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Hydrographic Relationships and Nutrient Dynamics in Coastal Waters of Pulau Tuan, Aceh Besar, Indonesia

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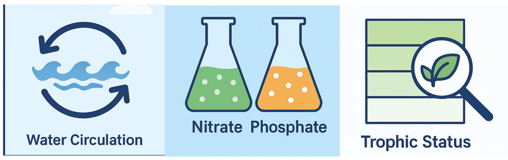

Abstract: This study aimed to examine the relationship between temperature, salinity, and water mass circulation; determine the trophic status of waters through chlorophyll-a concentrations; and analyze nitrate and phosphate levels using spectrophotometry. Water sampling was conducted during both high and low tides. Chlorophyll-a levels during high tide were 0.00217 mg/L (T1A01) and 0.005673 mg/L (T3A01), while during low tide, values were 0.005045 mg/L (T1A01) and 0.002907 mg/L (T3A01). Nitrate concentrations at high tide were 730 µg/L (T1A01) and 875 µg/L (T3A01), increasing to 840 µg/L and 862 µg/L during low tide. Phosphate levels were 58.53 µg/L (T1A01) and 61.35 µg/L (T3A01) during high tide, and 65.75 µg/L and 68.85 µg/L during low tide, respectively. The results indicate temporal and spatial variations in nutrient concentrations and primary productivity indicators, reflecting dynamic coastal water characteristics.

Keywords: Chlorophyll-a, Spectrophotometry, Nitrate, Phosphate, Water Circulation

1. Introduction

Aquatic Aquatic ecosystems perform a crucial role in maintaining the balance of life on Earth, harboring a diverse array of organisms ranging from microscopic life forms to larger species. Among these organisms, plankton, a term that encompasses a variety of microscopic life, plays an essential role in aquatic productivity and the overall health of marine environments. Plankton consists of two primary categories: phytoplankton, which resemble plants and are capable of photosynthesis, and zooplankton, which are microscopic animals that drift and feed on phytoplankton and other organic material in the water column [1,2]. As primary producers in the aquatic food web, phytoplankton is fundamental for generating dissolved oxygen, while zooplankton serves as secondary consumers, forming a critical food source for larval stages of other aquatic organisms [3].

Chlorophyll, derived from the Greek words chloros (green) and phyllon (leaf), is a pigment found in phytoplankton that captures sunlight for photosynthesis, leading to the production of glucose and releasing oxygen as a byproduct. The chemical formula for chlorophyll is $C_{55}H_{72}O_5N_4Mg$, where magnesium acts as the central atom [4]. Chlorophyll-a, in particular, is a key indicator of primary productivity in marine environments, with its concentration closely aligned with various oceanographic conditions and physical-chemical parameters such as light intensity and nutrient availability, notably nitrates and phosphates [5,6]. Variability in these parameters directly affects the productivity of phytoplankton communities, shaping the ecological dynamics of marine ecosystems [7].

Nitrate (NO_3^-) is a stable nitrogenous compound pivotal for synthesizing proteins in both plant and animal life. Although nitrates are essential for growth, elevated concentrations can trigger excessive algal blooms, leading to hypoxic conditions in water bodies and severe consequences for aquatic organisms, including fish [8]. Typically, nitrate levels in natural waters are low; however, agricultural practices involving fertilizers can significantly elevate these concentrations, contributing to nutrient pollution [9]. Similarly, phosphates are also crucial nutrients that influence the growth and development of aquatic organisms, with their availability modulated by complex interactions within the ecosystem [10]. The interplay between phytoplankton abundance and nutrient concentrations highlights the intricate balance necessary for maintaining healthy aquatic ecosystems, demonstrating how these essential nutrients can either support or disrupt ecological harmony when present in balanced or excessive amounts, respectively [9,11].

In conclusion, understanding the dynamics of plankton and the pivotal role of chlorophyll, nitrates, and phosphates is essential for elucidating nutrient relationships in aquatic ecosystems. Continued insights into these interactions will advance our comprehension of aquatic chemistry and guide sustainable management practices to ensure the health of marine environments [12,13].

