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ENVIRONMENTAL DRIVERS SHAPING PLANKTON COMMUNITY STRUCTURE ACROSS DIVERSE COASTAL ECOSYSTEMS IN SEKOTONG MARINE PROTECTED AREA, INDONESIA

Faktor Pengendali Lingkungan yang Membentuk Struktur Komunitas Plankton di Berbagai Ekosistem Pesisir Kawasan Konservasi Perairan Sekotong, Indonesia

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ABSTRACT

Plankton are crucial biological components driving the marine food web. This study aims to analyze the plankton community structure and identify the environmental drivers across diverse coastal ecosystems in Batu Putih Village, Sekotong Marine Protected Area (MPA), West Lombok. Field sampling was conducted in October 2025 across ten observation stations (encompassing mangrove, seagrass, coral reef, and anthropogenic zones) using a purposive sampling method. Data analysis included abundance, ecological indices (), and multivariate modeling via Canonical Correspondence Analysis (CCA). The results revealed that phytoplankton abundance ranged from 27 to 139 ind/L, peaking at the port area (ST10) and reaching its lowest in the coral reef ecosystem (ST5). Zooplankton abundance varied from 5 to 86 ind/L, with the highest concentration found in the mangrove ecosystem (ST8) and the lowest at ST1. The Bacillariophyceae (diatoms) and Copepoda groups emerged as the most dominant taxa. Generally, the diversity index was moderate with high evenness and low dominance, reflecting a relatively stable community. However, a community structure anomaly occurred at ST8, marked by a sharp decline in evenness () driven by the dominance of specific genera. The CCA ordination demonstrated that nitrate, phosphate, temperature, pH, and dissolved oxygen (DO) are the primary environmental drivers governing the spatial distribution of plankton. These findings indicate that while coastal waters generally support a stable community, anthropogenic-driven water quality fluctuations in specific zones could trigger ecological vulnerabilities. Consequently, continuous monitoring of water quality and managing domestic waste disposal are crucial to ensuring the long-term sustainability of the Sekotong MPA.

Keywords: Environmental drivers, Marine Protected Area, Plankton, Sekotong

ABSTRAK

Plankton merupakan komponen biologis krusial penggerak rantai makanan laut. Penelitian ini bertujuan menganalisis struktur komunitas plankton dan mengidentifikasi faktor pengendali lingkungan (*environmental drivers*) di berbagai ekosistem pesisir Desa Batu Putih, Kawasan Konservasi Perairan (KKP) Sekotong, Lombok Barat. Pengambilan sampel dilakukan pada Oktober 2025 di sepuluh stasiun (mangrove, lamun, terumbu karang, dan area antropogenik) menggunakan metode *purposive sampling*. Analisis mencakup kelimpahan, indeks ekologi (*H', E, D*), serta pemodelan *Canonical Correspondence Analysis* (CCA). Hasil menunjukkan kelimpahan fitoplankton berkisar 27–139 ind/L, tertinggi di pelabuhan (ST10) dan terendah di terumbu karang (ST5). Kelimpahan zooplankton berkisar 5–86 ind/L, tertinggi di mangrove (ST8) dan terendah di ST1. Bacillariophyceae (diatom) dan Copepoda menjadi kelompok paling dominan. Secara umum, indeks keanekaragaman tergolong sedang dengan keseragaman tinggi dan dominansi rendah, mengindikasikan komunitas yang relatif stabil. Namun, anomali berupa penurunan keseragaman (E=0.40) terjadi di ST8 akibat dominansi genus tertentu. Analisis CCA menegaskan bahwa nitrat, fosfat, suhu, pH, dan oksigen terlarut (DO) merupakan *environmental drivers* utama yang membentuk struktur dan sebaran spasial plankton. Temuan ini mengindikasikan bahwa meskipun kondisi perairan mendukung komunitas yang stabil, fluktuasi kualitas air akibat aktivitas antropogenik di zona spesifik berpotensi memicu kerentanan ekologi. Oleh karena itu, monitoring berkala kualitas air dan pembatasan limbah domestik menjadi langkah krusial guna menjaga keberlanjutan fungsi kawasan konservasi Sekotong.

Kata kunci: Environmental drivers, Kawasan Konservasi Laut, Plankton, Sekotong

INTRODUCTION

The waters of Batu Putih Village, Sekotong District, West Lombok Regency, represent a strategic coastal area integrated within the Marine Protected Area (MPA) of Gita Nada. This marine conservation zone encompasses various vital coastal ecosystems, ranging from mangroves and seagrass beds to coral reefs, which functions to maintain biological productivity and ecological equilibrium (Putri et al., 2023). The diverse habitat characteristics within the Gita Nada MPA generate complex spatial variations in environmental conditions, driven by natural oceanographic dynamics as well as the impacts of surrounding anthropogenic activities (Larasati et al., 2015). In addition to serving as a protection zone for marine biota, these waters play a pivotal role in sustaining the local community through marine tourism and sustainable fisheries sectors.

