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Ammonium, Nitrate, and Phosphate in Coastal Waters of Red River Biosphere Reserve, Vietnam

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ABSTRACT

Nutrient availability in coastal areas plays a crucial role in supporting primary producers and maintaining the aquatic food chain. The spatial variation of nutrients, including ammonium, nitrate, and phosphate, can significantly influence coastal ecosystems' structure, leading to both positive and negative results. This study examines the fine-scale spatial variation of physicochemical parameters and nutrient concentrations in shrimp ponds and adjacent coastal waters from two wetland areas: Ba Lat Estuary (BLE) and Thai Thuy (TTW) in the Red River Delta, Vietnam. Ammonium concentrations ranged from 155.80 to 1,500.80 µg/L, with an average value of 666.83±260.02 µg/L. Nitrate concentrations varied from 25.10 to 996.40 µg/L, averaging of 285.42±255.05 µg/L, while phosphate concentrations exhibited significant variability, ranging from 0.70 to 128.70 µg/L. Nutrient concentrations in the RRD were relatively high compared to other regions globally. The findings revealed that tidal dynamics and aquaculture activities significantly influence nutrient variations in coastal waters. The increasing nutrient concentrations in the coastal marine environment of the Red River Biosphere could lead to eutrophication risks, which could adversely affect mangroves, estuarine areas, and other coastal ecosystems. This results emphasize the critical need to reduce nutrient discharge and implement wastewater treatment from anthropogenic activities to safeguard ecosystems and protect the coastal estuary environment. Further research is essential to investigate the spatial and temporal dynamics of nutrients in this region to fully understand their impacts on coastal marine ecosystems.

1. INTRODUCTION

The coastal zone is a highly dynamic area with many important economic activities such as industry, seaports, aquaculture, and tourism. However, this area is susceptible to pollution originating from the mainland, leading to risks of environmental degradation and vulnerability. The overabundance of nutrients such as nitrogen, phosphorus, and silicate can cause negative impacts on the coastal marine environment, such as eutrophication, degradation of estuaries and coastal areas, loss of marine habitats, and biodiversity degradation (Barcellos et al., 2019; Fauzi et al., 2013; Fauzi et al., 2014). Potential nutrient pollution sources affecting the marine environment include industrial activities, urban wastewater, agricultural production, domestic waste, and coastal aquaculture. Studies in Brazil and India showed that the increase in phosphorus discharge might cause deterioration of water quality, sediments, and biodiversity in mangrove areas (Barcellos et al., 2019; Manna et al., 2010; Mukhopadhyay et al., 2006). However, the increase in nutrient concentrations also shows positive effects, such as maintaining mangrove forests (Dangremond et al., 2019) and improving mangroves' growth rate and biomass (Hayes et al., 2017). These nutrients also play an essential role in the

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growth of phytoplankton, contributing to maintaining food webs in coastal ecosystems. The inland nutrient sources have supported and maintained marine ecosystems, including mangroves, estuaries, and coastal tidal flats. Nutrients in the coastal marine environment serve both beneficial and detrimental functions. Therfore, it is important to effectively manage pollution in these areas to ensure the sustainable use of natural resources and the protection of the surrounding environment.

A study on nutrient loads in the Red River Delta (RRD), Vietnam showed that agricultural irrigation activities and leakage from the soil environment are the primary causes leading to the increase in nitrogen and phosphorus content in the Red River water sources (Luu et al., 2012). Recent studies also show that nitrogen, phosphorus and silicate concentrations in the Red River water has gradually reached the limit point of eutrophication (Le et al., 2014). Therefore, determination of the role and impact of nutrients in the Red River Delta are necessary to protect the ecosystems and biodiversity in the future. However, the fine-scale spatial assessment has not been conducted on the nutrients in coastal waters, highlighting the neccesary for updated information in the RRD. The present study aims to determine the distribution of nutrients such as ammonium, nitrate, and phosphate, and other physiochemical parameters in the Red River Delta Biosphere Reserve, Vietnam. Study results will provide invaluable information for mangrove conservation and efforts to reduce the impact of anthropogenic activities in the RRD and other similar regions worldwide.