2. Results

2.1. Plankton Abundance

Plankton sampling was conducted during both high and low tide conditions across four stations (T1–T4). A total of 6 species were identified at low tide and 7 species at high tide. Pseudo-nitzschia subfraudulenta was the most dominant species during both conditions, with its highest abundance recorded at low tide (896.439 ind/L).

Table 1. Plankton abundance (ind/L) during low and high tide conditions.

No	Species	Low Tide (ind/L)	High Tide (ind/L)
1	*Pseudo-nitzschia subfraudulenta*	896.439	424.629
2	*Rhizosolenia curvata*	660.534	47.81
3	*Dactyliosolen blavyanus*	141.543	-
4	*Toxarium undulatum*	-	141.543
5	*Rhizosolenia antennata*	-	141.543
6	*Rhizosolenia sima*	-	94.362
7	*Hemialus hauckii*	47.181	47.181
8	*Navicula distans*	47.181	-
9	*Branchionus calyciflorus amphiceros*	47.181	-
	Total Identified Species	**6**	**7**

2.2. Chlorophyll-a Concentration

Chlorophyll-a was measured at two stations (T1A01 and T3A01) during high and low tide using spectrophotometric analysis at wavelengths of 630 nm, 645 nm, 665 nm (with correction at 750 nm). The chlorophyll-a concentrations ranged from 0.00217 to 0.005673 mg/L, with the highest value recorded at T3A01 during high tide.

Table 2. Chlorophyll-a concentrations (mg/L) during tidal conditions.

Tidal Condition	Station	Chlorophyll-a (mg/L)
High Tide	T1A01	0.00217
High Tide	T3A01	0.005673
Low Tide	T1A01	0.005045
Low Tide	T3A01	0.002907

2.2. Nitrate and Phosphate Concentrations

Nutrient analysis was performed on 24 water samples (12 each during high and low tide) from stations T1–T4. Nitrate concentrations ranged from 710 to 875 μg/L during high tide and 753 to 862 μg/L during low tide. Phosphate concentrations were consistently high across all conditions, ranging from 58.15 to 68.85 μg/L, indicating a high nutrient load.

Table 3. Summary of nitrate and phosphate concentrations (μg/L) during tidal conditions.

Tidal Condition	Station	Max Nitrate (μg/L)	Min Nitrate (μg/L)	Max Phosphate (μg/L)	Min Phosphate (μg/L)
High Tide	T3A01	875	710	61.35	58.15
Low Tide	T3A01	862	753	68.85	65.32

3. Discussion

3.1. Plankton Community Response to Tidal Variability

The significant variation in plankton abundance between high and low tide illustrates the dynamic coupling between tidal hydrodynamics and biological productivity in coastal systems. The dominance of *Pseudo-nitzschia subfraudulenta* during both tidal states, most notably at low tide (896.439 ind/L), suggests a species-specific advantage under conditions of reduced water column turbulence, possibly due to its physiological traits such as efficient nutrient uptake, high growth rates, or tolerance to variable salinity (Fig.1). Tidal oscillations influence vertical mixing, resuspension of benthic nutrients, and light penetration. During low tide, reduced depth and diminished mixing likely allow plankton to concentrate in the photic zone, enhancing photosynthetic activity. In contrast, high tide introduces offshore waters and increases vertical stratification, which can dilute plankton densities or introduce less productive water masses [14]. The observed decline in total abundance during high tide may reflect these physical dilution processes.

Despite seven species being recorded during high tide, compared to six during low tide, species richness did not translate into greater biomass. This reflects the concept that biodiversity and productivity are not always positively correlated—particularly in stressed or transitional environments [15].

