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Spatiotemporal Dynamics of Water Quality in Intensive Coastal Aquaculture of Shrimp and Clams in Nam Dinh Province, Vietnam

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Abstract

Coastal aquaculture zones, including areas for shrimp and mollusk farming, are subject to multiple stressors, such as internal farming activities, inland runoff, and extreme weather events. These factors contribute to spatiotemporal fluctuations in water quality, directly affecting aquaculture productivity and sustainability. This study aimed to assess the current status of the water quality in the shrimp and clam farming areas across the Nam Dinh coastal districts identify the spatial and temporal variation trends, and propose appropriate management measures. Environmental parameters, including pH, dissolved oxygen (DO), salinity, alkalinity, COD, ammonium (N-NH_4^+), nitrite (N-NO_2^-), hydrogen sulfide (H_2S), total suspended solids (TSS), and total Vibrio count, were monitored biweekly. The samples were collected on the same day between 5:00 and 7:30 a.m. The results indicated significant temporal fluctuations in water quality, with a clear deterioration trend during the rainy season and in storm-affected months, particularly in September, during the passage of Typhoon Yagi. In the shrimp farming areas, the water source quality tended to decline during June-August. Localized differences were also observed: Nghia Hung was characterized by low DO levels, while Hai Hau experienced large salinity fluctuations. In the clam farming zones, water quality was lowest in June and July. Giao Thuy exhibited a higher frequency of salinity values falling below acceptable thresholds compared to Nghia Hung, suggesting greater variability in salinity levels. These findings provide a scientific basis for local authorities and farmers to plan adaptive water management strategies, such as storing high-quality water for use during periods of environmental stress.

Keywords

Nam Dinh, intake water, shrimp farming, clam farming, water quality

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Introduction

Nam Dinh plays an important role in advancing the fisheries sector in Northern Vietnam. According to the Nam Dinh Fisheries Sub-Department, the province's total aquatic production in 2024 reached 202,580 tons, with aquaculture contributing 141,434 tons and capture fisheries accounting for 61,146 tons. The total value of fisheries production was estimated at VND 12 trillion, representing approximately 30.6% of the province’s agricultural, forestry, and fisheries output. Brackish and marine aquaculture plays a central role, with a total farming area of 6,045 hectares and an estimated production of 71,730 tons, an increase of 5.9% compared to 2023. Key cultured species include brackish-water shrimp, clams, and marine fish. Notably, whiteleg shrimp (*Litopenaeus vannamei*) farming has continued to expand, with various intensive systems including lined ponds, tanks, and greenhouse-based models. In 2024, the total area of brackish-water shrimp farming reached approximately 3,200 hectares, including 1,100 hectares of whiteleg shrimp farming, with a production of 4,500 tons. High-tech intensive and super-intensive farming models have been increasingly adopted, particularly in Giao Phong and Giao Thien communes (Giao Thuy district), and Hai Trieu and Hai Hoa communes (Hai Hau district), with productivity exceeding 30 tons ha^{-1}. In parallel, commercial clam farming remains stable, with around 2,200 hectares under cultivation and an estimated production of 49,800 tons. In recent years, clam farming in Nam Dinh has faced multiple challenges. Environmental pollution, coupled with the impacts of climate change, including irregular rainfall, abrupt fluctuations in temperature, and salinity shifts, have resulted in mass mortalities. Moreover, clam culture grounds have been severely affected by mud accretion. The production cycle has also become considerably longer: while farmers previously harvested within 24 months, production now requires 36-38 months. Amid growing environmental challenges, effective water quality monitoring and management have become essential. In Nam Dinh, heavy reliance on natural water sources, often subject to unpredictable fluctuations, poses significant risks for coastal shrimp and clam farming. Recognizing the critical role of environmental conditions in ensuring production efficiency and sustainability, the province has implemented regular water quality monitoring programs to provide early warnings and improve farm management. This study aimed to evaluate the water quality conditions in the shrimp and clam farming areas across the coastal districts of Nam Dinh during the 2023-2024 period. The results provide a scientific basis for recommending effective environmental management strategies to support the sustainable development of coastal aquaculture in the region.

Methods

Monitoring locations, frequency, and parameters

Water samples were collected twice monthly from May to December in both 2023 and 2024, coinciding with the peak aquaculture season in Nam Dinh province. The period from January to April was excluded due to the low intensity of farming activities. Sampling sites were selected to represent the major clam farming areas (Giao Thuy and Nghia Hung) and shrimp farming areas (Giao Thuy, Nghia Hung, and Hai Hau), based on production scale and recommendations from the provincial management office (**Table 1**).

The monitoring parameters for the shrimp farming areas included 10 indicators: pH, dissolved oxygen (DO), salinity, alkalinity, ammonium (N-NH_4^+), nitrite (N-NO_2^-), COD, hydrogen sulfide (H_2S), total suspended solids (TSS), and the total Vibrio count. For the clam farming areas, the dataset was comprised of 10 parameters: pH, DO, salinity, alkalinity, N-NH_4^+, N-NO_2^-, H_2S, TSS, density and composition of harmful algae, and the total Vibrio count. At each site, samples were collected from three cross-sectional points.

