrodynamic measurements were not collected, this spatial pattern should be interpreted as suggestive of, rather than conclusive evidence for, differential hydrodynamic flushing (Bui et al., 2012; Cerralbo et al., 2019).

Temporally, dry-season samples are predominantly associated with the positive F1 axis, reflecting increased nutrient accumulation and salinity due to reduced freshwater input, enhanced evaporation,

and limited dilution (Mustafa et al., 2022). In contrast, wet-season samples shift toward the negative F1 axis, indicating dilution effects driven by freshwater input and increased runoff, which reduce nutrient concentrations and alter coastal water chemistry (Cereja et al., 2022).

The spatiotemporal interaction is particularly evident at SBL, where a pronounced shift in PCA position between wet and dry seasons indicates strong environmental variability and sensitivity to seasonal forcing. This pattern is consistent with coastal systems in which land-based nutrient inputs and seasonal rainfall variability exert a dominant influence on water column chemistry (Senathirajah and Pattiaratchi, 2025). In comparison, KYN exhibits comparatively stable positioning across seasons, a pattern consistent with the greater tidal energy and water mass exchange expected at a strait-facing site. It should be noted, however, that this interpretation is inferred from site morphology and geographic positioning rather than measured current velocities or residence times; the observed seasonal stability at KYN may also reflect other factors, including the relatively younger age of the pond complex there and potentially lower total effluent volumes compared with PTN (Malik et al., 2023).

Several limitations of this study should be considered when interpreting the results. First, the two-component PCA solution explained 49.61% of total variance (F1: 32.02%; F2: 17.59%), leaving approximately 50% unexplained by the first two principal components. To address this limitation, two-way ANOVA was applied to the PC factor scores to statistically test the significance of the patterns identified by PCA. For F1 representing the nutrient and mineralization gradient the ANOVA model explained 90.3% of the variance in factor scores ($R^2 = 0.903$), with site ($F = 14.301$; $p < 0.001$), season ($F = 162.052$; $p < 0.001$; partial $\eta^2 = 0.835$), and their interaction ($F = 31.508$; $p < 0.001$) all highly significant. Season was the dominant factor for F1, consistent with the strong seasonal contrast in nutrient accumulation between dry and wet periods. For F2 representing the physical water quality gradient dominated by temperature, TSS, pH, and NOx the model explained 84.0% of variance in factor scores ($R^2 = 0.840$), with site as the dominant factor ($F = 33.215$; $p < 0.001$; partial $\eta^2 = 0.757$), followed by season ($F = 4.893$; $p = 0.034$; partial $\eta^2 = 0.133$) and their interaction ($F = 21.102$; $p < 0.001$; partial $\eta^2 = 0.664$). The high R^2 values for both components confirm that the spatial and seasonal factors account for the dominant sources of structured variability in the PCA gradients, and that the patterns identified in the biplot are statistically robust. The remaining ~50% of total variance reflects higher-order environmental variation not structured along the first two axes, likely including short-term tidal and diel fluctuations, biological interactions such as phytoplankton uptake and grazing, unmeasured sediment–water exchange fluxes, and site-specific non-aquaculture inputs; inclusion of additional variables such as sediment organic matter content, current velocity, or phytoplankton community composition in future studies may improve the total variance explained. Prior to ANOVA, model assumptions were verified: for F1, Shapiro–Wilk test confirmed residual normality and Levene's test confirmed homogeneity of variance (Levene statistic = 2.225; $p = 0.058$). For F2, residual normality was confirmed (Shapiro–Wilk $p = 0.197$); although Levene's test based on the mean yielded $p = 0.049$, tests based on the median ($p = 0.170$) and trimmed mean ($p = 0.057$) indicated a minor violation, and the ANOVA was considered appropriate given the balanced design and satisfied normality assumption. Second, spatial interpolation for contour maps (Figures 2–6) was performed using inverse distance weighting in Surfer (version 29) from five station mean values per site per season, each derived from triplicate measurements (15 raw observations per site per season). Although triplicate sampling improves the reliability of individual station values, the spatial resolution of the interpolation is determined by the number of stations rather than replicates. With five input points per site, the contours are sensitive to the value and position of individual stations, and inverse distance weighting does not yield formal error estimates or confidence intervals.

The resulting maps should therefore be interpreted as indicative of broad spatial trends rather than precise concentration gradients, particularly for phosphate and ammonia which exhibit high spatial variability; they are intended to complement the tabulated station data (Tables 3–5) rather than serve as a basis for independent spatial analysis. Denser sampling grids or continuous sensor transects would substantially reduce this uncertainty in future studies. Third, the seasonal snapshot design precludes

detection of short-term variability driven by tidal cycles, storm events, or episodic pond discharge, and limits characterization of interannual dynamics. Fourth, hydrodynamic conditions were inferred qualitatively from site morphology and published literature rather than directly measured. All interpretations attributing spatial differences in nutrient accumulation to differential water exchange or tidal flushing are explicitly inferential; conclusions regarding hydrodynamic influence reflect associations consistent with site morphology rather than causally demonstrated relationships, and quantitative confirmation would require current measurements or numerical circulation modeling.

Fifth, a fully quantitative analysis of pond age and area was not possible: pond area data were available only for PTN (>250 ha), and operational age was resolved only into two broad categories (<10 years vs. >25 years), precluding formal statistical analysis across sites. The role of pond characteristics was therefore discussed qualitatively, comparing PTN with younger sites in relation to the association between operational history and sediment organic loading (Sabilu et al., 2021); future studies should document pond age, area, stocking density, and feed input systematically to enable quantitative attribution.

4. Conclusions

Phosphate, ammonia, and NOx exceeded national marine water quality standards at all impacted sites in both seasons, with elevated chlorophyll-a indicating nutrient-associated trophic responses. Dry-season concentrations were consistently higher than wet-season values, a pattern compatible with reduced dilution, though the mechanisms were not directly measured. PCA–ANOVA identified season as the statistically dominant driver of nutrient variability (partial $\eta^2 = 0.835$) and site as the primary control on physical conditions (partial $\eta^2 = 0.757$); both results should be interpreted in light of the acknowledged limitations of seasonal snapshot sampling and the absence of hydrodynamic data. Spatial differences including the strongest enrichment at PMK and highest ammonia at PTN are consistent with site morphology and pond characteristics but are not conclusively explained by them. These results suggest that management should prioritize phosphorus reduction, more conservative dry-season discharge practices, and targeted monitoring at sites with restricted water exchange.

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Ethics Statement

Ethical approval was not required for this study because it did not involve human participants or animals. The research was conducted using wastewater samples collected from shrimp pond cultivation effluents.

CRediT Author Statement

Edwin Jefri: Idea Development, Research Design, Program Development, Manuscript Draft Preparation, Visualization. **Jamaluddin Jompa**: Research Design Resources, Supervision, Manuscript Draft Preparation, Project Administration. **Nadiarti Nurdin Kadir**: Visualization, Supervision, Formal Analysis. **Nurliah Buhari**: Visualization, Manuscript Review and Revision, Project Administration. **Maya Lakshmi Ganapathy**: Manuscript Draft Preparation, Data Curation.

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