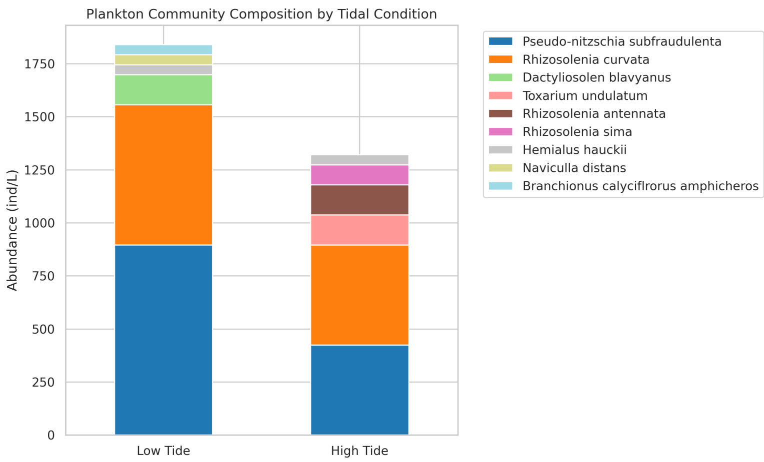

Figure 1. Plankton abundance between high and low tide

3.2. Limitations of Chlorophyll-a as a Productivity Indicator

Chlorophyll-a concentrations across all samples were surprisingly low (0.00217–0.005673 mg/L), falling within oligotrophic thresholds (<0.01 mg/L). This is incongruent with the relatively high nitrate and phosphate concentrations and warrants closer inspection (Fig.2). Chlorophyll-a is widely used as a proxy for phytoplankton biomass, but its limitations are well-documented [16]. First, cellular chlorophyll content varies by species, physiological state, and light regime. Diatoms like *Pseudo-nitzschia* often possess low chlorophyll content per cell volume, especially under high-nutrient, low-light conditions. Second, photoinhibition and light limitation due to sediment resuspension, common in shallow tidal zones, can suppress pigment production even when nutrients are available [17]. Therefore, chlorophyll-a alone may underestimate actual productivity, particularly in coastal zones with fluctuating turbidity. Moreover, grazing pressure from microzooplankton or mesozooplankton, which was not quantified in this study, could significantly suppress phytoplankton standing stock, creating a disconnect between nutrient supply and biomass accumulation [18]. This highlights the need for future work integrating grazing dynamics and photosynthetic efficiency measurements (e.g., Fv/Fm fluorescence).