Sample collection and preservation

Water samples were collected using a Wildco bathometer (S/N: 1120-G42) at a depth of 30cm and preserved at 3-5°C. Phytoplankton

Table 1. Monitoring locations

Aquaculture area	District	Monitoring site description	Coordinates
Brackish-water shrimp farming	Giao Thuy	Intake sluice, Lien Phong, Giao Phong commune	20°12'26.5"N 106°24'16.2"E
		Thanh Nien sluice, Bach Long commune	20°12'28.1"N 106°25'15.1"E
		Ong Dinh sluice, Tan Hong, Giao Thien commune	20°15'48.9"N 106°32'32.5"E
	Nghia Hung	Thanh Huong sluice, Nghia Binh commune	20°02'25.0"N 106°12'21.9"E
		CM3 sluice, Con Xanh area, Nam Dien commune	19°57'26.3"N 106°08'12.4"E
Brackish-water shrimp farming	Hai Hau	Intake sluice, Xuan Ha, Hai Hoa commune	20°03'36.5"N 106°14'53.3"E
		Intake sluice, Tay Tien, Hai Trieu commune	20°04'14.7"N 106°15'35.1"E
		Intake sluice, Hai Chinh commune	20°06'27.6"N 106°17'32.6"E
		An Hoa sluice, Hop Thanh, Hai Dong commune	20°10'27.2"N 106°20'58.5"E
		Intake sluice, aquaculture area, Hai Phuc commune	20°10'60.0"N 106°21'03.9"E
Clam farming	Giao Thuy	Clam seed farming area, Giao Xuan commune	20°12'37.1"N 106°29'24.0"E
	Nghia Hung	Clam seed farming area, Nam Dien commune (eco-zone)	19°58'00.5"N 106°09'41.3"E

samples were collected using a 20µm mesh plankton net, fixed with 5% formalin, and subsequently preserved in 70% ethanol.

Sample analysis

All parameters were analyzed at an ISO 17025:2017 certified laboratory of the Center for Environmental and Disease Monitoring in Aquaculture. Physicochemical parameters in the water were analyzed following the guidelines of Baird & Bridgewater (2017), as detailed below:

The values of pH and DO were measured using a YSI Professional Series meter (S/N: 18K100418). Salinity was determined using an Atago PAL-06S refractometer (S/N: S214454). Alkalinity was measured by titration with sulfuric acid. $N\text{-}NO_2^-$, $N\text{-}NH_4^+$, and H_2S concentrations were determined by colorimetric methods using a Hitachi U-2900 spectrophotometer (S/N: 30E13-007). COD was analyzed by titration with 0.01M FAS after digestion at 150°C for 2 hours under reflux conditions. TSS were determined gravimetrically after drying at 103-105°C.

The density and composition of harmful algae were identified to the genus/species level using a Sedgwick–Rafter counting chamber (S/N: 3-1801-G20) under a light microscope (Olympus CX23).

The total Vibrio count was analyzed following the method described by Buller (2004). Water samples were serially diluted with sterile 2% NaCl solution, and an aliquot of 100 µL from each dilution was spread onto Thiosulfate–Citrate–Bile salts–Sucrose (TCBS) agar plates (Merck, Germany). The plates were incubated at 29.0°C for 24 hours. After the incubation period, all bacterial colonies that developed on the agar plates were counted, and the Vibrio density in the sample was determined using the formula: $\mathbf{X = (10^K \times A) \div 0.1}$. In this equation, **X** represents the bacterial density in one milliliter of the sample, expressed as colony-forming units per milliliter (CFU mL^{-1}); **A** is the number of colonies counted on the agar plate; **K** denotes the dilution factor of the sample that was plated; and 0.1 indicates the inoculated volume in milliliters.

Data analysis

Data were compiled and analyzed using Microsoft Excel 2010. Descriptive statistics and analysis of variance (ANOVA) were performed using the Real Statistics add-in for Microsoft Excel to assess temporal variations in water quality. Pairwise comparison method of Tukey's HSD was used to determine the statistical significance of differences between group means (P <0.05). Principal component analysis (PCA) was conducted using Stata 12 software.

Results

Temporal variation in intake water quality in shrimp and clam farming areas

Temporal changes in the quality of the intake water at the shrimp and clam farming areas in Nam Dinh are presented in **Figure 1**. Monthly average pH ranged from 7.74 ± 0.37 (July) to 8.01 ± 0.26 (October), with significantly higher values in October compared to September (P <0.05). The decline in July was likely due to peak rainfall. All pH values remained within the optimal range (7.5-8.5) recommended by TCVN 13656:2023.