2. METHODOLOGY

2.1 Study site

The Red River Delta Biosphere Reserve in northern Vietnam is recognized as one of the country's largest mangrove forest and wetland conservation areas. This area encompasses a range of habitats, including mangroves, wetlands, salt marshes, estuaries, beaches, etc., supporting a high biodiversity with more than 30 different mangrove and mangrove-associated species. These ecosystems serve as habitats for numerous rare and endangered species of flora and fauna. Additionally, they play an important role in stabilizing sediment, protecting coastlines, and mitigating the impacts of climate change. The sampling sites were Ba Lat Estuary (BLE) and Thai Thuy Wetland Area (TTW) in Red River Delta Biosphere Reserve, Vietnam (Figure 1). The BLE was the largest estuary in Northern Vietnam, which provided an essential stopover for migratory birds and waterfowl. The BLE is the first Ramsar site in Vietnam and plays a critical role in biodiversity conservation and supporting local peoples' livelihoods. The BLE and TTW are situated in the tropical monsoon climate region, with the rainy season from May to October and the dry season from November to April. Mangroves are widely distributed along coastlines of BLE and TTW, with dominant mangrove species are *Kandelia obovata*, *Soneratia caseolaris*, *Rhizophora stylosa*, *Aegiceras corniculatum*, and *Avicennia marina*. The TTW is located at the north of the Red River Delta Biosphere Reserve and is rich in wetland resources such as mangroves, tidal flats, and estuary areas. The aquaculture activities are highly developed in both regions, with the main products being black tiger shrimps, white legs shrimp, clams, and sea bass. The extensive and eco-oriented shrimp farming is widespread in Ba Lat Estuary (BLE) and Thai Thuy wetlands (TTW). Intensive (or industrial) shrimp farming is the second largest production activity, distributed unevenly in the study areas. Shrimp farming developed from the 1990s to the 2010s, with the massive mangrove forest loss due to land conversion (Long et al., 2021).

2.2 Field sampling

Coastal seawater samples were collected and surveyed in three environment types, including creeks and estuaries, intensive shrimp farming ponds, and extensive shrimp ponds along the coastal zone of Red River Delta Biosphere Reserve. In the present study, the Ba Lat Estuary (BLE) and Thai Thuy Wetlands area (TTW) in the RRD were sampling locations to analyze nutrient concentration in coastal waters. Samples in BLE were collected in December 2020, including 31 water samples in coastal waters (Cw), 31 water samples in extensive ponds (EcoP), and 5 water samples in intensive shrimp ponds (InsP) (Figure 1). In TTW, a total of 11, 2, and 4 samples were collected in coastal waters, extensive shrimp ponds, and intensive shrimp ponds, respectively (Figure 1). Water samples were stored in primary polyethylene plastic bottles, stored in iceboxes, and transported to the laboratory for laboratory analysis. Physiochemical parameters such as pH, TDS, Eh, DO, and salinity were measured in-situ immediately during sampling.

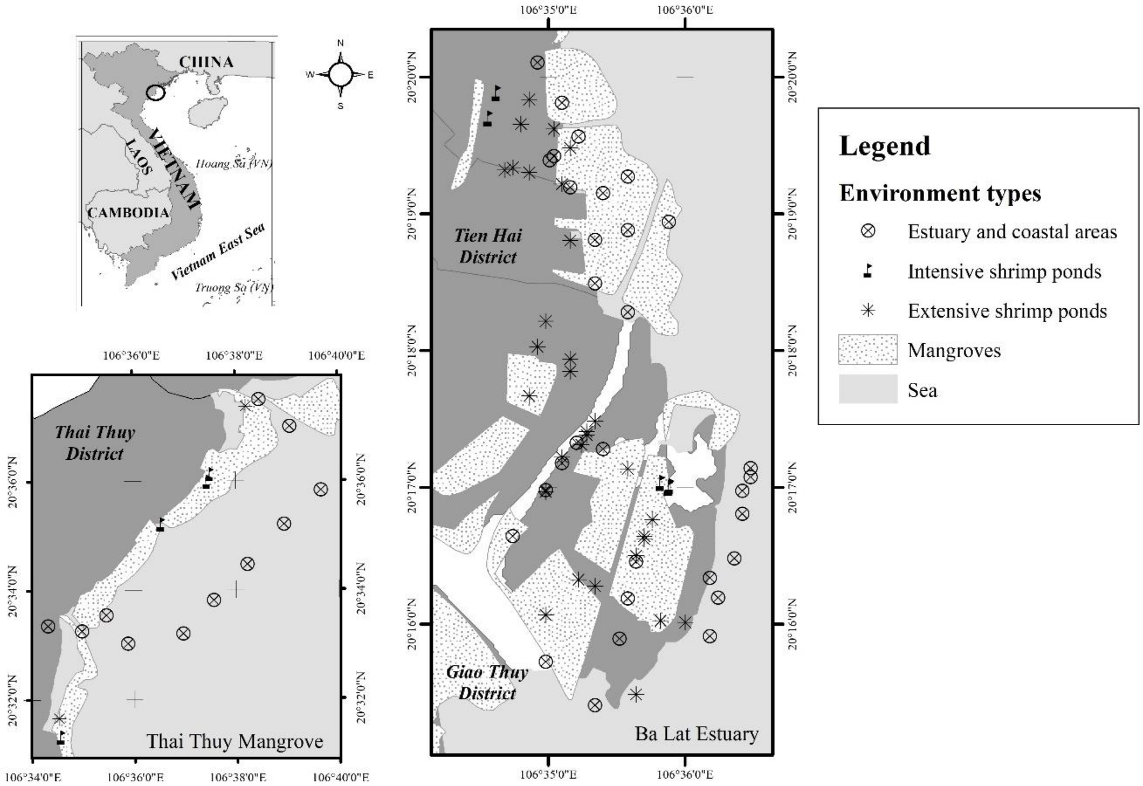

Figure 1. Sampling location in Ba Lat estuary (BLE) and Thai Thuy wetlands (TTW)

2.3 Measurement of physiochemical parameters

The physicochemical parameters of the coastal water environment, including pH, TDS, Eh, DO, and salinity, were measured directly in the field by the Horiba WQC 330 handheld system. The seawater's pH, salinity, and TDS were measured by 300-PH2 and 300-C2 digital electrodes, respectively. The seawater's redox potential was measured by glass electrode 9300-10D with Horiba digital converter. The accuracy of instruments was 0.5% and 0.1 mV for digital and glass electrodes, respectively.

