



Tidal-Diurnal Interactions and Nitrogen Dynamics: Integrating Variability into Sustainable Brackish Water Pond Management

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ABSTRACT

Water quality is a fundamental determinant of aquaculture success, shaping the growth, health, and survival of the cultured species. In traditional pond irrigation systems, tidally driven variability alters the physicochemical conditions, creating risks of stress, reduced productivity, and mortality. This study quantified the tidal–diurnal controls on water quality dynamics in Sawohan Village, Sidoarjo, Indonesia, across a freshwater–brackish–saline gradient. Water quality was monitored at three ponds during spring and neap tides, both during the day and night, yielding 48 sampling events. The measured parameters included pH, salinity, dissolved oxygen (DO), alkalinity, nitrate, nitrite, and ammonia. Data were analyzed using descriptive statistics and two-way ANOVA. The tidal phase and sampling time significantly affected several parameters ($p < 0.05$). The pH showed the lowest value of 7.47 in brackish ponds during nighttime spring tides, while salinity ranged from <0.5 ppt during neap tides to 19.0 ppt in the saline pond during daytime spring tides. DO was consistently lower at night than during the day and occasionally fell below the 5 mg.L^{-1} aquaculture threshold during nighttime neap tides. Alkalinity remained within $116.88\text{--}150.33 \text{ mg.L}^{-1}$, with higher values at night, particularly during the spring tides. Nitrate concentrations frequently exceeded national and aquaculture guideline values, whereas nitrite and ammonia approached or exceeded their respective thresholds in brackish and saline ponds, especially during nighttime neap tides. Overall, these results demonstrate that tidal–diurnal interactions strongly influence nitrogen dynamics and water quality stability in traditional pond irrigation systems and should be explicitly considered in aquaculture water quality assessment and monitoring.

1. INTRODUCTION

Global aquaculture is increasingly recognized as a cornerstone of food security, economic resilience, and sustainable development under the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 14 (Life Below Water). With global demand for aquatic protein projected to increase by more than 30% by 2030, ensuring the ecological sustainability of aquaculture systems has become a pressing concern (FAO 2024). Coastal and estuarine aquaculture, in particular, faces critical challenges from climate-induced sea-level rise, eutrophication, and chemical pollution, which jeopardize both production and ecosystem health (Hossain et al. 2025).

Rapid environmental change underscores the urgency for developing sustainable and adaptive management systems. Among sectors closely linked to ecosystem stability, fisheries are particularly vulnerable because of their strong dependence on environmental quality. Fluctuating water conditions and anthropogenic activities cause changes in water composition, often driven by external factors beyond local ecosystem control. As salinity levels and seawater pollution from effluents and

other contaminants continue to rise, maintaining pond water quality remains a critical concern requiring both scientific and sustainable management interventions (Wang et al. 2023).

Sawohan Village in Sidoarjo District stands out among coastal regions engaged in aquaculture for its preservation of a traditional pond irrigation system. This system reflects local ecological knowledge and water management practices, showcasing how communities have adapted to the unique geographical and ecological challenges of coastal environments. Wetlands dominate the landscape in Sawohan Village, covering 900.15 hectares of a total area of 940.59 hectares—over 95% of the village's land area. This extensive wetland coverage offers substantial opportunities for aquaculture expansion. The widespread utilization of wetlands indicates strong community involvement in the fisheries sector and underscores the economy's reliance on coastal ecosystems. Traditional shrimp and milkfish farming continues to be essential for sustaining the livelihoods of local residents (Meilani & Rahmadanik 2021).

One of the key environmental drivers influencing the sustainability of pond irrigation systems in this area is the tidal cycle. As the primary hydrodynamic force, tides regulate the volume and timing of seawater entering ponds, thereby directly influencing water quality and the efficiency of aquaculture operations (Muhtadi et al. 2024). The two principal tidal phases (spring and neap tides) differ in their amplitude and duration. Spring tides, which occur when the moon and sun align with the Earth, exert the maximal gravitational pull, leading to the highest and lowest tides. During this time, seawater flow into the pond can significantly increase, resulting in increased nutrient input, changes in salinity gradients, and higher water exchange efficiency (Sa'adah & Widagdo 2020).

Effective pond aquaculture necessitates careful attention to various environmental conditions to prevent adverse outcomes. Poor water quality can cause physiological stress, decrease productivity, and increase mortality risks among cultured species. In brackish water pond systems, water quality is affected by several physicochemical factors, including dissolved oxygen (DO), salinity, nitrite, ammonia, temperature, and pH. Therefore, the sustainability of wetland use in Sawohan Village is fundamentally dependent on these parameters, which are closely tied to tidal fluctuations—a key feature of traditional irrigation systems.

Despite a substantial body of literature on aquaculture sustainability and tidal influences in estuarine and intensive pond environments, few studies have systematically examined the combined effects of tidal cycles and spatial irrigation gradients on water quality in traditional systems. Recent research predominantly concentrates on intensive

or industrial aquaculture, nutrient loading, and effluent management (Salin & Ataguba 2018). However, a notable gap remains in understanding how tidal phases and diel cycles influence physicochemical water parameters and nitrogen species across freshwater–brackish–saline gradients in smallholder, traditional irrigation-based aquaculture in Southeast Asia. Additionally, most studies lack replication, randomization, or spatially explicit sampling designs, which limits the reliability and broader applicability of their findings (Xiao et al. 2025).

This study systematically examines the quality of brackish water used for irrigation across freshwater, brackish, and saline pond gradients in Sawohan Village, considering different tidal and diurnal conditions. Currently, detailed data on the spatial characteristics of pond irrigation water quality, particularly in the coastal areas of Sidoarjo, are scarce. Additionally, tidal-based irrigation methods have not been thoroughly explored, especially regarding maintaining optimal water quality for aquaculture. Therefore, this research investigates how tidal phase (spring versus neap) and time of day (day versus night) jointly influence key parameters such as pH, salinity, dissolved oxygen, alkalinity, nitrate, nitrite, and ammonia throughout the irrigation network. The goal is to quantify the effects of tidal and diurnal variations on these water quality parameters and assess their compliance with national and aquaculture standards. Mapping current conditions and identifying potential pollution sources are crucial steps toward managing irrigation systems that are both sustainable and adaptable to the environmental changes increasingly observed in recent years.

This study advances current research by combining replicated, randomized field sampling with physicochemical measurements—such as pH, salinity, dissolved oxygen, and temperature—and chemical pollution indicators, including ammonia, nitrite, nitrate, and alkalinity, within a traditional pond irrigation system. By integrating tidal phase and time-of-day data with spatial variability across irrigation channels, it expands previous analyses of tidal influences and offers site-specific evidence to inform adaptive aquaculture irrigation management for local smallholder communities.

2. MATERIALS AND METHODS

2.1. Study Site

The research was carried out in a traditional pond irrigation area situated in Sawohan Village, Kepetingan Hamlet, Sidoarjo Regency, East Java Province (Meilani & Rahmadanik 2021). The area was chosen because it exhibits a complete hydrological gradient, ranging from freshwater inflows to brackish water transition zones and

saline aquaculture ponds, thereby representing the variety of water conditions encountered by local farmers. Three representative sites along this gradient were systematically selected: (1) a freshwater pond (7°26'43.1"S, 112°47'18.9"E), (2) a brackish water pond (7°27'05.5"S, 112°47'25.3"E), and (3) a saline aquaculture pond near the estuary connecting the river and the sea (7°27'19.7"S, 112°47'39.8"E).