In the shrimp farming areas, DO ranged from 4.13 ± 0.66 mg L^{-1} (June) to 5.35 ± 0.85 mg L^{-1} (December), with significantly higher DO values from August to December than in May to June (P <0.05) (**Figure 1**). Salinity in the shrimp farming areas varied between 16.84 ± 10.09‰ (September) and 27.32 ± 4.73‰ (November), and were significantly lower during the rainy season (May–September) compared to November–December (P <0.05). Alkalinity ranged from 86.53 ± 17.43 mg L^{-1} (September) to 106.21 ± 36.25 mg L^{-1} (August), with significantly higher levels in September-October than in earlier months (P <0.05). COD fluctuated from 1.72 ± 1.18 to 2.30 ± 1.05 mg L^{-1}, showing no significant monthly variation (P = 0.54). N-NH_4^+ peaked in June (0.26 ± 0.14 mg L^{-1}) and was lowest in October (0.16 ± 0.10 mg L^{-1}), with no significant differences (P >0.05). N-NO_2^- ranged from 0.02 ± 0.02 to 0.04 ± 0.03 mg L^{-1}, with the highest values in June and December; and levels in September were significantly higher than in May and November (P <0.05), likely due to organic matter decomposition and inhibited nitrification under unstable late-season conditions. H_2S remained low (0-0.02 ± 0.04 mg L^{-1}). TSS increased from 47.74 ± 37.59 mg L^{-1} (May) to 83.94 ± 46.00 mg L^{-1} (December), with significantly higher values in December (P <0.05). Vibrio counts ranged from 418.21 ± 650.77 to 847.29 ± 1214.42 CFU mL^{-1}, with no significant variation (P >0.05).

Water quality in the clam farming areas exhibited seasonal variation but generally remained within acceptable ranges. pH values ranged from 7.73 ± 0.38 (September) to 8.10 ± 0.20 (October), with no significant monthly differences (P >0.05). Dissolved oxygen peaked in December (6.75 ± 1.30 mg L^{-1}), which was significantly higher than in June and September (P <0.05). Salinity dropped markedly in September (12.00 ± 8.35‰) due to Typhoon Yagi and freshwater influx, then increased significantly in November–December (up to 25.50 ± 2.74‰; P <0.05). Alkalinity was highest in May (115.25 ± 29.31 mg L^{-1}), significantly exceeding levels in September and October (P <0.05). Ammonium (0.121-0.410 mg L^{-1}) and nitrite (0.019-0.049 mg L^{-1}) showed no significant fluctuations (P >0.05). H_2S remained negligible (≤ 0.006 mg L^{-1}), while TSS varied widely (33.97-77.05 mg L^{-1}). The harmful algae density peaked in May (6,351 ± 16,837 cells L^{-1}), within safe limits. Vibrio counts ranged from 10.75 ± 12.47 to 681.00 ± 1110.9 CFU mL^{-1}, with no significant differences (P >0.05).

Spatial variation in intake water quality in shrimp and clam farming areas

Spatial variation in the intake water quality was evaluated in this study by analyzing the percentage of samples falling outside permissible thresholds across the shrimp and clam farming areas (**Figure 2**). Parameters not included in the figure were consistently within acceptable limits during the monitoring period. In the shrimp farming areas, the proportion of pH measurements falling outside the acceptable range differed significantly among the three districts (P <0.05), with Giao Thuy reporting the highest proportion (19%), followed by Nghia Hung (6%) and Hai Hau (5%). For dissolved oxygen (DO), although the percentage of samples outside the acceptable range was highest in Nghia Hung (67%), followed by Giao Thuy and Hai Hau (both 56%), these differences were not statistically significant (P >0.05). In contrast, salinity levels exhibited a statistically significant difference among districts (P <0.05), with Hai Hau showing the highest proportion (62%), followed by Giao Thuy (50%) and Nghia Hung (48%). Alkalinity values outside the acceptable range did not differ significantly among the districts, with Giao Thuy at 10%, Nghia Hung at 8%, and Hai Hau at 4%. Total suspended solids