In preserving the functionality and energy flow within these heterogeneous coastal ecosystems, plankton communities hold a highly critical biological position. Phytoplankton act as primary producers that drive the marine food web through their photosynthetic capability and contribution to the primary productivity of the waters (Leidonald, 2022; Damai and Thoy, 2023). Concurrently, zooplankton serve as secondary consumers and a bridge for energy transfer from primary producers to higher trophic levels (Nurmalitasari et al., 2023). The dynamics, abundance, and species succession within this plankton community structure constitute the primary foundation supporting food web stability across various ecosystem zonations in the conservation area.

Ecologically, the plankton community structure exhibits high sensitivity toward fluctuations in water quality parameters, widely recognized as environmental drivers. Fluctuations in physico-chemical parameters such as temperature, transparency, pH, dissolved oxygen (DO), and nutrient supplies (nitrate and phosphate) significantly shape the spatial distribution patterns and taxonomic composition of plankton (Larasati et al., 2025). The rapid response of plankton toward shifts in these environmental drivers renders their community structure ideal for use as sensitive bioindicators to evaluate aquatic health levels and environmental pressure degrees in a region (Effendi, 2023; Diah, 2020). Consequently, an in-depth analysis concerning the correlation between hydro-oceanographic conditions and plankton structures can present a comprehensive overview of the actual state of coastal ecosystems.

As a conservation zone that also acts as a center for new economic growth, the waters of Batu Putih Village confront a severe ecological dilemma. On one hand, its status as part of the Gita Nada MPA demands absolute protection for sensitive ecosystems. On the other hand, the escalation of anthropogenic activities—ranging from local port operations and marine tourism to domestic waste runoff from settlements—poses a significant potential to degrade environmental quality. These pressures induce erratic fluctuations in physico-chemical water parameters, which directly threaten the stability of the plankton community structure as the foundation of the marine food web. Phenomema such as decreased dissolved oxygen (DO) levels at several points and high turbidity resulting from port activities serve as strong signals of ongoing ecosystem destabilization.

To date, most monitoring efforts in the Sekotong conservation area remain restricted to macro-aspects, such as the physical coverage area of coral reefs or mangroves. However, fundamental shifts due to environmental pressures always initiate from the biological responses of microscopic organisms like plankton through shifts in species composition, declines in evenness, or the dominance of specific taxa. Without a comprehensive understanding of how environmental drivers configure plankton community structures along these different ecosystem gradients, mitigation impacts and zonation management in the Gita Nada MPA will lack an accurate scientific foundation. This ecological vulnerability underscores that studies on plankton-environmental interactions in this area are no longer merely complementary taxonomic data, but an urgent necessity for the early detection of protected area degradation symptoms.

Based on this evident urgency, this study was conducted using a multivariate statistical modeling approach (Canonical Correspondence Analysis) to comprehensively analyze how environmental drivers shape the community structure, spatial distribution, and succession of plankton across diverse coastal ecosystems in Batu Putih Village, Sekotong Marine Protected Area, West Lombok.

MATERIALS AND METHODS

Study Time and Area

Data collection and field observations were carried out in October 2025 across the coastal waters of Batu Putih Village, Sekotong District, West Lombok Regency. The study area is administratively and geographically situated within the Gita Nada Marine Protected Area (MPA). Following the field phase, sample processing and laboratory analyses were conducted at two distinct facilities tailored to the specific parameters tested. Taxonomic enumeration, identification, and abundance calculations of plankton were performed at the Marine Hydrobiology Laboratory, Department of Fisheries and Marine Science, Faculty of Agriculture, University of Mataram. Meanwhile, chemical water analyses to detect nutrient concentrations (nitrate and phosphate) were carried out at the Analytical Chemistry Laboratory, Faculty of Mathematics and Natural Sciences (FMIPA), University of Mataram.

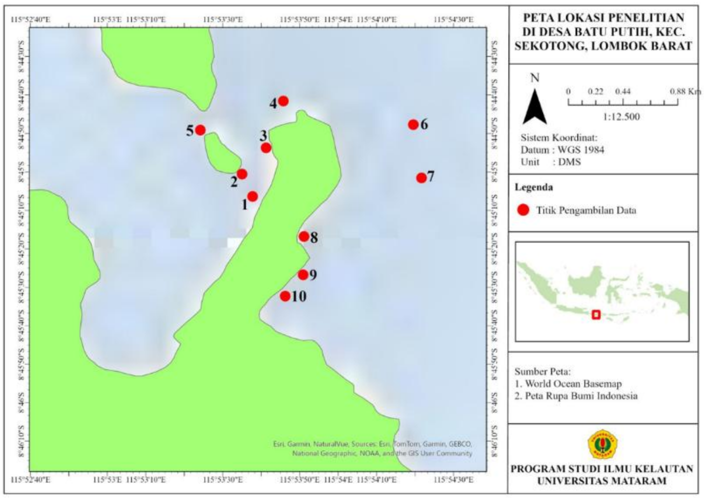

Figure 1. Map of research stations and sampling locations across various coastal ecosystems in Batu Putih Village, Sekotong Marine Protected Area, West Lombok.