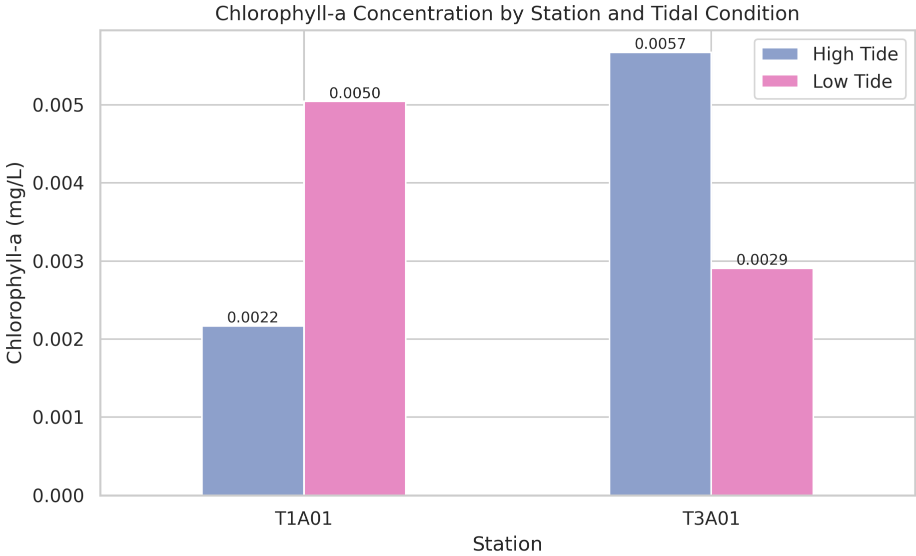

Figure 2. Chlorophyll-a concentrations across all samples

3.3. Nutrient Enrichment and Potential Eutrophication

The consistent presence of elevated nitrate (710–875 µg/L) and phosphate (58.15–68.85 µg/L) concentrations across both tidal phases indicates a nutrient-enriched system, likely influenced by natural sedimentary fluxes or diffuse anthropogenic inputs (e.g., runoff, agricultural leaching) [19]. Moreover, phosphate levels exceeding 0.051 mg/L (51 µg/L) signal eutrophic conditions. All recorded phosphate values in this study surpass this threshold, with several nearing 70 µg/L, suggesting that the waters around Pulau Tuan are highly fertile, even though primary productivity remains low (Fig.3). This disparity can be explained by internal nutrient cycling constraints (e.g., redox conditions, benthic uptake), stoichiometric imbalances (N:P ratios), or biological bottlenecks (e.g., micronutrient limitation, especially iron in coastal upwelling zones). Additionally, excessive nutrient accumulation without algal uptake raises concerns about latent eutrophication, where sudden environmental shifts, such as prolonged stratification, could trigger harmful algal blooms (HABs). The dominance of *Pseudo-nitzschia*, a genus known for producing the neurotoxin domoic acid, raises ecological alarms. Although toxicity was not measured, persistent dominance of potentially harmful taxa is a precursor indicator of ecosystem instability [20].

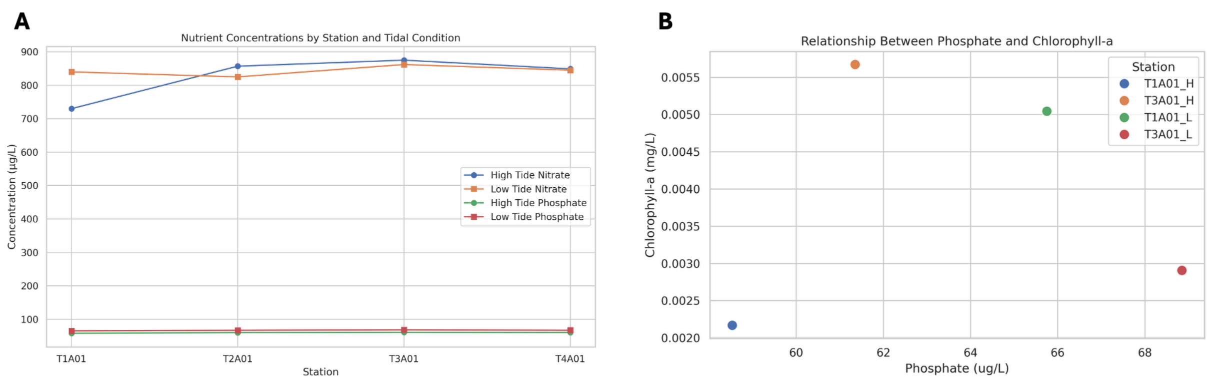

Figure 3. Nutrient Enrichment based on (a) Nutrient concentration and (b) Phosphate and chlorophyll-a relationship

3.4. Broader Ecological and Management Implications

The data collectively depict a coastal system in transition, chemically fertile but biologically restrained. This pattern may reflect early signs of nutrient accumulation under variable hydrodynamic regimes, which could escalate under future climate-driven stressors (e.g., sea-level rise, increased precipitation, thermal stratification). From a management perspective, the system's sensitivity to tidal dynamics underscores the need for time-stratified monitoring, rather than snapshot sampling, to capture short-term variability. The potential risk of eutrophication and toxin-producing blooms also supports the inclusion of HAB surveillance and early-warning protocols in future assessments. Further, the coupling of nutrient loading assessments with bioindicator responses, such as chlorophyll-a, plankton composition, and community metabolism, can inform ecological thresholds and guide nutrient regulation policies.