Fieldwork took place from July to August, aligning with the spring and neap tide phases. This timing was chosen because transitional tide conditions help minimize extreme salinity fluctuations and reduce water quality changes that could impact aquaculture performance. Sampling occurred during four spring-tide and four neap-tide events spread across the two months. During each tidal event, water quality measurements were taken at the three sites both during the day and night, resulting in 48 data points (3 sites × 2 tidal phases × 2 times of day × 4 sampling dates). For each combination of site, tidal phase, and time of day, three independent sub-samples were collected and averaged to produce a single measurement, meeting the minimum sample size requirements based on an a priori power analysis ($\alpha = 0.05$, $\beta = 0.8$), thus ensuring the statistical validity of the results (Perugini et al. 2018).

Sampling points were randomly shifted within a 5-meter radius at each site to reduce micro-scale spatial bias. Potential confounding factors—such as rainfall events, agricultural runoff, and human waste disposal—were monitored through daily weather data from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG), visual inspections of irrigation flows, and weekly interviews with local farmers. To account for short-term temporal variability,

measurements were taken during two fixed periods each day: morning (10:00–12:00) and evening (21:00–23:00). All measurements were performed under consistent meteorological conditions, with instruments calibrated before each field session. Fig. 1 illustrates the study locations with geographic coordinates, a scale bar, a north arrow, and hydrological features derived from a Google Earth basemap, ensuring spatial clarity.

2.2. Data Collection

This study employed a descriptive, quantitative approach to evaluate the quality of brackish water in pond irrigation canals by measuring various physical and chemical parameters. The use of a quantitative method was essential for collecting environmental data, such as pH, salinity, temperature, and dissolved oxygen (DO), which were analyzed statistically through ANOVA and independent t-tests (Davis & Boyd 2021). The descriptive aspect provided contextual insights into water quality conditions without introducing any interventions or experimental treatments into the natural environment.

To ensure the results' representativeness and reproducibility, measurements of each parameter were taken in triplicate at each site, across different tidal phases and times of day. These triplicate values were averaged after quality control checks. Prior to analysis, data were screened for outliers using Grubbs' test ($p < 0.05$), followed by assessments of normality (Shapiro–Wilk) and homogeneity of variance (Levene's test). Data not meeting assumptions were log-transformed. Differences across locations, tidal phases, and times of measurement were evaluated with

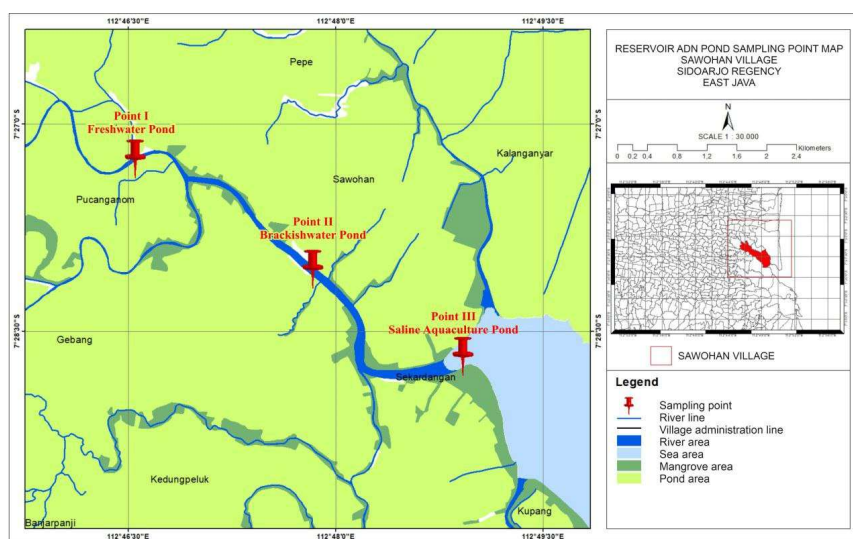


Fig. 1: Location and pond stations point.
(pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

one-way or two-way ANOVA, with Tukey's HSD post-hoc tests. Paired tidal comparisons utilized independent t-tests. The analyses were limited to univariate methods to align with the research design and the results section, excluding multivariate ordination techniques such as Principal Component Analysis. All statistical analyses were conducted using R version 4.3.0 (R Core Team 2020).

The study was further validated through a field survey employing standardized instruments, as detailed in Table 1, to ensure consistent data collection across various locations. All measurement protocols adhered to both the Indonesian National Standards (SNI) and internationally recognized guidelines (ISO/ASTM) to guarantee comparability and reproducibility. For example, pH measurements complied with SNI 06-6989.11-2004 and ISO 10523:2008, dissolved oxygen (DO) followed SNI 06-6989.14-2004, APHA 4500-O G, and ISO 5814:2012, temperature measurements conformed to SNI 06-6989.23-2005 and ASTM D5463-12, and alkalinity analysis was conducted according to SNI 06-6989.19-2004, APHA 2320 B, and ISO 9963-1:1994. Before each field session, electrochemical sensors for pH and salinity were calibrated with manufacturer-recommended standard solutions, pH buffers 4.0, 7.0, and 10.0 for a two- or

three-point calibration, and a 35 ppt conductivity standard for salinity measurements. Dissolved oxygen was measured using an AquaCombo HM 3070 DO meter, calibrated following the manufacturer's instructions and adjusted for salinity to ensure accuracy. For alkalinity, nitrate, nitrite, and ammonia tests, reagent blanks and certified reference standards were periodically run, and approximately 10% of measurements were duplicated to verify precision.

This methodological framework enabled the assessment of both spatial distribution (across freshwater, brackish, and saline sites) and temporal stability (replication across different tidal conditions), while minimizing potential confounding from anthropogenic inputs or short-term weather variability (Tarunamulia et al. 2016).

3. RESULTS

3.1. pH

Analysis of the data presented in Fig. 2 shows that pH levels in the irrigation ponds of Kepetingan Hamlet exhibit significant fluctuations influenced by sampling time and location. The pH values differ across various sampling points and tidal conditions, reflecting dynamic changes in

Table 1: List of parameters and instruments used in the research.

Parameter	Measurement Method	Instrument	Location
pH	Digital pH meter (calibrated before use) (SNI 06-6989.11-2004)	pH meter AquaCombo HM 3070	In situ
Salinity	Salinity meter (calibrated before use)	LAQUA HORIBA EC1100	Laboratorium
Dissolved Oxygen (DO)	Digital DO meter (SNI 06-6989.14-2004 dan APHA 4500-O G) (calibrated before use)	DO meter AquaCombo HM 3070	In situ
Temperatur	Thermometer (SNI 06-6989.23-2005)	-	In situ
Alkalinity	Acid base titration (SNI 06-6989.19-2004 dan APHA 2320 B)	-	Laboratorium
Chemical Contents	Using test kits (specialized test kits for nitrate, nitrite, and ammonia) (APHA 4500)	Test Kit Seaschem-MultiTespicsart	In situ & Laboratorium

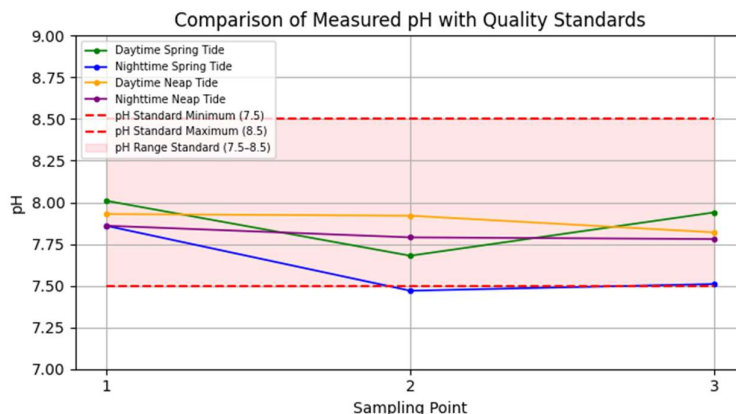


Fig. 2: Results of pH measurements under spring and neap tide conditions against quality standards. (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

water chemistry. Measurements were conducted during two specific times, daytime and nighttime, under two tidal phases: spring tide and neap tide. These conditions define four main categories: daytime spring tide, nighttime spring tide, daytime neap tide, and nighttime neap tide.