2.4 Nutrient analysis

Ammonium, nitrate, and phosphate concentrations in seawater were analyzed using a CFA Skalar SAN++ continuous flow automated analysis system (Skalar Analytical BV, Breda, The Netherlands) at the VNU key laboratory of geoenvironment and response climate change, faculty of geology, university of science, Vietnam National University, Hanoi. Before conducting the analysis, the water sample was filtered through a quantitative filter paper to remove suspended matter in the solution. After filtering, water samples were kept in ice buckets and analyzed on the same day after filtration. The analysis of nutrient concentration in water was performed according to Skalar Analytical guidelines (Skalar Analytical B.V., 2019). The analytical detection limit for nitrate, ammonium, and phosphate are 15, 5, and 2 µg/L, respectively. Samples with expected ammonium, nitrate, and phosphate concentrations above 500 µg/L should be diluted at least two times before analysis. After ten samples were analyzed in a batch, a standard sample was repeated for peak correction during analysis. The system was operated automatically by Skalar's Flow Access V3 control software (Skalar Analytical B.V., 2019). Standard samples were evaluated to ensure that the change in detector signal was not more than 5% and the R-value of the analytical standard curve was higher than 0.990.

2.5 Statistical analysis

The General Linear Model (GLM) was applied to test the differences in physiochemical parameters and nutrient concentrations among locations (BLE and TTW) and environment types. Principal component analysis (PCA) assessed the relationship between physiochemical parameters and nutrient concentrations in the Thai Thuy Wetlands and Ba Lat estuary regions. IBM SPSS v20.0 and Microsoft Excel were applied to perform statistical tests in the present study. The statistical differences were confirmed with p values<0.05.

3. RESULTS AND DISCUSSION

3.1 Physiochemical parameters of coastal water

The values of water quality parameters such as pH, redox potential (Eh), TDS, and salinity are shown in Figure 2. The pH of coastal waters in TTW and BLE ranged from 7.5 to 8.3 and 6.5 to 9.4, respectively. The mean pH values of coastal waters were 7.88±0.30 and 7.57±0.44 for TTW and BLE, respectively. The DO of coastal waters in TTW and BLE ranged from 5.4 to 9.2 and 4.1 to 8.8, with average values of 7.07±1.07 and 7.89±0.76 for TTW and BLE, respectively. The pH and DO values in TTW were higher than BLE, but a statistical difference was not observed between the two sampling locations (Table 1, $p>0.05$). The redox potential of coastal waters in TTW and BLE ranged from 163.3 to 212.2 and 127.0 to 224.5 mV, respectively. The mean redox potential values of coastal waters were 190.79±13.55 and 179.02±17.90 for TTW and BLE, respectively. TTW and BLE's total dissolved solids ranged from 5.3 to 15.0 and 3.8 to 31.5 mg/L with average values of 11.44±3.33 and 17.76±7.05 (g/L) for TTW and BLE, respectively. The mean salinity was 13.46±4.14 and 18.22±7.35 (‰) for coastal water from TTW and BLE, respectively. The statistical difference between the two study sites was observed in redox potential, salinity, and TDS (Table 1, GLM test, $p<0.05$).