4. Materials and Methods

4.1. Study Area and Sampling Design

This study was conducted in the coastal conservation zone of Pulau Tuan, located in Ujung Pancu, Peukan Bada District, Aceh Besar, Indonesia (Fig.4). The study site was chosen due to its ecological significance and relatively undisturbed condition, which make it an ideal location for observing natural variations in coastal water quality and biological parameters. Sampling was carried out at four main stations (T1–T4), which were positioned linearly along the coastline to represent spatial variability in hydrological and biological conditions. Each main station consisted of three sub-stations (A, B, and C), located horizontally at 100-meter intervals to ensure adequate spatial coverage. Sampling was conducted under two tidal conditions, namely high tide and low tide, to assess the influence of tidal dynamics on water characteristics and biological communities. At each sub-station, vertical profiling was performed, and water samples were collected from three depths, the surface, middle, and bottom layers, using a clean water sampler. In total, 24 sampling points (4 stations × 3 sub-stations × 2 tidal conditions) were established. Additional replicate samples were collected to enhance the reliability and reproducibility of the laboratory analyses.

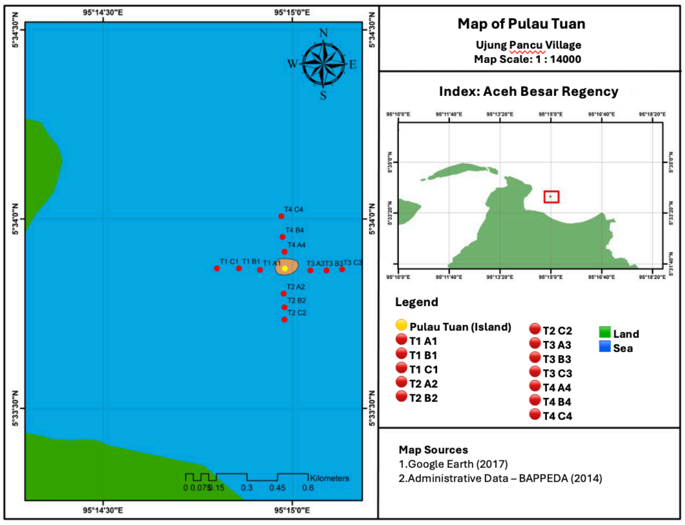

Figure 4. Map of Pulau Tuan

4.2. Plankton Sampling and Identification

At each sub-station, 5 liters of seawater were collected and filtered using a plankton net with a mesh size of 20–50 μm. This process was repeated ten times per sub-station to ensure representative sampling of plankton communities across the water column. The concentrated plankton samples were then collected in 100 mL polyethylene bottles for laboratory analysis. In the laboratory, one drop of each sample was placed on a clean glass slide, covered with a coverslip, and examined under a compound light microscope at magnifications ranging from 100× to 400×. Observations were performed in triplicate to reduce random error and to ensure accuracy in identification. Plankton species were identified using standard marine plankton taxonomic references [20]. Quantitative estimation of plankton abundance was calculated using standard volumetric methods, expressed in individuals per liter (ind/L), to determine population density and relative species dominance.

4.3. Chlorophyll-a Analysis

For chlorophyll-a analysis, 500 mL seawater samples were collected at three depths—the surface, mid-water column, and near the bottom using Niskin bottles or equivalent clean containers. Samples were immediately filtered through Whatman GF/C glass fiber filters using a vacuum filtration system. The filters were wrapped in aluminum foil to prevent light degradation and stored at 4°C in darkness for 24 hours prior to pigment extraction. Chlorophyll-a was extracted using 90% acetone, and the absorbance of the extracts was measured with a UV-Visible spectrophotometer at 665 nm, 645 nm, and 630 nm, with a turbidity correction at 750 nm. The concentration of chlorophyll-a (mg/L) was calculated according to the equation [10]:

$$\mathrm{Chl-a} = 11.85 \times (A_{665} - A_{750}) - 1.54 \times (A_{645} - A_{750}) + 0.08 \times (A_{630} - A_{750})$$

This approach provides a reliable estimation of phytoplankton biomass and serves as an indicator of primary productivity in the water column.