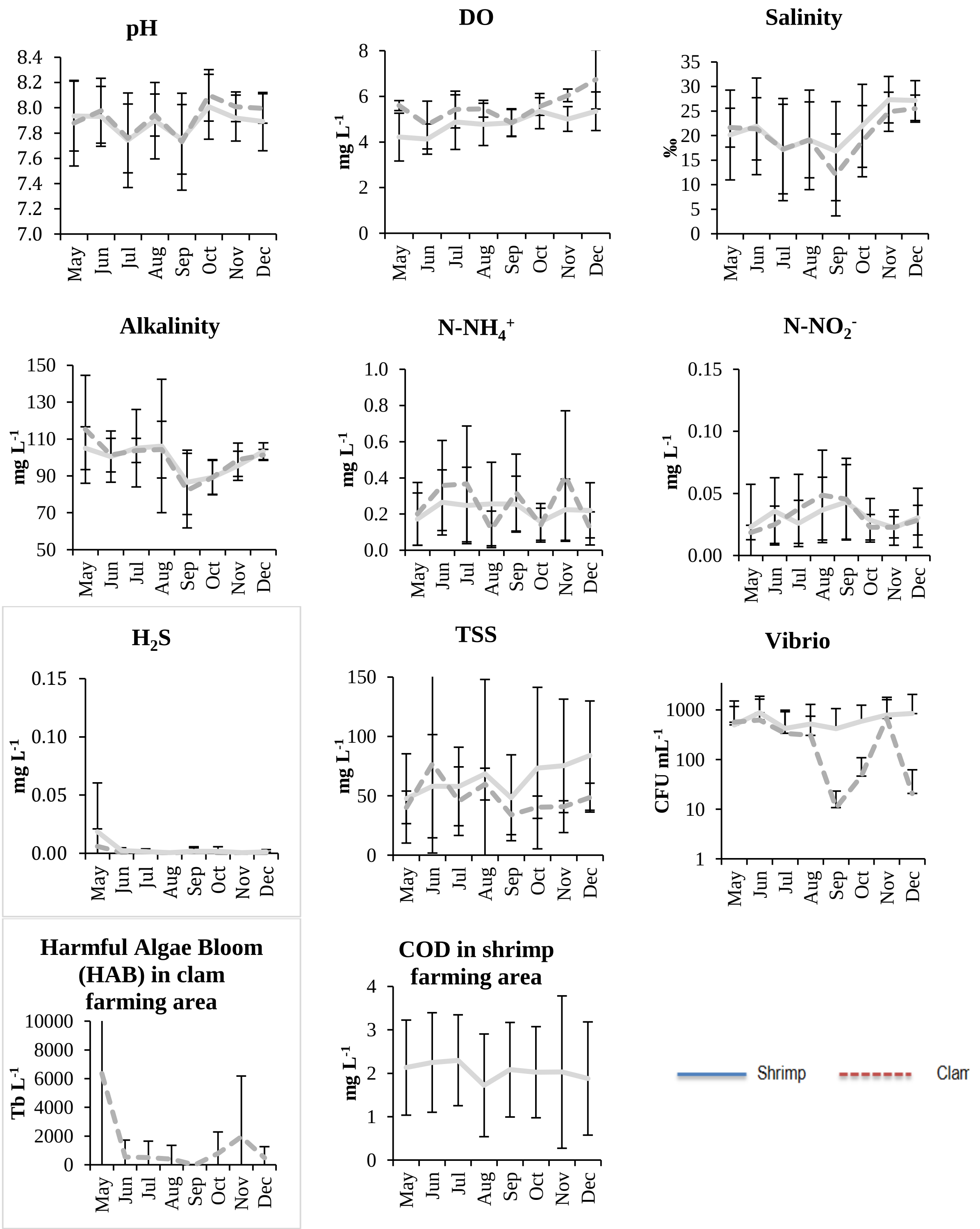

Figure 1. Temporal variation in the intake water quality at the shrimp and clam farming areas in Nam Dinh

(TSS) showed a significant difference (*P* <0.05), with Hai Hau having the highest proportion of samples exceeding the permissible limit (23%), compared to Giao Thuy (8%) and Nghia Hung, which had none (0%).

In the clam farming areas, only salinity showed a statistically significant difference between Giao Thuy and Nghia Hung (*P* <0.05), with a notably higher proportion of samples exceeding the acceptable threshold in Giao Thuy