The analysis revealed contrasting patterns across the tidal phases. During spring tides, pH values tended to decrease from freshwater ponds to brackish water ponds and then increased again in saline ponds. Conversely, during neap tides, pH levels generally declined progressively from freshwater to saline ponds during neap tides. Notably, at one sampling point, the brackish water pond during the nighttime spring tide, a pH of 7.47 was recorded, which was below the minimum allowable threshold of 7.5, as stated in national and international water quality standards (Ministry of Environment 2004, SNI 8036.2:2014, Davis & Boyd 2021). Spring tide conditions demonstrated more pronounced pH fluctuations, particularly during the night, where pH levels dropped more steeply from upstream to downstream. In contrast, during the neap tide at night, the pH values showed an upward trend across the same sequence of points. During the day, the differences in pH between spring and neap tides were less prominent: point 1 decreased (from 8.01 to 7.93), point 2 increased (from 7.60 to 7.92), and point 3 decreased (from 7.94 to 7.82).

A two-way ANOVA demonstrated significant effects of tidal phase ($F(1,44) = 6.72$, $p = 0.013$, partial $\eta^2 = 0.12$) and time of day ($F(1,44) = 9.15$, $p = 0.004$, partial $\eta^2 = 0.17$) on pH levels, along with a notable interaction between these factors ($F(1,44) = 5.08$, $p = 0.029$) (Table 2). Post-hoc Tukey tests revealed that nighttime spring tides had significantly lower pH values compared to all other conditions ($p < 0.05$), while daytime spring and neap tides showed no significant difference. Effect size analysis indicated a moderate to large impact of diurnal variation, confirming that nighttime conditions intensify tidal effects on pH.

These differences align with the diel biological processes. During daylight hours, photosynthetic CO_2 uptake tends to increase pH levels, while at night, respiration and CO_2 accumulation cause pH to decrease (Boyd 2012). The buffering capacity of the ponds, mainly influenced by alkalinity, helps moderate these fluctuations but may be overwhelmed during strong tidal inflows, especially in brackish water sites where mixing with estuarine waters reduces carbonate stability (Xiao et al. 2025). Consequently, the lower pH observed during nighttime spring tides results from both diminished photosynthetic activity and the increased mixing of acidic estuarine waters.

Although the overall values stayed within acceptable safety limits, the results highlight the sensitivity of pond

water chemistry to hydrodynamic and diurnal variations. These findings align with recent global studies. Hossain et al. (2025) noted that aquaculture ponds influenced by tides experienced diel pH fluctuations of up to 0.5 units. Salin and Arome Ataguba (2018) pointed out that nighttime acidification episodes can increase physiological stress in cultured species. Similarly, Sriyasa et al. (2015) in Aquaculture Environment Interactions found that suboptimal pH levels at night reduced shrimp growth by impairing feed conversion efficiency. In summary, while short-term fluctuations are statistically significant, they remain within regulatory ranges; however, if sustained over time, they could lead to chronic physiological stress.

3.2. Dissolved Oxygen (DO)

As illustrated in Fig. 3, dissolved oxygen (DO) levels varied significantly among the three sampling sites, affected by tidal phases and the timing of sampling. Four tidal scenarios were considered: daytime spring tide, nighttime spring tide, daytime neap tide, and nighttime neap tide. Nighttime neap tide conditions produced the lowest DO values, with some measurements below acceptable standards. In contrast, daytime spring tides typically showed higher and more consistent DO levels than nighttime neap tides. These findings underscore the strong impact of tidal movements and diurnal timing on DO fluctuations in pond waters.

Dissolved oxygen (DO) is a vital parameter for aquaculture water quality, as low levels can adversely affect aquatic life and disturb pond ecosystems (Hanif et al. 2021). The results showed that DO levels during daytime spring tides in freshwater ponds dropped below the standard minimum of 5 mg.L^{-1} , indicated by the red dashed line and shaded area in Fig. 3. Throughout both tidal phases, DO concentrations generally increased from freshwater to brackish and then to saline ponds, both during day and night. This pattern was especially consistent during neap tide conditions.

A two-way ANOVA revealed significant main effects of the time of day ($F(1,44) = 8.64$, $p = 0.005$, partial $\eta^2 = 0.16$) on dissolved oxygen (DO) concentrations, while tidal phase showed no significant effect ($F(1,44) = 2.11$, $p = 0.152$, partial $\eta^2 = 0.05$). A marginal interaction was observed ($F(1,44) = 3.21$, $p = 0.080$), indicating that tidal effects were more prominent at night (see Table 2). Post-hoc Tukey tests demonstrated that DO levels during nighttime neap tides were significantly lower than during daytime spring tides ($p < 0.05$). Effect size analysis suggested that diurnal variation accounted for a greater proportion of the variation in DO than tidal phase alone.

Mechanistically, these results align with diel oxygen dynamics in aquaculture systems: during the day,

Table 2: Summary of two-way ANOVA results testing the effects of tidal phase (spring vs. neap) and time of day (day vs. night) on water-quality parameters.

Parameter	Source of variation	F (1,44)	p-value	Partial η^2	Significance	Key post-hoc / pairwise findings
pH	Tidal phase	6.72	0.013	0.12	*	Nighttime spring tides showed significantly lower pH than all other tidal–time combinations (Tukey HSD, $p < 0.05$).
	Time of day	9.15	0.004	0.17	**	Nighttime pH was lower than daytime pH across sites and tidal phases.
	Tidal \times Time	5.08	0.029	–	*	Interaction indicates the strongest pH decrease from day to night under spring tide conditions.
Dissolved oxygen (DO)	Tidal phase	2.11	0.152	0.05	n.s.	No significant tidal difference within daytime ($p = 0.266$) or nighttime ($p = 0.3156$).
	Time of day	8.64	0.005	0.16	**	DO was consistently lower at night than during the day.
	Tidal \times Time	3.21	0.080	–	n.s. (marg.)	Nighttime neap tides produced significantly lower DO than daytime spring tides (Tukey HSD, $p < 0.05$).
Salinity	Tidal phase	18.52	<0.001	0.29	***	Salinity during daytime spring tides at the saline pond (point 3, mean = 19.00 ppt) was higher than all neap-tide conditions (Tukey HSD, $p < 0.01$). Daytime spring vs. neap: $p = 0.000019$, nighttime spring vs. neap: $p = 0.04377$.
	Time of day	5.74	0.021	0.12	*	Salinity was slightly higher during the day than at night.
	Tidal \times Time	4.11	0.048	–	*	Tidal effects on salinity were more pronounced during daytime than nighttime.
Alkalinity	Tidal phase	7.92	0.007	0.15	**	Nighttime spring tides at point 3 (mean = 150.33 mg.L ⁻¹) showed higher alkalinity than daytime neap tides at all points (Tukey HSD, $p < 0.05$). Daytime spring vs. neap: $p = 0.207$ (n.s.), nighttime spring vs. neap: $p = 0.031$.
	Time of day	5.41	0.024	0.11	*	Alkalinity was generally higher at night than during the day.
	Tidal \times Time	4.36	0.042	–	*	Tidal effects on alkalinity were stronger at night.
Nitrate	Tidal phase (nighttime)	5.21	0.027	0.11	*	Daytime: no significant difference between spring and neap tides ($p = 0.41713$). Nighttime: spring vs. neap significantly different ($p = 0.009$).
	Time of day	6.85	0.012	0.14	*	Nitrate concentrations showed greater variability and higher values at night.
	Tidal \times Time	2.14	0.150	–	n.s.	Nighttime neap tide concentrations at point 3 were lower than daytime concentrations at points 1 and 2 (Tukey HSD, $p < 0.05$).
Nitrite	Tidal phase	2.41	0.128	0.05	n.s.	Mean nitrite differences between spring and neap were not significant by day ($p = 0.2698$) or night ($p = 0.44103$).
	Time of day	6.27	0.016	0.13	*	Time of day significantly affected nitrite concentrations.
	Tidal \times Time	3.14	0.084	–	n.s. (marg.)	Daytime neap tide at saline pond (point 3, mean = 1.31 mg.L ⁻¹) was higher than other point–tide combinations (Tukey HSD, $p < 0.05$).
Ammonia	Tidal phase	7.88	0.007	0.15	**	Tidal differences were not significant during the day ($p = 0.679$) but were significant at night ($p = 0.001$), with higher values under neap tide.
	Time of day	9.42	0.004	0.18	**	Ammonia concentrations were higher at night than during the day.
	Tidal \times Time	6.01	0.018	–	*	Nighttime neap tides at points 2 and 3 had higher ammonia than all daytime measurements (Tukey HSD, $p < 0.01$).