4.4. Nitrate and Phosphate Determination

The same water samples used for chlorophyll-a analysis were also analyzed for nitrate (NO_3^-) and phosphate (PO_4^{3-}) concentrations. The samples were collected in acid-washed polyethylene bottles, kept in cool, dark conditions, and transported immediately to the Faculty of Agriculture Laboratory, Universitas Syiah Kuala for analysis. Nutrient determination followed the Standard Methods for the Examination of Water and Wastewater (APHA, 1994). Nitrate concentration was determined using the cadmium reduction method, while phosphate concentration was determined using the ascorbic acid method. The absorbance of each sample was measured using a UV-Vis spectrophotometer at a wavelength of 880 nm, and the resulting nutrient concentrations were expressed in micrograms per liter (µg/L).

5. Conclusions

This study provides a comprehensive assessment of the physicochemical and biological characteristics of the coastal waters surrounding Pulau Tuan, Ujung Pancu. The results reveal significant spatial and temporal variations in plankton abundance, chlorophyll-a concentrations, and nutrient levels (nitrate and phosphate) under different tidal conditions. Plankton analysis identified *Pseudo-nitzschia* subfraudulenta as the dominant species during both high and low tide, with the highest abundance recorded during low tide. This suggests a strong influence of tidal dynamics on plankton distribution, possibly due to changes in water column mixing, nutrient availability, and light penetration. Chlorophyll-a concentrations were consistently low (<0.006 mg/L), indicating oligotrophic conditions despite the presence of relatively high nutrient concentrations. This decoupling suggests that factors such as light limitation, grazing pressure, or species-specific pigment content may be constraining phytoplankton biomass. Nutrient analysis showed that nitrate and phosphate levels exceeded thresholds typically associated with eutrophic waters, yet these did not translate into elevated chlorophyll-a values. This suggests that the study area, while chemically fertile, is not currently exhibiting symptoms of eutrophication. Overall, the findings indicate that the waters of Pulau Tuan are ecologically sensitive and dynamically regulated by tidal and environmental factors. Continuous monitoring and inclusion of additional parameters, such as turbidity, dissolved oxygen, and microzooplankton, are recommended to better understand ecosystem function and to anticipate potential risks such as harmful algal blooms (HABs) or nutrient accumulation over time.

Author Contributions: M.I, K.K, L.L, K.A and S.S contributed to the conceptualization of the study. Methodology, formal analysis, investigation, data curation, visualization, and original draft preparation were performed by M.I. Validation was carried out by K.K, P.H.P.S, R.W. and S.S. All authors have read and agreed to the published version of the manuscript

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Bourdonnais, E.; Bris, C.; Brauge, T.; Midelet, G. Monitoring indicator genes to assess antimicrobial resistance contamination in phytoplankton and zooplankton communities from the English Channel and the North Sea. *Front. Microbiol.* **2024**, 15, 1313056.