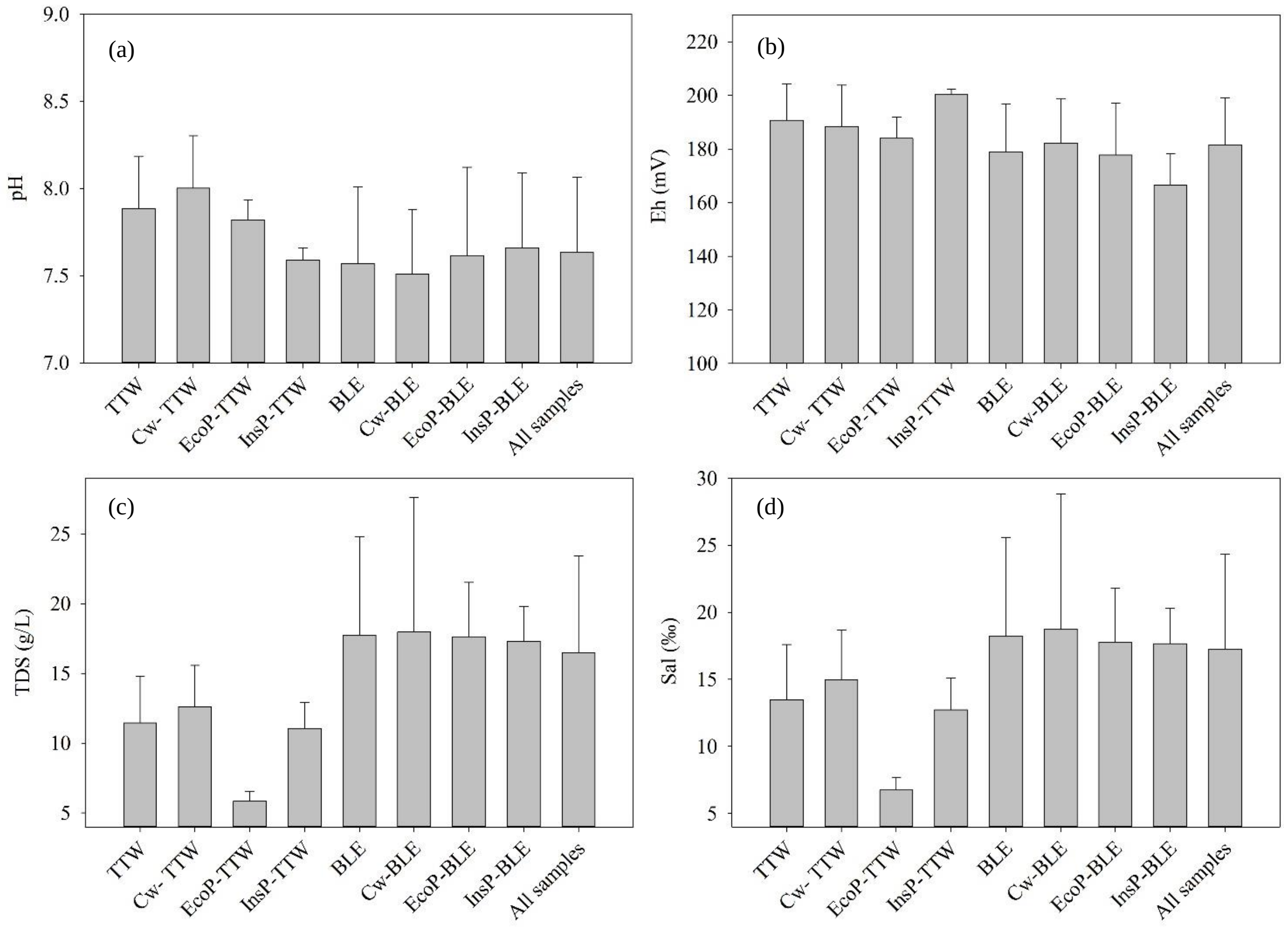

Figure 2. Water quality parameters in TTW and BLE: (a) pH, (b) redox potential, (c) total dissolved solids, and (d) salinity. Error bars represent the standard deviation (SD) of the mean. Acronyms are shown in Table 1.

The PCA results of water quality parameters showed that the first factors accounted for 57.20% and 32.07% of the variance for TTW and BLE, respectively. The second factor accounted for 19.39% in TTW and 23.06% of the variance in BLE. High loading of the first factor was observed in TDS, salinity, DO, and pH of samples from TTW, whereas the BLE observed high loading of the first factor in salinity and TDS. The PCA results suggested that TDS, salinity, DO, and pH from TTW have a strong relationship (Figure 3).

Table 1. The concentrations of ammonium, nitrate, and phosphate in BLE and TTW

Location	Ammonium (µg/L)		Nitrate (µg/L)		Phosphate (µg/L)		n
	Mean	SD	Mean	SD	Mean	SD	
Thai Thuy Wetlands (TTW)	558.27	343.29	316.57	171.42	18.77	35.06	17
Coastal and estuary (Cw)	461.91	157.94	270.08	120.87	5.79	3.62	11
Extensive shrimp ponds (EcoP)	903.22	-	644.63	-	73.87	-	2
Intensive shrimp ponds (InsP)	650.80	427.21	280.38	111.93	26.92	32.77	4
Ba Lat Estuary (BLE)	694.38	229.46	276.26	272.67	9.76	17.34	67
Cw	750.99	251.12	443.80	309.38	6.75	5.92	31
EcoP	680.70	158.11	127.12	97.79	10.99	22.26	31
InsP	428.16	305.65	162.10	176.07	20.79	27.34	5
All samples	666.83	260.02	284.42	255.05	11.58	22.12	84