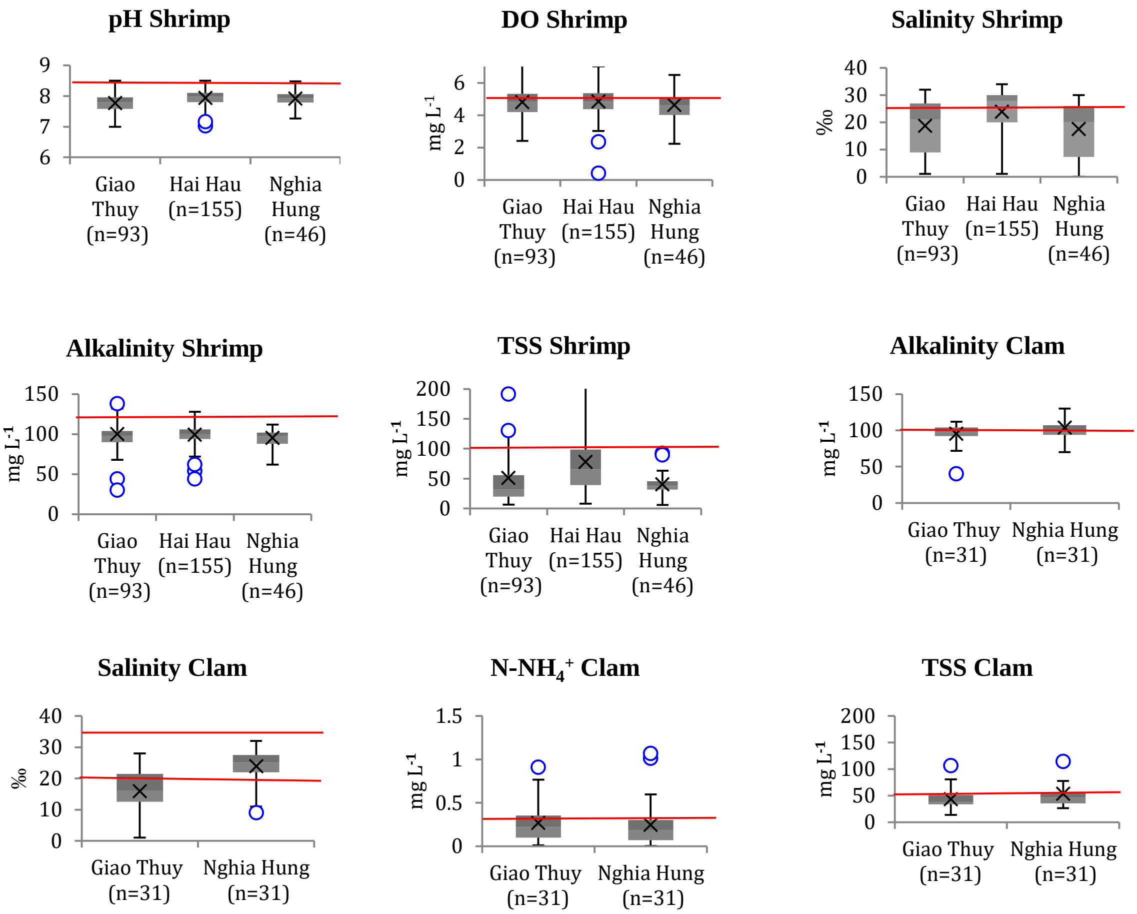

Figure 2. Percentage of the intake water samples falling outside permissible limits in the shrimp and clam farms (n = number of samples, the red line indicates the allowable threshold).

(59%) compared to Nghia Hung (16%). Other parameters, including alkalinity (Giao Thuy: 50%, Nghia Hung: 47%), ammonium (N-NH_4^+) (34% and 25%), and TSS (both 28%) did not show statistically significant differences, although the values in Giao Thuy were generally higher.

Principal component analysis and correlation analysis of environmental conditions

Regarding the quality of the intake water in the shrimp farming areas, the results of the principal component analysis (PCA) showed that the first two principal components together explained 60.88% of the total variance in the dataset. Specifically, the first principal component (PC1) accounted for 36.15%, while the second principal component (PC2) explained 24.73% (**Figure 3**). The distribution of sampling points along these components revealed clear temporal variations in the water quality parameters across the shrimp farming sites (**Figure 3A**).

For the intake water quality in the clam farming areas, the first principal component (PC1) accounted for 35.72% of the total variance, while the second principal component (PC2) explained 24.53%. Combined, these two components captured approximately 60.2% of the total variability in the dataset, which was adequate for visualizing and interpreting the main trends in water quality at the clam farming sites (**Figure 3B**).

Discussion

This study evaluated the temporal variation and interrelationships among key water quality parameters in shrimp and clam farming areas

(A)

(B)