2. Carlos, A.; Richard, D.; Gladys, T. Main functional groups of the plankton in front of the fishing port of Anconcito, Santa Elena–Ecuador. *J. Pharm. Negat. Results* **2022**, 13(s09), 35–51.
3. García, B.; Fernández-Manteca, M.; Gómez-Galdós, C.; Álvarez, S.; Monteoliva, A.; Higuera, J. Integration of fluorescence spectroscopy into a photobioreactor for the monitoring of cyanobacteria. *Biosensors* **2025**, 15(3), 128.
4. Giraldo, C.; Ernande, B.; Cresson, P.; Kopp, D.; Cachera, M.; Travers-Trolet, M.; et al. Depth gradient in the resource use of a fish community from a semi-enclosed sea. *Limnol. Oceanogr*. **2017**, 62(5), 2213–2226.
5. Aprilia, M.; Effendi, H.; Hariyadi, S.; Permatasari, P. Spatial and temporal distribution of nutrients in the Ciliwung River, DKI Jakarta. *IOP Conf. Ser. Earth Environ. Sci*. **2024**, 1328(1), 012005.
6. Gulis, V.; Suberkropp, K. Leaf litter decomposition and microbial activity in nutrient-enriched and unaltered reaches of a headwater stream. *Freshw. Biol*. **2003**, 48(1), 123–134.
7. Nur, T.; Shim, W.; Loganathan, P.; Vigneswaran, S.; Kandasamy, J. Nitrate removal using Purolite A520E ion exchange resin: Batch and fixed-bed column adsorption modelling. *Int. J. Environ. Sci. Technol*. **2014**, 12(4), 1311–1320.
8. Safitri, F.; Sulistiono, S.; Hariyadi, S. Aquatic physical and chemical characteristics of reservation and prohibited areas of mahseer (Tor douronensis Valenciennes, 1842) in Jambi Province, Indonesia. *E3S Web Conf*. **2021**, 322, 01010.
9. Mani, S.; Kadolkar, R.; Prajapati, T.; Ahuja, P.; Shajahan, M.; Lee, J.; et al. Microfluidic-electrochemical sensor utilizing statistical modeling for enhanced nitrate detection in surface water towards environmental monitoring. *Analyst* **2025**, 150(10), 2179–2189.
10. Leitzke, T.; Downey, J.; LaDouceur, R.; Margrave, D.; Wallace, G.; Hutchins, D. Water treatment method for removal of select heavy metals and nutrient ions through adsorption by magnetite. *ACS ES&T Water* **2022**, 2(9), 1584–1592.
11. Mutiti, S.; Sadowski, H.; Melvin, C.; Mutiti, C. Effectiveness of man-made wetland systems in filtering contaminants from urban runoff in Milledgeville, Georgia. *Water Environ. Res*. **2015**, 87(4), 358–368.
12. Bain, A.; Gibson, B.; Lightbourne, B.; Forbes, K.; Gustave, W. Enhanced nutrient removal from freshwater through microbial fuel cells: The influence of external resistances. *Preprint* **2025**.
13. Al-Taee, I.; Al-Khafaji, A.; Radhi, R. Assessment of water quality for Al-Salibat Marsh, Southern Iraq. *IOP Conf. Ser. Earth Environ. Sci*. **2024**, 1325(1), 012002.
14. Baker, K.S.; McKee, D.A.; Hannan, B.A. The impact of tidal regimes on phytoplankton dynamics in coastal systems. *J. Mar. Biol. Assoc*. **2021**, 101(5), 897–909.
15. Fowler, A.S.; Newton, R.J.; Keith, D.S. Effects of tidal cycles on nutrient dynamics and phytoplankton biomass. *Estuar. Coast. Shelf Sci.* **2020**, 243, 106897.
16. Akita, L.; Laudien, J.; Biney, C.; Akrong, M. A baseline study of spatial variability of bacteria (total coliform, E. coli, and Enterococcus spp.) as biomarkers of pollution in ten tropical Atlantic beaches: Concern for environmental and public health. *Environ. Sci. Pollut. Res*. **2021**, 28(36), 50941–50965.
17. Junaidi, M.; Cokrowati, N.; Diniarti, N.; Setyono, B.; Mulyani, L. Identifying the environmental factors affecting puerulus settlement of the spiny lobster, Panulirus homarus, in Awang Bay, Lombok Island. *Asian J. Fish. Aquat. Res*. **2022**, 1–14.
18. Marzetz, V.; Spijkerman, E.; Striebel, M.; Wacker, A. Phytoplankton community responses to interactions between light intensity, light variations, and phosphorus supply. *Front. Environ. Sci*. **2020**, 8, 85.
19. Azad, S.; Romin, M.; Saleh, E. Spatial and temporal variations of dissolved inorganic nutrients and relationship with phytoplankton density in coastal water of Kudat, Sabah, Malaysia. *J. Geosci. Environ. Prot*. **2023**, 11(12), 229–240.
20. Cherotich, E.; Nyabaro, O.; Rayori, D.; Kenanda, E. Assessment of Chemosit River pollution with urbanization of Chemosit Centre, Kericho County, Kenya. *Pan Afr. Sci. J*. **2024**, 3, 55–63.