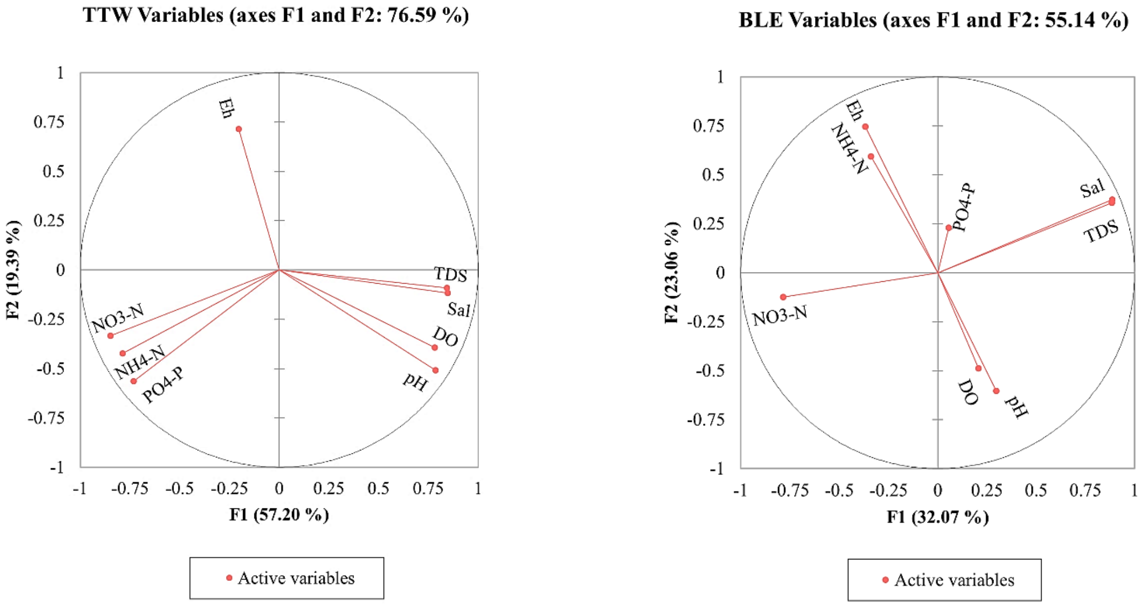

Figure 3. Principle component analysis results of physiochemical characteristics and nutrients in BLE and TTW

3.2 Nutrient concentration in coastal waters of Red River Delta

The concentration of ammonium (NH_4-N), nitrate (NO_3-N), and phosphate (PO_4-P) are shown in Table 1. In the TTW, the mean values of ammonium were 461.9±57.9, 903.2±845.1, and 650.8±427.2 µg/L for coastal waters, extensive shrimp ponds, and intensive shrimp ponds, respectively. The significant variation in ammonium concentration of waters in extensive shrimp ponds resulted from small sample sizes or differences in water retention time. The mean ammonium concentration in BLE was 751.0±251.1, 680.7±158.1, and 428.2±305.6 µg/L for coastal waters, extensive shrimp ponds, and intensive shrimp ponds, respectively. In the TTW, the mean concentration of ammonium decreased from EcoP through InsP to Cw sites, whereas in the BLE, ammonium concentration decreased in the order of Cw, EcoP, and InsP (Figure 5).

The mean concentration of nitrate (NO_3-N) was 316.6±171.0 and 276.3±272.7µg/L TTW and BLE, respectively. The average nitrate concentration in BLE were 443.8±309.4, 127.1±97.8, and 162.1±176.1 µg/L for coastal waters, extensive shrimp ponds, and intensive shrimp ponds, respectively. In the TTW, the mean concentration of nitrate decreased from EcoP through InsP to Cw with average values of 644.6±205.5, 280.4±11.9, and 270.1±120.9 µg/L, respectively (Figure 4). The phosphate concentration in water ranged from 2.8 to 137.6 and from 0.7 to 127.9 µg/L for TTW and BLE, respectively. However, the phosphate concentration has a large variation in EcoP samples, with the highest and lowest values observed in this sampling site (Table 1).