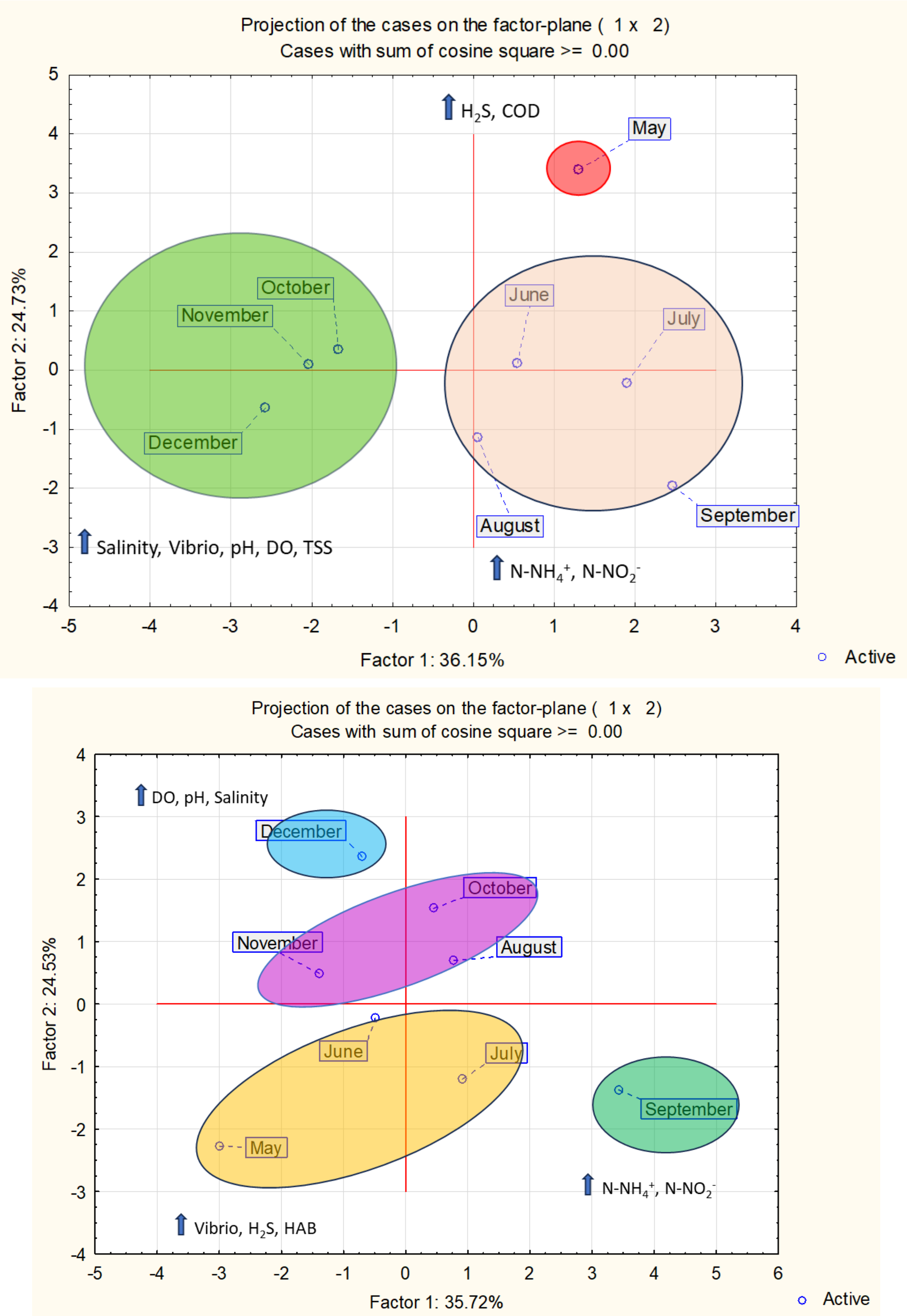

Figure 3. Principal component analysis (PCA) of the monthly water quality variation in the shrimp farms (A) and clam farms (B)

using principal component analysis (PCA) and correlation analysis. These findings provide important insights into seasonal environmental fluctuations and their potential impacts on animal health and aquaculture management.

Variation of intake water quality in shrimp farming areas

There was a noticeable increase in H_2S and COD in May, likely due to the onset of the rainy season in Northern Vietnam. The rains may have caused runoff from surrounding agricultural and residential areas, transporting organic matter into the water system. Combined with a drop in pH due to rainwater dilution, these conditions could have enhanced H_2S release from sediments. According to Chien (1992), the safe total sulfide concentration for *Penaeus monodon* is 0.033 mg L^{-1}. Therefore, pre-treatment of incoming water is advisable before filling ponds. H_2S can be removed using aeration systems or chemical oxidation with potassium permanganate ($KMnO_4$) at 6-8 times the H_2S concentration. Alternatively, iron oxides may be applied at 1 kg m^{-2} or more to precipitate H_2S into non-toxic metal sulfides. Sodium nitrate ($NaNO_3$) can be added to maintain oxidizing conditions near the sediment-water interface, reducing H_2S diffusion. While biological agents and zeolite are often marketed for H_2S control, their effectiveness varies, and the cost may be prohibitive (Boyd, 2014).

In June, July, and August, elevated concentrations of ammonium ($N\text{-}NH_4^+$) and nitrite ($N\text{-}NO_2^-$) were observed, possibly due to the discharge of effluents from the first shrimp crop. In addition, rainfall during this period may have mobilized nitrogen-rich waste from the surrounding land. Uneaten feed and excreta are the primary sources of $N\text{-}NH_4^+$ in aquaculture ponds. While a portion of dietary nitrogen is incorporated into biomass, the remainder is excreted as organic nitrogen or ammonia ($N\text{-}NH_3$). Controlling the accumulation of NH_3 is thus critical for maintaining pond health (Boyd *et al.*, 1998). Elevated temperatures during these months accelerated the microbial decomposition of organic matter, increasing the release of $N\text{-}NH_4^+$ and $N\text{-}NO_2^-$. Organic matter decomposition rates can double for every 10°C increase up to 40°C (Boyd *et al.*, 1998). This buildup raises concerns over NH_3 and $N\text{-}NO_2^-$ toxicity. NH_3 toxicity increases at lower salinities, with safe levels for *Litopenaeus vannamei* postlarvae estimated at 0.12, 0.16, and 0.16 mg L^{-1} for salinities of 15‰, 25‰, and 35‰, respectively (Lin *et al.*, 2001). Whetstone *et al.* (2002) considered $N\text{-}NO_2^-$ levels below 0.23 mg L^{-1} safe for shrimp. According to Boyd *et al.* (1998), nitrite toxicity is inversely related to chloride concentration and thus salinity. Chen & Chen (1988) reported a safety threshold of 4.5 mg L^{-1} for *P. monodon* postlarvae. More generally, water quality with < 0.5 mg L^{-1} nitrite is considered good, and 0.5-2 mg L^{-1} as moderate (Boyd *et al.*, 1998). Nitrite impairs growth and can cause mortality at high levels. Gross *et al.* (2004) found that exposure to 4 mg L^{-1} of $N\text{-}NO_2^-$ for two days reduced shrimp growth without immediate mortality. Studies by Fregoso-López *et al.* (2018) and Valencia-Castañeda *et al.* (2018) highlighted the increased toxicity of nitrogenous compounds like NH_3 and NO_2^- at low salinities. Estimated safe concentrations of total ammonia and nitrite for *L. vannamei* postlarvae at salinities of 1 and 3‰ are 0.54-0.81 mg L^{-1} ($N\text{-}NH_3$) and 0.17-0.25 mg L^{-1} ($N\text{-}NO_2^-$), respectively (Ramírez *et al.*, 2017). In response to these challenges, farmers should maintain a reserve of clean water during this period and minimize water exchange with external sources to reduce biosecurity risks and nitrogen loading.