Notes: Significance codes: $p < 0.001$, $p < 0.01$, $p < 0.05$, n.s. = not significant, marg.= marginal ($0.05 \leq p < 0.10$). Partial η^2 values are reported where available in the text; dashes (–) indicate that effect sizes were not reported for interaction terms.

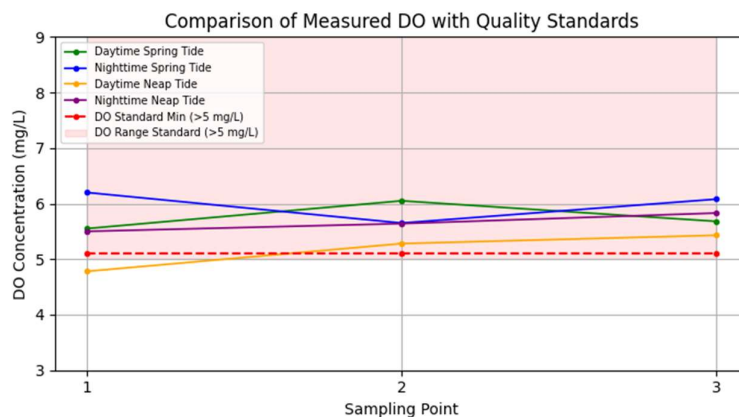


Fig. 3: Results of Dissolved Oxygen (DO) measurements under spring and neap tide conditions against quality standard. (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

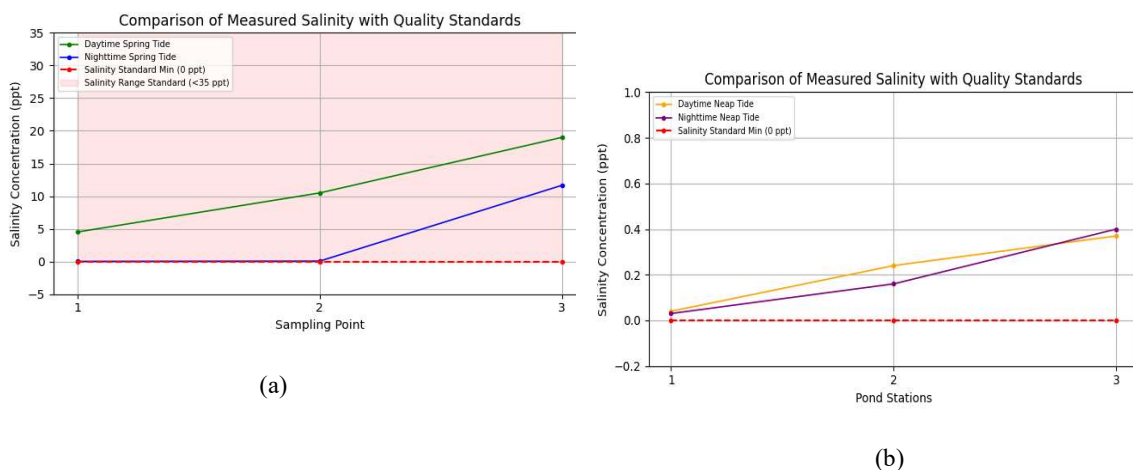


Fig. 4: Results of salinity measurements under (a) Spring Tide and (b) Neap Tide conditions against quality standards (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

photosynthesis by phytoplankton and aquatic plants produces oxygen, elevating DO levels, whereas at night, respiration dominates, leading to oxygen depletion (Boyd 2012). The influence of tidal mixing is twofold: spring tides enhance re-oxygenation by increasing water exchange, whereas neap tides reduce flushing, resulting in stagnation and oxygen decline (Sriyasa et al. 2015). Additionally, warmer nighttime temperatures may exacerbate oxygen depletion due to the reduced solubility of O_2 in water (Xiao et al. 2025).

Statistical analyses using ANOVA and correlation tests showed no significant differences in dissolved oxygen (DO) levels between spring and neap tides during daylight hours ($p = 0.266$, $p > 0.05$). At night, although DO levels varied more among sampling points, the p-value was 0.3156, indicating no statistically significant difference between the tidal phases. Overall, these results suggest that DO fluctuations are more influenced by diurnal biological

activity than by tidal cycles alone. However, interactions between tides and daily biological processes may worsen oxygen depletion under certain conditions. These findings highlight the importance of an integrated monitoring approach that combines physical factors (such as tides and temperature) with biological processes (like photosynthesis and respiration) to inform adaptive management strategies in coastal wetland aquaculture.

3.3. Salinity

Salinity measurements during both spring and neap tides consistently displayed similar spatial distribution patterns across all three sampling sites, observed during the day and night. During daytime spring tides, salinity rose sharply from 4.52 ppt at point 1 (freshwater pond) to 19.00 ppt at point 3 (saline pond), with an average of 11.34 ppt. At night, a similar upward trend was observed, though with lower

values, ranging from 0.03 ppt to 11.67 ppt, averaging 3.92 ppt. In contrast, neap tide conditions maintained low salinity levels throughout the day and night, varying from 0.04–0.37 ppt during the day (average 0.22 ppt) and 0.03–0.40 ppt at night (average 0.20 ppt). These results indicate that tidal amplitude plays a significant role in the inflow of saline water into irrigation channels (Fig. 4).

Based on standard salinity classification thresholds, Hadi et al. (2024) observed that during daytime spring tides, point 1 was within the primary drainage or moderately saline category, while points 2 and 3 exhibited saline to highly saline conditions. During neap tides, salinity levels across the points were mostly freshwater to marginal, with point 3 occasionally reaching marginal salinity. These patterns were similar but less pronounced at night. Points 1 and 2 consistently remained freshwater under both tidal conditions, whereas point 3 was highly saline during spring tides and marginal during neap tides. The salinity classifications are as follows: less than 0.5 ppt (fresh), 0.5–1 ppt (marginal), 2–5 ppt (moderately saline), 5–10 ppt (saline), and 10.01–35 ppt (highly saline).