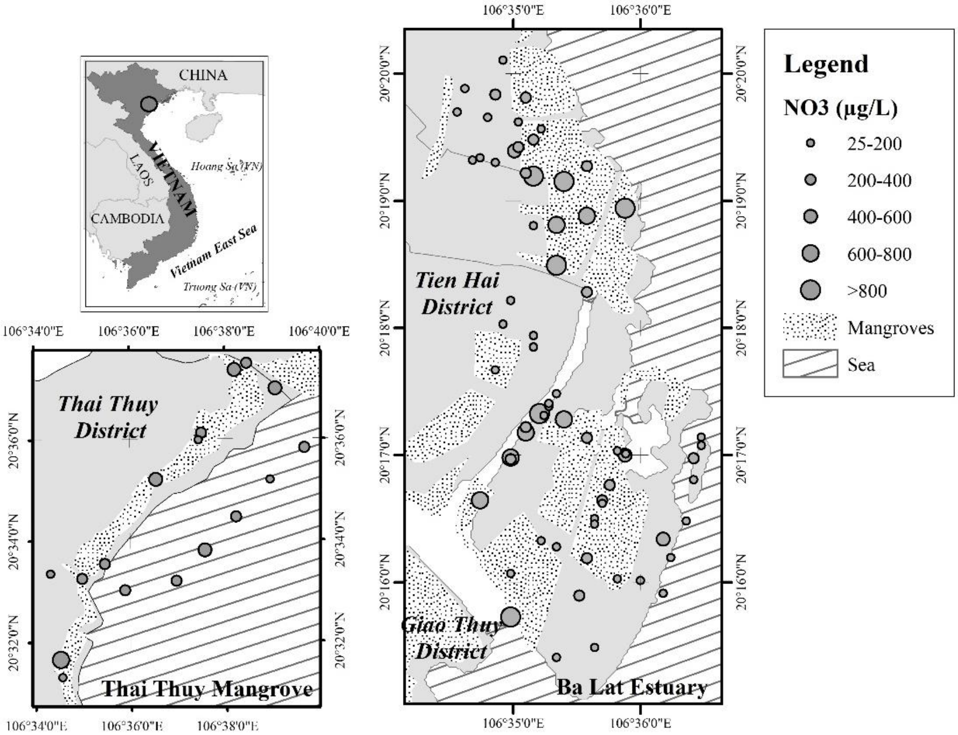

Figure 4. Nitrate concentration in the coastal waters of TTW and BLE in the Red River Biospheres Reserve

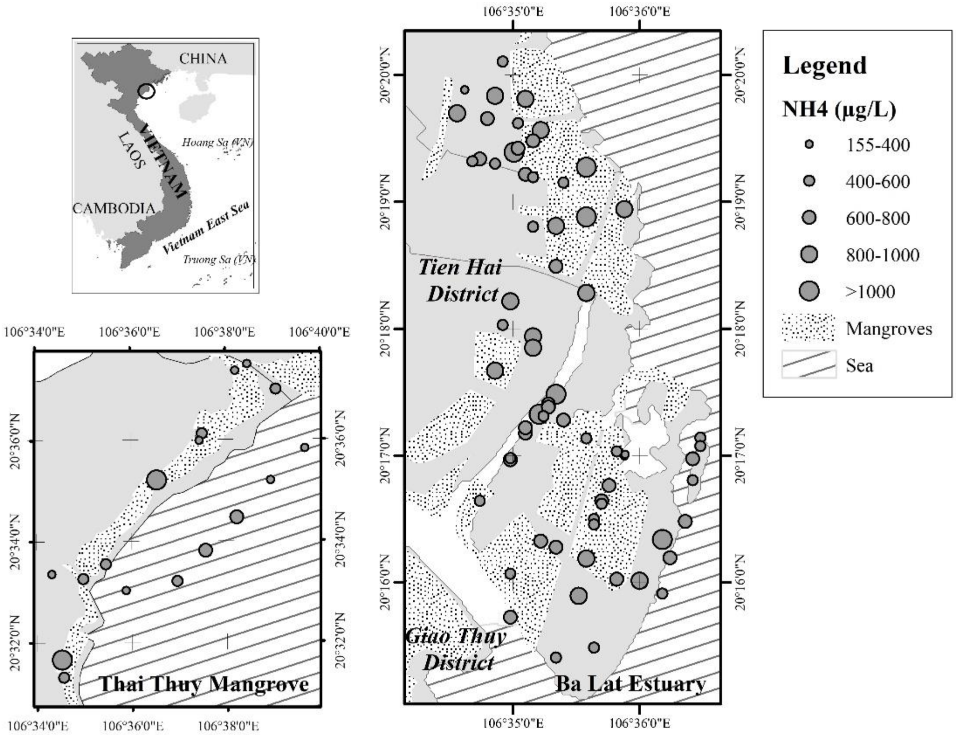

Figure 5. Ammonium concentration in coastal waters of TTW and BLE in Red River Biosphere Reserve

The PCA analysis result in TTW showed that the ammonium, nitrate, and phosphate have a strong relationship (Figure 3). A similar trend was not observed in BLE, with Eh and ammonium having a strong relationship in PCA analysis. High-loading factors of nutrients in TTW may be related to the sources of the nutrient environment. The PCA results of BLE showed that the nutrient concentration in this area might be influenced by various factors rather than anthropogenic sources from the mainland. The GLM test showed that phosphate concentration showed a statistical difference between sampling locations, environment types, and two factors interaction (GLM, $p<0.05$). The nitrate and ammonium concentrations in each location showed statistical differences among the environment types (GLM, $p<0.05$) (Table 2). In the BLE, we observed the strong relationship between redox potential and ammonium in coastal water, which may relate to the denitrification process in mangrove and wetland ecosystems.