In October to December, increases in salinity and total Vibrio density were observed. These coincided with the dry season, when reduced rainfall and increased evaporation lead to increased salt concentrations. In this study, Vibrio levels were positively correlated with salinity (r = 0.26, **Figure 4A**), consistent with findings reported by Randa *et al.* (2004). The end of the culture cycle is a vulnerable period due to a higher shrimp density and more unstable environmental conditions. Farmers should carefully monitor salinity and apply periodic disinfection, while managing water exchange to reduce pathogen load. Salinity also influences shrimp physiology, including survival, protein retention, and fat content (Maicá *et al.*, 2014). Lower salinity can reduce the risk of bacterial and viral infections (Fregoso-López *et al.*, 2018), but abrupt salinity reductions may compromise immunity and trigger viral outbreaks. Liu *et al.* (2006) demonstrated that decreasing salinity from 22‰ to 18‰ or 14‰ increased susceptibility to white spot syndrome virus (WSSV). Vibrio levels above 1,000 CFU/mL are considered a disease risk threshold (Anand Ganesh *et al.*, 2010). Vibriosis is a severe bacterial disease that poses a major threat to

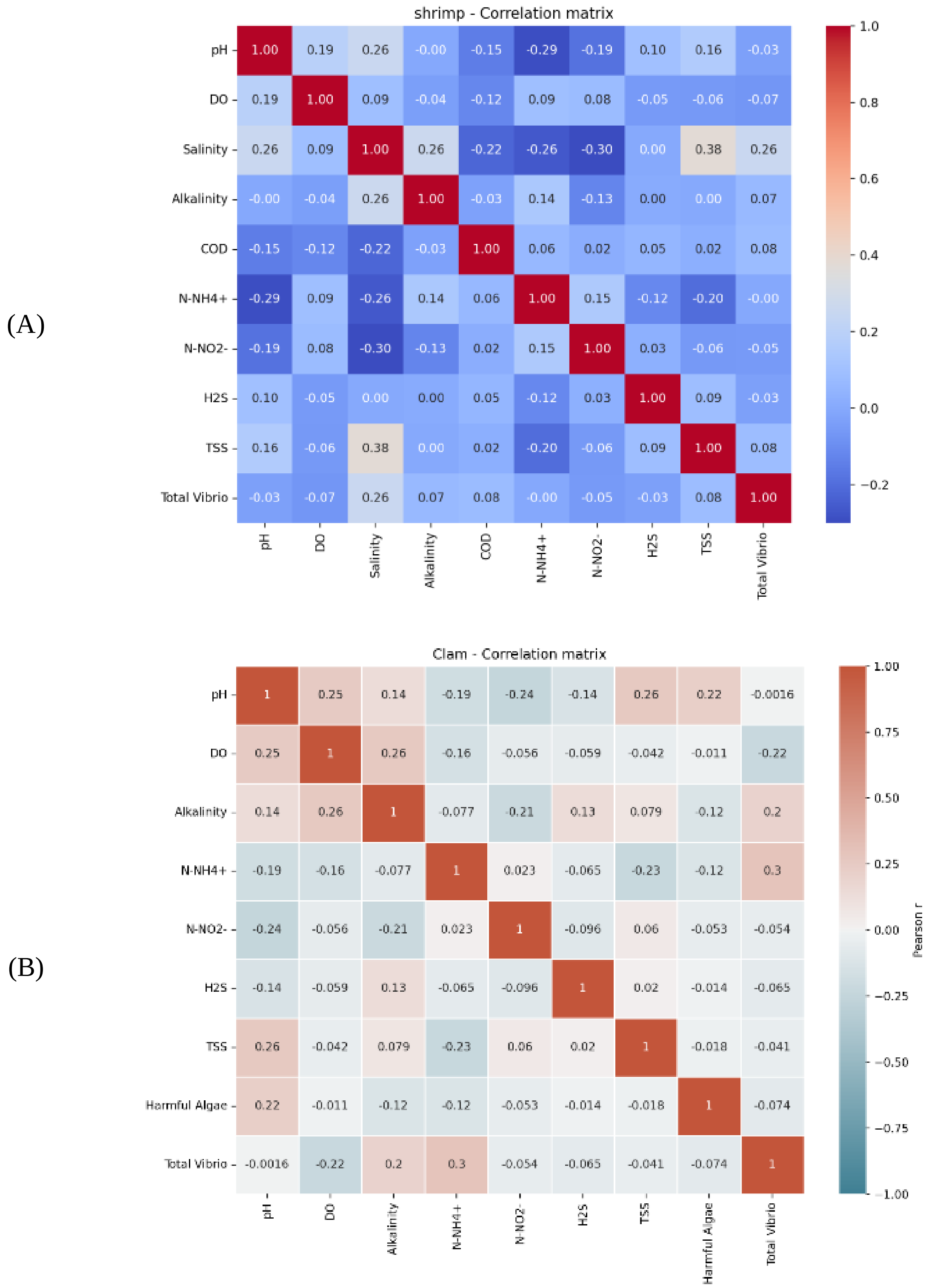

Figure 4. Correlation matrix of the environmental conditions in the shrimp farms (A) and clam farms (B).