A two-way ANOVA revealed significant effects of tidal phase ($F(1,44) = 18.52$, $p < 0.001$, partial $\eta^2 = 0.29$) and time of day ($F(1,44) = 5.74$, $p = 0.021$, partial $\eta^2 = 0.12$) on salinity, along with a notable interaction between these factors ($F(1,44) = 4.11$, $p = 0.048$) (Table 2). Post-hoc Tukey tests indicated that salinity during daytime spring tides at point 3 (mean = 19.00 ppt) was significantly higher than during all neap tide conditions ($p < 0.01$). These results suggest that tidal phase is the primary driver of salinity variability, with diurnal effects also contributing in a statistically significant manner.

Mechanistically, the marked increase in salinity during spring tides reflects a stronger tidal amplitude and an increased intrusion of seawater into the irrigation channels.

Conversely, the lower salinity observed during neap tides indicates limited saltwater intrusion, with freshwater inflows and groundwater seepage sustaining near-freshwater conditions (Hossain et al. 2025). The day–night differences can be partly explained by evaporative concentration during daylight hours and mixing or stratification processes at night, which tend to reduce salinity levels (Xiao et al. 2025). In traditional pond systems, hydraulic connectivity with estuarine flows amplifies these fluctuations, creating a dynamic gradient from freshwater upstream to highly saline conditions downstream.

Statistical analysis confirmed that tidal phase significantly influences salinity levels. During daytime, the difference between spring and neap tides was highly significant ($p = 0.000019$, $\alpha = 0.05$). Nighttime salinity differences were also statistically significant, with a p-value of 0.04377, showing a similar increasing trend from point 1 to point 3. Overall, these results indicate that tidal and diurnal interactions play a key role in driving salinity variability in traditional pond irrigation systems. Although salinity levels remained below the threshold for aquaculture suitability (< 35 ppt) (Ministry of Environment 2004, SNI 2014, Davis & Boyd 2021), the degree of variability highlights the need for adaptive irrigation and salinity management strategies to support sustainable aquaculture amid dynamic coastal conditions.

3.4. Alkalinity

Alkalinity was measured at three sampling points under four tidal conditions: daytime spring tide, nighttime spring tide, daytime neap tide, and nighttime neap tide. All recorded alkalinity values were above the minimum acceptable threshold (> 0 mg.L⁻¹), as indicated by the pink-shaded area in Fig. 5. This suggests that the water system possesses sufficient buffering capacity to resist pH fluctuations, which is an essential factor for maintaining chemical stability in

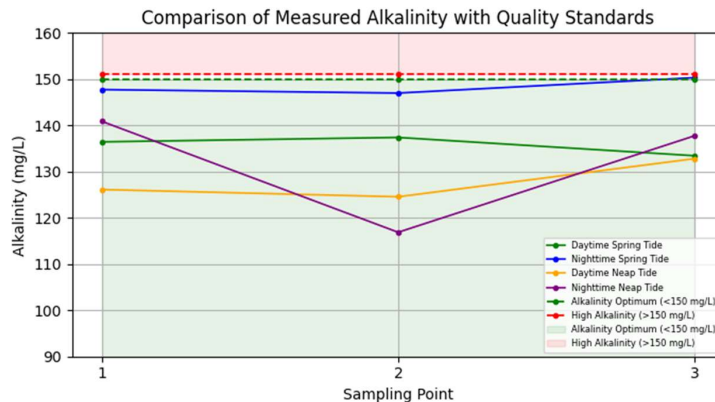


Fig. 5: Results of alkalinity measurements under spring tide and neap tide conditions against quality standards. (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

aquaculture environments. During daytime spring tides, the alkalinity values ranged from 133.44 to 137.40 mg.L⁻¹, with an average of 135.76 mg.L⁻¹, reflecting a relatively uniform distribution across all points. At night, under the same tidal conditions, alkalinity increased consistently, reaching its peak at 150.33 mg.L⁻¹ at point 3, and averaging 148.36 mg.L⁻¹ overall, the highest among all measured conditions. In contrast, daytime neap tides resulted in lower alkalinity, ranging from 124.56 to 132.81 mg.L⁻¹, with a mean of 127.83 mg.L⁻¹. Nighttime neap tides showed greater variability, with values from 116.88 mg.L⁻¹ (point 2) to 137.75 mg.L⁻¹ (point 3), and an average of 131.83 mg.L⁻¹.

Two-way ANOVA demonstrated significant effects of tidal phase ($F(1,44) = 7.92, p = 0.007$, partial $\eta^2 = 0.15$) and time of day ($F(1,44) = 5.41, p = 0.024$, partial $\eta^2 = 0.11$) on alkalinity. Furthermore, a significant interaction effect was observed ($F(1,44) = 4.36, p = 0.042$), indicating that the tidal influence on alkalinity was more pronounced at night (Table 2). Post-hoc Tukey tests revealed that nighttime spring tides at point 3 (mean = 150.33 mg.L⁻¹) were significantly higher than daytime neap tides at all points ($p < 0.05$). These findings suggest that alkalinity remains generally stable across most conditions, yet exhibits statistically meaningful variation under specific tidal–diurnal interactions.

Mechanistically, alkalinity in pond systems is primarily driven by the carbonate–bicarbonate buffering mechanism (via CaCO₃ and MgCO₃ dissolution) and is influenced by hydrological inputs. Elevated alkalinity during spring tides likely reflects the inflow of estuarine water, which typically carries higher bicarbonate concentrations (Davis & Boyd 2021). Conversely, reduced alkalinity during neap tides may result from freshwater dilution, rainfall, and limited seawater intrusion (Hossain et al. 2025). The diurnal difference, that is, higher alkalinity at night, can be associated with the reduced

photosynthetic uptake of bicarbonate and the predominance of respiration, which increases the dissolved inorganic carbon in the water column (He et al. 2023). In addition, organic matter decomposition during the night may contribute to carbonate release, thereby increasing the buffering capacity.

Statistical analysis revealed that the differences in alkalinity between spring and neap tides during the daytime were not significant ($p = 0.207, p > 0.05$), indicating that the tidal influence on alkalinity was minimal during daylight hours. However, at night, the p -value was 0.031 ($p < 0.05$), indicating a statistically significant difference in alkalinity levels between the tidal phases. These results suggest that although alkalinity remained within acceptable limits under all conditions, its concentration was more sensitive to tidal changes at night. This may reflect variations in water mixing, organic activity, or other physicochemical interactions that are amplified in the absence of light.

Overall, these results confirm that alkalinity in traditional pond irrigation systems is generally sufficient to buffer pH but is modulated by tidal–diurnal interactions. The integration of alkalinity monitoring with other parameters (pH, DO, and salinity) provides a holistic understanding of water stability and supports sustainable aquaculture management under variable coastal conditions.

3.5. Chemistry Condition

3.5.1. Nitrate

Statistical analysis of nitrate concentrations revealed no significant difference between spring and neap tide conditions during daytime, with a p -value of 0.41713 ($p > 0.05$). This suggests that tidal fluctuations in daylight hours do not substantially affect nitrate distribution across the sampling sites. Descriptively, nitrate concentrations during the day followed a consistent trend: increasing from freshwater ponds

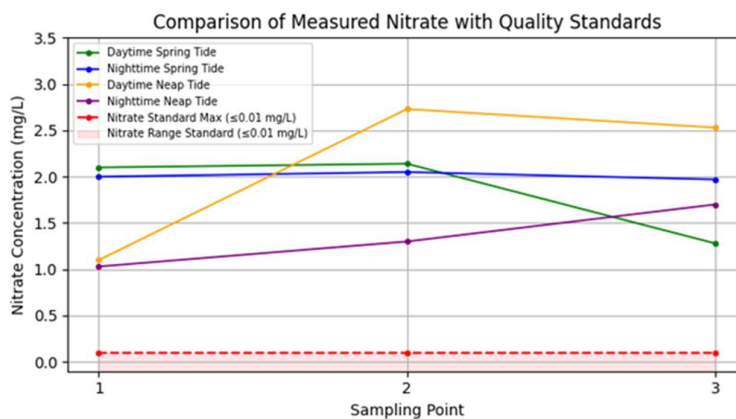


Fig. 6: Results of nitrate concentration (mg.L⁻¹) measurements under spring and neap tide conditions compared with quality standards. (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

(point 1) to brackish water ponds (point 2), then decreasing at saline ponds (point 3), under both tidal conditions.