Table 2. The GLM analysis results of physiochemical parameters and nutrients in BLD and TTW

Source	Parameters	Type III Sum of Squares	df	Mean Square	F	Sig.
Location	NH_4-N	22,035.781	1	22,035.8	0.4	0.540
	NO_3-N	193,146.606	1	193,146.6	4.3	0.042
	PO_4-P	4,188.972	1	4,189.0	10.8	0.002
	pH	0.353	1	0.4	2.0	0.156
	DO	60.476	1	60.5	2.3	0.134
	Eh	1,944.789	1	1,944.8	6.8	0.011
	Sal	353.491	1	353.5	7.4	0.008
	TDS	495.983	1	496.0	11.5	0.001
Environmental types	NH_4-N	285,418.036	2	142,709.0	2.5	0.092
	NO_3-N	149,986.078	2	74,993.0	1.7	0.195
	PO_4-P	8,825.278	2	4,412.6	11.3	0.000
	pH	0.120	2	0.1	0.3	0.706
	DO	10.388	2	5.2	0.2	0.822
	Eh	133.394	2	66.7	0.2	0.793
	Sal	133.605	2	66.8	1.4	0.252
	TDS	78.809	2	39.4	0.9	0.406
Location* Environmental types	NH_4-N	713,335.224	2	356,667.6	6.1	0.003
	NO_3-N	776,757.509	2	388,378.8	8.6	0.000
	PO_4-P	6,258.984	2	3,129.5	8.0	0.001
	pH	0.595	2	0.3	1.7	0.185
	DO	7.360	2	3.7	0.1	0.870
	Eh	1,389.489	2	694.7	2.4	0.096
	Sal	79.981	2	40.0	0.8	0.435
	TDS	63.700	2	31.8	0.7	0.482

4. DISCUSSION

4.1 Factors influencing physiochemical parameters of coastal waters

The redox potential, salinity, and TDS showed a clear spatial variation trend between TTW and BLE, with the salinity and TDS in TTW significantly lower than those of BLE and vice versa for redox potential. These patterns resulted from tidal dynamics and water exchange between mangroves, shrimp ponds, and coastal water. The salinity and TDS in TTW showed a significant variation among Cw, InsP, and, EcoP zones, whereas salinity and TDS in BLE were more stable in all sampling areas (Table 1). The lower values of salinity and TDS in TTW may be related to water discharge from low salinity aquaculture activities (sea bass production) in TTW, which led to the decreasing trend of salinity and TDS in adjacent shrimp ponds. The physiochemical parameters of coastal and estuarine seawater have seasonal and tidal fluctuations (Trang et al., 2013; Wösten et al., 2003) and seasonal variation was also considered an important influencing factor of physiochemical parameters in river estuaries (Fatema et al., 2014; Pham, 2017; Prabu et al., 2008; Saravanakumar et al., 2008). A study in Pichavaram mangroves showed that the monsoon, river discharge, and tidal variation strongly influence physiochemical parameters in coastal waters (Prabu et al., 2008). In the present study, water samples in the RRD were collected in the dry season, and physiochemical parameters may be strongly affected by tidal flushing rather than river discharge from the mainland. The seasonal variation analysis of nutrient dynamics should be determined in the future research. Additionally, physiochemical parameters are also affected by the water exchange process between the aquaculture ponds and coastal waters in this region. According to tidal cycles, local people will drain wastewater from inside aquaculture ponds into the adjacent tidal creeks at low tide and receive fresh supply water at high tide. Overall, physiochemical parameters of coastal water in this area are influenced by three factors of aquaculture wastewater, mangroves exchange water, and tidal seawater. This pattern is a complex exchange process in coastal estuaries, especially in the RRD. Therefore, long-term monitoring is necessary to assess changes of these parameters in future studies.

4.2 Nutrient variation in the coastal ecosystems of the Red River Delta

The nutrients content in the RRD was higher than those of coastal areas in Vietnam and worldwide (Table 3). The ammonium and nitrate concentrations in the RRD were relatively high compared to Cam and Bach Dang estuaries in northern Vietnam (Trang et al., 2013), and equivalent to Can Gio Area, Ho Chi Minh City (Pham, 2017), Paguil Bay, Philippines, and Merbok estuary, Malaysia (Canini et al., 2013; Fatema et al., 2014). The sources of these nutrients are mainly from human-caused anthropogenic activities such as agriculture, aquaculture, industry, urban waste, etc., and a small part due to natural processes such as the decomposition of organic matter and growth of microorganisms (Downing, 1999; Reopanichkul et al., 2010).

Table 3. The concentration of nutrients in selected study sites in the world

Location	Environment types	NH_4-N (µg/L)	NO_3-N (µg/L)	PO_4-P (µg/L)	References
Red River Delta	Extensive shrimp ponds	305.6-1,500.8	25.1-789.9	0.7-137.6	Current study
	Intensive shrimp ponds	155.8-1,274.9	37.5-472.5	5.3-75.8	
	Estuary and coastal areas	239.1-1,413.6	64.4-996.4	2.2-24.0	
Hai Phong (Vietnam)	Estuary	16.5-571.5	86.7-285.4	8.81-39.00	Trang et al. (2013)
Can Gio (Vietnam)	Estuary	150-300	600-1,500	150-320	Pham (2017)
Phuket (Thailand)	Nearshore water	0.00-93.15	0.00-41.30	0.00-81.30	Reopanichkul et al. (2010)
Panguil Bay (Philipines)	Coastal water	-	300-900	100-500	Canini et al. (2013)
Merbok (Malaysia)	Estuary	100-1,180	50-210	60-80	Fatema et al. (2014)
Allowable limit (local)		100 (Vietnam technical regulation on Marine water quality QCVN10:2023)	60 (ASEAN)	200 (Vietnam technical regulation on Marine water quality QCVN10:2023)	ASEAN-Secretariat (2008)