shrimp farming worldwide (Hany *et al*., 2022). The large variation in Vibrio counts among the sampling sites can be attributed to differences in water quality. In particular, some locations showed higher concentrations of N-NH_4^+, COD, TSS, and salinity compared to others. These factors provide favorable conditions for Vibrio proliferation, thereby contributing to the observed increase and variability in bacterial abundance in the aquaculture environments. Clinical signs of Vibrio infection include lethargy, anorexia, darkened or necrotic hepatopancreas, gill discoloration, white abdominal spots, and necrosis in various tissues.

In December, elevated TSS levels were recorded, likely due to the accumulation of organic matter (e.g., uneaten feed, shrimp feces, and dead algae) over the culture period. Seasonal die-off of algae, driven by environmental and nutrient shifts, contributed to the suspended biomass. Cooler temperatures at this time may have reduced microbial decomposition efficiency, slowing sedimentation. In contrast, during the earlier months (May-October), organic matter buildup was limited and microbial activity was higher, resulting in lower TSS. Elevated TSS may impair shrimp immunity and increase disease risk. Farmers are advised to treat incoming water to remove suspended solids prior to pond filling to maintain stable water quality.

Spatially, differences in the environmental indicators were also observed among the three districts. Giao Thuy had the highest proportion of samples outside the acceptable ranges for pH and alkalinity. Nghia Hung recorded the most samples with DO values below the threshold. Hai Hau showed the highest exceedance rates for salinity and TSS. Several parameters, including pH, salinity, and TSS, exhibited statistically significant differences among the districts.

Variation of intake water quality in clam farming areas

The PCA results indicated that June and July were associated with increased levels of Vibrio density, harmful algae, and ammonium ($N\text{-}NH_4^+$), suggesting a decline in water quality during this period. September was characterized by elevated concentrations of nitrite ($N\text{-}NO_2^-$) and ammonium, potentially influenced by the rainy season and the impact of Typhoon Yagi. In contrast, August, October, and November exhibited relatively more stable environmental conditions. Notably, December showed higher salinity levels, likely due to reduced rainfall and increased evaporation toward the end of the year, reflecting seasonal climatic variation.

In this study, nitrite concentrations at the clam farming sites ranged from 0.01 to 0.05 mg L^{-1}, well below the acute or chronic toxicity thresholds. However, in some events, nitrite concentrations ($N\text{-}NO_2^-$) exceeded the acceptable thresholds at the clam farming sites suggesting that the aquatic environment had been impacted by organic pollution. Both the Giao Thuy and Nghia Hung clam farming areas are subject to land-based runoff, including wastewater from sewage, agriculture, and particularly brackish water shrimp farming systems, which are often located adjacent to the clam farms. According to Epifanio and Srna (1975), the 96-hour median lethal concentration (LC50) for clams exposed to $N\text{-}NO_2^-$ ranges from 1.863 to 1.955 mg L^{-1}. Therefore, clams in these regions are not currently at risk of nitrite-induced toxicity.

Ganesh (2010) recommended that Vibrio densities in aquaculture systems be maintained below 1,000 CFU mL^{-1}, as levels above this threshold significantly increase the risk of disease outbreaks. Correlation analysis in this study revealed a positive relationship between total Vibrio counts and both ammonium ($N\text{-}NH_4^+$) ($r = 0.30$) and alkalinity ($r = 0.20$), and a negative correlation with dissolved oxygen (DO) ($r = -0.22$) (**Figure 4B**). These findings are consistent with previous studies indicating that Vibrio proliferation is favored in environments rich in organic matter and low in oxygen (Sampaio *et al*., 2022). Similar correlations between Vibrio abundance and elevated ammonium concentrations have also been observed in coastal aquaculture systems (Ganesh, 2010). Collectively, these results provide practical insights for aquaculture management by identifying periods when ammonium concentrations are likely to rise and salinity may decrease to critical thresholds, thereby serving as an early warning system that enables farmers to adopt proactive measures in culture practices.

Conclusions

This study revealed that the intake water quality in the shrimp and clam farming areas along the Nam Dinh coastline is subject to both temporal and spatial variation, influenced by internal farming practices, land-based runoff, and extreme weather events such as Typhoon Yagi. Temporally, deteriorating water conditions were marked by increased levels of inorganic nitrogen (N-NH_4^+ and N-NO_2^-) and harmful algae, and Vibrio were observed from May to September, particularly during the rainy season. Spatial differences were also evident, with Nghia Hung frequently showing low DO levels, Hai Hau experiencing large salinity fluctuations, and Giao Thuy recording more frequent occurrences of salinity values outside acceptable thresholds. From October to December, salinity and total suspended solids (TSS) tended to rise, indicating a shift in environmental conditions toward the end of the farming season. These findings underscore the importance of regular monitoring and effective water quality management, especially during high-risk periods, to maintain stable aquaculture conditions and minimize environmental and disease-related risks.

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