At night, however, the statistical analysis showed a significant difference ($p = 0.009$, $p < 0.05$), indicating that tidal variations at night had a stronger influence on nitrate levels. Nitrate concentrations fluctuated across sites, especially at point 3, where levels decreased modestly from 1.97 mg.L^{-1} to 1.7 mg.L^{-1} between nighttime spring and neap tides. A two-way ANOVA confirmed a significant main effect of time of day ($F(1,44) = 6.85$, $p = 0.012$, partial $\eta^2 = 0.14$) and a smaller but significant effect of tidal phase at night ($F(1,44) = 5.21$, $p = 0.027$, partial $\eta^2 = 0.11$). No significant interaction was observed ($F(1,44) = 2.14$, $p = 0.15$), indicating that diel processes were stronger drivers of nitrate variability than tidal amplitude (Table 2). Post-hoc Tukey tests revealed that nighttime neap tide concentrations at point 3 were significantly lower than daytime concentrations at points 1 and 2 ($p < 0.05$).

Mechanistically, the observed patterns can be attributed to diel nitrogen cycling. During the day, phytoplankton uptake reduces nitrate availability, particularly in brackish water ponds where nutrient demand is high. At night, remineralization of organic matter and microbial denitrification under low DO conditions increase variability (Davis & Boyd 2021). The reduced nitrate levels in saline ponds during nighttime neap tides likely reflect a combination of limited mixing, higher organic matter decomposition, and denitrification, which consumes nitrate and releases N_2 gas (Hossain et al. 2025). Furthermore, anthropogenic sources such as agricultural runoff and pond fertilization may elevate nitrate at upstream freshwater points, which then decline downstream through dilution and microbial processing (Salin & Ataguba 2018).

As shown in Fig. 6, nighttime nitrate concentrations exhibited sharper fluctuations between tidal conditions,

especially at Point 2 to Point 3. Although still within ecologically tolerable limits for most aquaculture systems, this variability during nighttime remains environmentally significant. Similar findings in Pekalongan waters demonstrated that nitrate distribution is influenced by tidal cycles, water depth, and coastal organic inputs, with reported values ranging from 0.0065 to 0.1072 mg.L^{-1} , further reinforcing the role of localized hydrodynamic processes (Muhaemin et al. 2023). Comparable studies in tropical aquaculture systems showed nitrate levels typically ranging between 0.2 – 2.5 mg.L^{-1} , with diel peaks linked to photosynthetic activity and respiration (He et al. 2023, Salin & Arome Ataguba 2018). These studies support the present findings that nighttime processes, rather than daytime tidal changes, exert stronger control over nitrate dynamics.

3.5.2. Nitrite

Nitrite is a key indicator of aquaculture water quality, particularly because of its toxicity at elevated concentrations. Based on Fig. 7, all nitrite values are above the standard threshold ($\leq 0.1 \text{ mg.L}^{-1}$), as indicated by the red-dashed line and shaded area. However, variations were still observed among the sampling points and tidal phases, suggesting complex ecological interactions. Daytime spring tide conditions show a steady decline in nitrite levels, exceeding the specified threshold of $\leq 0.1 \text{ mg.L}^{-1}$ (Ministry of Environment 2004, SNI 8036.2:2014, Surya et al. 2024). However, during the neap tide at night, a significant increase was recorded at point 3, where the concentration increased from 0.57 to 1.31 mg.L^{-1} . This increase indicates the potential for nitrogen accumulation under stagnant neap tide conditions. The trend that occurred at night showed a constant fluctuation. The distance between points 1 and 2 decreased, and that between points 2 and 3 showed a massive increase during spring and neap tide conditions at night.

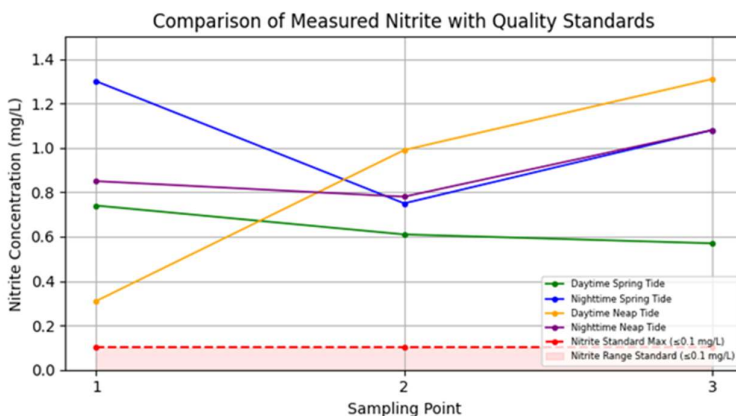


Fig. 7: Results of nitrite concentration (mg.L^{-1}) measurements under spring tide and neap tide conditions against quality standards. (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

A two-way ANOVA indicated no significant main effect of tidal phase ($F(1,44) = 2.41, p = 0.128$, partial $\eta^2 = 0.05$) but revealed a significant effect of time of day ($F(1,44) = 6.27, p = 0.016$, partial $\eta^2 = 0.13$). The interaction effect between the tidal phase and time of day was marginal ($F(1,44) = 3.14, p = 0.084$), suggesting that diel variation exerted a stronger influence on nitrite concentrations than tidal amplitude (Table 2). Post-hoc Tukey tests confirmed that nitrite levels at point 3 during daytime neap tides (mean = 1.31 mg.L^{-1}) were significantly higher than those at other sampling points and under other conditions ($p < 0.05$). These findings highlight the site-specific susceptibility of saline ponds to nitrite accumulation, particularly when tidal flushing is diminished.

Mechanistically, nitrite is an intermediate compound in the nitrification pathway ($\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$). Under optimal oxygen conditions, nitrite is rapidly oxidized to nitrate. However, during nighttime or under low DO conditions, incomplete nitrification can cause nitrite accumulation (Boyd 2012). Stagnant conditions during neap tides reduce hydrodynamic mixing, promoting nitrite buildup (Hossain et al. 2025). Additionally, organic matter loading from feed residues or agricultural runoff may enhance microbial activity, leading to elevated ammonia inputs that overwhelm the nitrification capacity, resulting in transient nitrite peaks (Xiao et al. 2025). The decline at point 1 during nighttime at neap tide is consistent with freshwater dilution and faster turnover rates, whereas downstream saline ponds experience nitrite accumulation due to lower flushing efficiency.

Statistically, no significant differences were found between spring and neap tides for either day ($p = 0.2698$) or night ($p = 0.44103$) measurements, indicating that while nitrite values fluctuated, the changes were not statistically

significant. Nonetheless, even sublethal nitrite fluctuations are ecologically important because chronic exposure can cause methemoglobinemia (“brown blood disease”) in fish and shrimp, impairing oxygen transport and growth performance (Salin & Ataguba 2018). This underscores the need to effectively manage nitrogen pathways in pond aquaculture systems.

The results demonstrate that nitrite levels in the study area exceed safety thresholds, indicating localized excesses during neap tide conditions. While pH and salinity stayed within safe limits, the persistent elevation of nitrites above acceptable levels highlights the need for effective nitrogen management to sustain aquaculture productivity and ecosystem health. These observations result from the interplay of biological nitrogen cycling, tidal flushing, and daily oxygen fluctuations. Ongoing monitoring and proactive management are crucial to reducing nitrite-related risks and ensuring the long-term viability of coastal pond aquaculture.