The distribution of ammonium in coastal water showed a large variation in both TTW and BLE in the RRD. The highest ammonium value was observed in the EcoP site in TTW, whereas the lowest was InsP from BLE. In both areas, the mean ammonium concentration in the EcoP site was higher than in the InsP and Cw samples. This pattern may be related to the decomposition of organic matter and shrimp waste in extensive shrimp ponds, which usually lack of waste water treatment system. Intensive shrimp ponds use water propellers to provide oxygen in water, enhancing the nitrification process and reducing ammonia concentration. The other reason is organic matter ammonification in EcoP with a high density of mangrove trees surrounding the aquaculture ponds (Alongi, 2018; Feller et al., 2003; Taillardat et al., 2020). The high availability of mangrove litter in EcoP will enhance loads of organic matter decomposition, leading to increased ammonium concentration in water (Taillardat et al., 2020). The strong relationship between ammonium concentration and redox potential in BLE supported this pattern (Miao et al., 2006). The ammonium concentration in coastal water of BLE and TTW showed an opposite trend, with the ammonium values of Cw samples in BLE higher than those of EcoP and InsP and vice versa for samples from TTW regions. This trend resulted from the natural characteristics of BLE and TTW regions. The BLE is large estuary with complex tidal creek systems and receives a massive amount of ammonium from adjacent shrimp ponds and mangrove forests (Taillardat et al., 2020), causing the increase of ammonium in the water column.

The nitrate concentration in the RRD showed an opposite trend with ammonium in coastal environments, with the mean concentration in the BLE lower than those of TTW areas. The strong relationship between ammonium, nitrate, and phosphate in the TTW (Figure 3) suggested that the nutrients in this area may originate from the same sources. This pattern was not observed in water samples from BLE, with the nitrate having high loading in PC1. In contrast, ammonium has high loading in PC2 (Figure 3). These results indicated that the nitrate sources in the BLE and TTW may be originated from mainland discharge and local sources, respectively. The BLE received nutrient loads from the urban and industrial areas in northern Vietnam, which led to the high concentration of nitrate in water. Furthermore, the decrease of water discharge volume in the dry season may lead to a weak nutrient dilution process in estuaries, causing an increase trend in nutrient concentration from coastal water adjacent to mangrove forests and aquaculture ponds.

A previous study in the RRD showed that mangrove forests play essential roles in nutrient composition exchange between estuarine and coastal waters. Mangroves in this area were considered net sinks of nutrients from the mainland, where nutrients are assimilated for biomass growth and preserved nutrients in the sediment stratum (Wösten et al., 2003). However, the increase in nutrient discharge may lead to an increased mortality rate of mangroves and degrade other coastal ecosystems (Lovelock et al., 2009). The aquaculture in the coastal zone was also considered an important factor influencing the nutrient dynamic in this region. The effluent from shrimp ponds (both EcoP and InsP) may be led to eutrophic risks in mangrove forests and adjacent coastal waters (Páez-Osuna, 2001; Queiroza et al., 2019; Robertson, 1995). Therefore, reducing nutrient sources from the mainland is necessary for treating aquaculture wastewater in the coastal zone. In addition, the conservation of mangroves is also a solution to reduce nutrient loads released into the marine environment due to filtering pollutants and net sinks of nutrients in the coastal estuary area (Lin and Dushoff, 2004; Tanaka and Choo, 2000).

5. CONCLUSION

Ammonium, nitrate, and phosphate in coastal waters were influenced by tidal flushing, aquaculture discharge, and nutrient exchange between mangrove forests and estuarine water in the Red River Delta. The variation of nutrients in coastal waters and shrimp ponds from the RRD resulted from three main sources of mainland discharge, aquaculture activities, and decomposition of organic matter in coastal zone. Even though the nutrient concentration in intensive shrimp ponds was lower than those of extensive shrimp ponds and adjacent coastal waters, the effluent discharge from this area could be a significant source of nitrogen and phosphorus discharge to the environment. This research indicated that there had been an increase in nutrient concentrations (ammonium, nitrate) in the coastal waters and adjacent aquaculture ponds of the RRD. The prolonged elevation of nutrient levels in the coastal marine environment is expected to result in eutrophication, which will have adverse effects on mangrove forests, tidal flats, estuaries, and other coastal ecosystems. Therefore, spatial and temporal monitoring is necessary to clarify the variation and dynamics of nutrients in coastal marine environments in the future.

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