3.5.3. Ammonia

Ammonia is one of the most critical water quality parameters in tropical aquaculture because of its toxicity and sensitivity to environmental conditions. As shown in Fig. 8, ammonia was measured at three sampling points under four tidal time combinations. All values were under the recommended threshold ($\leq 0.3 \text{ mg.L}^{-1}$), as indicated by the red dashed line.

The highest concentrations were recorded during nighttime neap tides, particularly at points 2 and 3, reaching approximately 0.4 mg.L^{-1} . In contrast, daytime spring tide conditions produced more stable and lower values, although still above the standard, with concentrations of 0.15 mg.L^{-1} at point 1, 0.18 mg.L^{-1} at point 2, and 0.19 mg.L^{-1} at point 3. A two-way ANOVA revealed a significant main effect of time of day ($F(1,44) = 9.42, p = 0.004$, partial $\eta^2 = 0.18$)

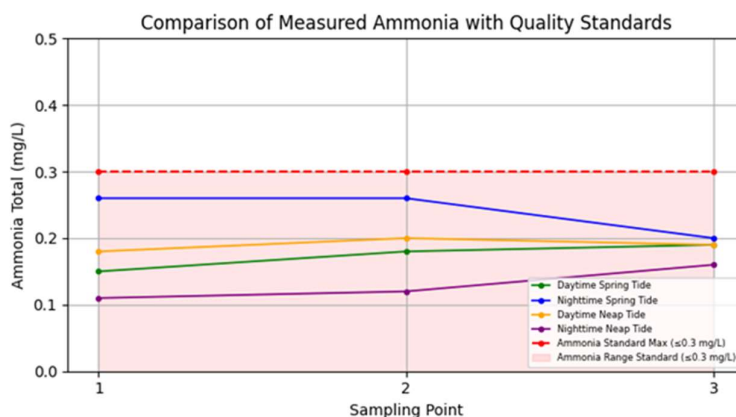


Fig. 8: Results of Ammonia concentration (mg.L^{-1}) measurements under spring and neap tide conditions against quality standards. (pond 1: freshwater pond, pond 2: brackish water pond, pond 3: saline aquaculture pond)

and tidal phase ($F(1,44) = 7.88$, $p = 0.007$, partial $\eta^2 = 0.15$) on ammonia concentration, with a strong interaction effect ($F(1,44) = 6.01$, $p = 0.018$) (Table 2). Post-hoc Tukey tests confirmed that nighttime neap tides at points 2 and 3 were significantly higher ($p < 0.01$) than all daytime measurements at all points. This demonstrates that ammonia accumulation intensifies when tidal flushing is minimal and diurnal oxygen depletion occurs.

Mechanistically, ammonia in pond water exists in equilibrium between ionized ammonium (NH_4^+ , relatively non-toxic) and un-ionized ammonia (NH_3 , highly toxic). The proportion of NH_3 increases with increasing pH and temperature (Boyd 2012). During daytime spring tides, enhanced mixing and photosynthesis dilute ammonia levels and maintain more stable values than at night. Conversely, nighttime neap tides combine several stressors: reduced water exchange, higher organic decomposition, lower dissolved oxygen, and stable pH near alkaline levels, all of which favor NH_3 accumulation (Ip & Chew 2010). Elevated ammonia levels at downstream points (2 and 3) likely reflect both hydrodynamic stagnation and cumulative organic loading from upstream inputs, which is exacerbated by anthropogenic nutrient enrichment.

Statistical analysis revealed no significant difference between spring and neap tide conditions during the day ($p = 0.679$), with all sites showing a similar increase in ammonia concentration. However, at night, a significant difference was found ($p = 0.001$), and unlike daytime conditions, each sampling point exhibited a unique trend, further indicating that tidal and diurnal factors jointly modulated ammonia concentrations. These findings are consistent with global studies reporting diel ammonia variability in aquaculture ponds, where nighttime peaks often exceed safe thresholds because of oxygen depletion and incomplete nitrification (Xiao et al. 2025). Chronic exposure to NH_3 above 0.05 mg.L^{-1} has been linked to gill damage, oxidative stress, and reduced growth in fish and shrimp (Muharomah et al. 2025).

4. DISCUSSION

This study emphasizes the crucial role of tidal dynamics as a key hydrodynamic factor affecting coastal water quality, especially in traditional pond irrigation systems reliant on seawater supply. The primary tidal phases, spring and neap tides, vary in amplitude and duration, thereby influencing the patterns of water mixing (Muhtadi et al. 2024). During spring tides, the alignment of the Moon and Sun produces stronger gravitational forces, resulting in more extreme tidal ranges. This enhances seawater inflow and promotes mixing between marine water, freshwater, and anthropogenic inputs (Utami et al. 2024, Xu & Zhang 2025). In contrast, neap tides,

which have lower tidal amplitudes, are dominated by land-based water contributions. These conditions lead to changes in physicochemical parameters such as salinity, temperature, and dissolved oxygen (DO), causing noticeable differences in water quality (Muhtadi et al. 2024). Daytime fluctuations in salinity, marked by high mean values and standard deviations at saline points, further confirm the substantial impact of full tidal cycles on spatial variability.

The comprehensive analysis of various parameters revealed that tidal–diurnal interactions influence water quality through interconnected processes involving salinity, dissolved oxygen (DO), pH, alkalinity, and nitrogen species such as nitrate, nitrite, and ammonia. For instance, nighttime DO depletion inhibits complete nitrification, leading to increased levels of nitrite and ammonia. Additionally, alkalinity functions as a chemical buffer that stabilizes pH while also affecting the proportion of toxic un-ionized ammonia (NH_3). These interconnected mechanisms are consistent with global research on tropical aquaculture ponds, where diel cycles cause significant fluctuations in nitrogen dynamics and result in periods of heightened ecological stress.

Ammonia fluctuations serve as additional evidence of tidal influence. During spring tides, fluctuating ammonia levels in aquaculture ponds indicate active dilution, as increased seawater flow enhances mixing and oxygenation, thereby decreasing the accumulation of nitrogen compounds such as ammonia, nitrates, and water (Muhaemin et al. 2023, Surya et al. 2024, Xu & Zhang 2025). Conversely, at night during neap tides, ammonia tends to accumulate significantly. This is due to the predominance of land water with limited seawater dilution and reduced mixing during nighttime. Elevated ammonia levels at night during spring tides in several ponding stations approached the recommended threshold ($\leq 0.3 \text{ mg.L}^{-1}$), potentially posing a chronic risk to farmed shrimp and fish. This aligns with previous research linking ammonia to gill damage, reduced feeding efficiency, and mortality in tropical aquaculture systems (Ip & Chew 2010). These results highlight the importance of nitrogen management as a key factor in enhancing aquaculture resilience.

The distribution of aquatic vegetation, especially water hyacinth (*Eichhornia crassipes*), mirrors these physicochemical patterns (Fig. 9). As a species with low salinity tolerance, its presence is significantly less in saline ponds compared to freshwater or brackish environments (Bick et al. 2020). The limited growth of water hyacinths in saline conditions reduces their effectiveness in phytoremediation, where they typically help decrease ammonia levels through rhizofiltration and microbial activity in the rhizosphere (He et al. 2023). This underscores the importance of nature-

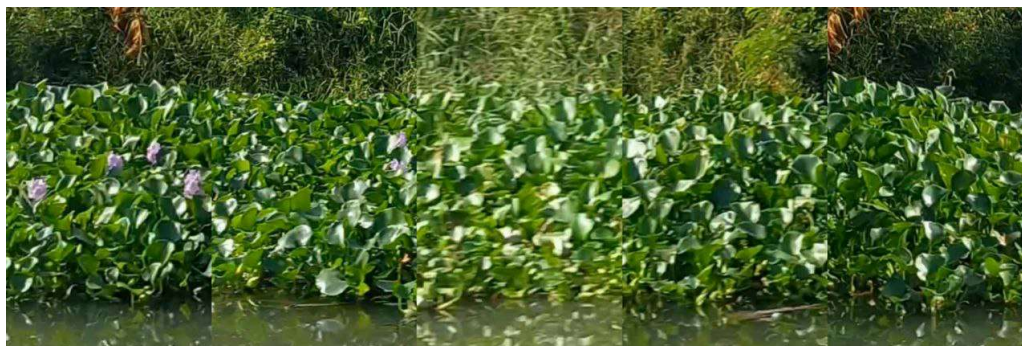


Fig. 9: Water hyacinth dominance in pond irrigation areas (*Eichhornia crassipes*).

based solutions for water quality management. Nonetheless, macrophyte-based treatment alone is inadequate in high-salinity, low-mixing settings and should be supplemented with engineered solutions like aeration, biofiltration, or controlled water exchange.

The relationship between alkalinity and pH provides important insights into water quality stability. At various sampling locations, alkalinity values tend to fluctuate inversely with pH, emphasizing its role as a buffer system that maintains the chemical balance of water. Alkalinity is also a major determinant of nitrogen speciation; under high pH conditions with low alkalinity, the toxic non-ionic form of ammonia (NH_3) is more dominant. Alkalinity instability can trigger sharp pH fluctuations, thereby disrupting chemical equilibrium and causing non-linear changes in nitrification and denitrification processes. A study by Sriyasak et al. (2015) further shows that changes in microbial composition and dissolved oxygen can significantly affect ammonia concentrations. Similarly, Hadi et al. (2024) found that pH and alkalinity dynamics in tidal irrigation systems are strongly influenced by the interaction between brackish water and seawater, which ultimately affects the chemical stability of the aquatic environment. These findings reinforce the importance of integrated monitoring of various parameters, such as buffering capacity, oxygen dynamics, and the nitrogen cycle, which are interrelated processes.

From a management perspective, the findings suggest several practical implications. First, targeted aeration during nighttime neap tides is essential to prevent DO depletion and incomplete nitrification, which are major drivers of nitrite, nitrate, and ammonia (regular monitoring required) accumulation. Second, feed management must be optimized to minimize nitrogenous waste, as overfeeding is a leading cause of chemical component buildup. Third, water exchange should be strategically scheduled during spring tides, when mixing capacity is highest, to dilute pollutants. Fourth, integrated multi-trophic aquaculture (IMTA) systems, including seaweed, mollusks, or biofilm reactors, can be used

to absorb excess nitrogen and improve ecological resilience. These adaptive strategies are consistent with international best practices for sustainable aquaculture.

On a broader scale, the study's findings contribute to global debates on sustainable food production and environmental governance. Elevated ammonia, nitrate and nitrite levels are not only local threats but also indicators of eutrophication risk in coastal ecosystems (Hossain et al. 2025). By demonstrating how tidal and diurnal dynamics govern nitrogen pathways, this research provides insights into climate adaptation strategies for coastal aquaculture. The results are directly relevant to the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 14 (Life Below Water). Addressing water quality instability in aquaculture ponds thus supports both local livelihood security and global sustainability agendas.

Overall, this study demonstrates that tidal phase, diurnal variation, and biological interactions jointly regulate key water quality parameters. Future studies should employ high-frequency monitoring (e.g., sensor networks, remote sensing) to capture fine-scale variability and incorporate predictive models that integrate hydrodynamics, biogeochemistry, and climate projections. Such approaches will advance adaptive aquaculture irrigation systems that are ecologically sustainable and resilient to environmental variability.

5. CONCLUSIONS

This study demonstrates that tidal phases exert a significant influence on the physical and chemical characteristics of pond water quality. The contrasting dynamics of spring and neap tides generate variations in water mixing processes and the distribution of key parameters, including alkalinity, salinity, dissolved oxygen (DO), ammonia, nitrate, and nitrite. These fluctuations directly affect the ecological conditions of aquaculture systems. The findings highlight

that understanding tidal dynamics is essential for developing sustainable pond management strategies. By integrating knowledge of tidal-driven variability, aquaculture practices can be made more adaptive and resilient to hydrodynamic changes in coastal environments.

Specifically, the results show that: (i) pH remained relatively stable within acceptable thresholds, with only localized deviations during nighttime spring tides, (ii) dissolved oxygen (DO) exhibited diel fluctuations, with nighttime values occasionally approaching critical limits but not differing significantly between tidal phases, (iii) salinity varied significantly between spring and neap tides ($F(1,44) = 18.52, p < 0.001$), confirming tidal amplitude as the dominant driver of hydrological gradients, (iv) alkalinity consistently buffered pH but exhibited significant nighttime increases under spring tides, indicating carbonate system shifts, (v) Nitrate and nitrite were predominantly above international and national limits during daytime and nighttime in every pond station, and (vi) ammonia concentrations consistently remained below the recommended limit ($\leq 0.3 \text{ mg.L}^{-1}$).

Nitrite concentrations exceeding the recommended threshold in certain tidal and daily cycles, especially during nighttime neap tides, when oxygen deficiency inhibits nitrification efficiency. The results of this study correlating nitrite with ammonia confirm that tidal stagnation and nighttime oxygen depletion are key factors in nitrogen imbalance in brackish water pond systems. Furthermore, based on research trends, a decrease in ammonia concentration accompanied by an increase in nitrite or vice versa during nighttime conditions indicates that partial oxidation of ammonia to nitrite occurs under sub-optimal aeration conditions. This incomplete nitrification process causes the accumulation of intermediate nitrogen species, disrupting the balance between nitrogen transformation and biological uptake. These daily and tidal interactions emphasize that hydrodynamic processes and oxygen variability highly influence nitrogen cycle efficiency.

These integrated findings highlight that the nitrogen cycle (ammonia–nitrite–nitrate transformation) is strongly influenced by the dynamics of the physical-chemical content of water. In addition to ammonia and nitrite, the combination of low DO levels at night and reduced water flow during neap tides creates high-risk conditions for the accumulation of nitrite and ammonia, which threaten the health of cultivated species. Consequently, effective pond management must adopt a systems approach, simultaneously addressing hydrodynamics, carbonate chemistry, and nitrogen pathways rather than relying on single-parameter control. From a management perspective, the study emphasizes the importance of implementing adaptive strategies, including:

(i) deploying aerators during nighttime neap tides to prevent DO depletion and incomplete nitrification, (ii) optimizing feed management to minimize nitrogenous waste, (iii) scheduling water exchange during spring tides for maximum dilution efficiency, and (iv) adopting integrated multi-trophic aquaculture (IMTA) or biofilters to absorb excess nitrogen.

These approaches align with sustainable aquaculture principles and can enhance resilience in smallholder systems. At a global scale, the findings contribute to ongoing debates on sustainable aquaculture and coastal management by demonstrating the sensitivity of pond irrigation systems to tidal–diurnal variability. The results align with multiple Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) by supporting food security, SDG 6 (Clean Water and Sanitation) through improved water quality management, SDG 13 (Climate Action) via adaptive strategies under hydrodynamic and climate variability, and SDG 14 (Life Below Water) by mitigating eutrophication risks. Future research should focus on high-frequency sensor-based monitoring and predictive modeling of nitrogen fluxes to anticipate extreme events and design climate-resilient aquaculture irrigation systems.

6. ACKNOWLEDGMENTS

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