Research Procedure

The execution of this research was structured into three integrated primary phases: pre-mapping, field collection, and laboratory processing. The initial stage commenced with the determination of sampling locations utilizing a purposive sampling method. This technique was selected to ensure the absolute representation of biological plankton data across various environmental gradients and distinct coastal ecosystem types within the conservation zone. Through this approach, the geographical positions of the 10 observation stations were precisely recorded using a Garmin GPSMAP 65s Global Positioning System (GPS) device, with the specific environmental characteristics detailed as follows:

Stations 1, 4, and 5 (ST1, ST4, ST5) were positioned within the coral reef zone; Station 2 (ST2) was situated within the seagrass ecosystem in a shallow lagoon area characterized by sandy-muddy substrates; Station 3 (ST3) was located within the jetty vicinity; Stations 6 and 7 (ST6, ST7) were allocated within the pearl oyster aquaculture area; Station 8 (ST8) was established precisely inside a dense mangrove forest ecosystem dominated by thick organic mud substrates; Station 9 (ST9) was positioned in the estuary (river mouth) zone influenced by continuous freshwater runoff from the mainland; and Station 10 (ST10) was set within a local port zone characterized by intense anthropogenic pressures and high vessel transport frequency.

Plankton Sampling and Handling

Quantitative plankton collection at each sampling site was performed by filtering 100 Liters of seawater through a standard Kahlsico plankton net with a mesh size of 20 µm (Aisoi, 2019). The filtered water accumulated in the bucket net was carefully poured into 30 mL plastic flacon bottles using a dropper pipette. For biological sample preservation and handling, 3–5 drops of a 4% Lugol chemical solution were added to each flacon bottle until the sample turned a light brownish color (Rahmawati *et al.*, 2020). The sample bottles were subsequently labeled and stored in an insulated coolbox (Marina 12 S) protected from direct sunlight exposure to prevent cell wall lysis before further processing.

Water Quality Data Collection and Measurement

The measurement of water quality variables as environmental drivers was carried out via two approaches: direct *in-situ* field measurements and subsequent *ex-situ* laboratory analysis. *In-situ* measurements included water temperature, pH, and salinity, which were recorded simultaneously using a multiparameter Horiba U-50 Water Quality Checker (WQC). Dissolved oxygen (DO) quantities were measured digitally utilizing a Lutron DO-5510 DO Meter, while water transparency and light penetration in the water column were visually assessed using a standard 30 cm diameter Secchi disk equipped with a scaled rope (Effendi, 2023). Additionally, to evaluate water mass dynamics, water current velocity was measured directly using a digital Flowatch FL-03 current meter positioned within the vegetative water column for a specific duration.

For *ex-situ* nutrient analysis, seawater samples were collected using a standard Nansen bottle at vegetative water column depths. The water samples were then transferred into sterile 250 mL polyethylene (PE) bottles, preserved at a cold temperature of 4°C inside a coolbox, and transported to the designated laboratory for analysis. Nitrate and phosphate concentrations were determined via spectrophotometric methods using a Shimadzu UV-1800 UV-Vis Spectrophotometer following standard commercial reagent coloring procedures (Diah, 2020). All glassware applied during the analytical process was rinsed with sterile distilled water to avoid cross-contamination.

Plankton Identification

Microscopic plankton identification procedures were conducted at the Marine Hydrobiology Laboratory, UNRAM. Samples within the polyethylene bottles were shaken constantly to ensure complete homogeneity. A 1 mL sub-sample was extracted using a micropipette and transferred carefully into a standard 50 x 20 x 1 mm Sedgwick-Rafter Counting Cell (SRC). Cell morphology observations were performed under an Olympus CX23 binocular microscope with objective lens magnifications ranging from 10x (total magnification of 100x). The observed morphological characteristics were cross-referenced with international marine plankton taxonomic identification keys, including the classical guides by Davis (1955), Yamaji (1966), and Hasle et al. (1996), as well as digital taxonomic databases from AlgaeBase and the World Register of Marine Species (WoRMS) (Guiry & Guiry, 2022).

Plankton Abundance Analysis

Plankton abundance (ind/L) was quantitatively calculated based on the SRC compartment quadrat swept method. The mathematical calculation followed a modified formula comparing the volume of water filtered in the field with the sub-sample volume on the counting cell (APHA, 2012). This formula multiplies the number of enumerated cells by the ratio of the collector bottle volume to the SRC volume, which is then divided by the total volume of seawater filtered by the net in the field. This calculation provides a precise density of individuals per liter of water at each observation station.

Plankton Ecological Metrics

To quantitatively evaluate the stability and general characteristics of the plankton community structure, three primary ecological indices were determined. The baseline mathematical evaluation began with the Shannon-Wiener diversity index (H'), which was computed to systematically assess the level of community complexity and taxonomic heterogeneity across the different observation sites (Putri et al., 2023). Furthermore, to understand how uniformly these documented individuals were distributed among the observed species within the ecosystem, Pielou's evenness index (E) was applied as a measures of abundance equality (Nurmalita and Sudarsono, 2023). Finally, Simpson's dominance index (D) was utilized as a complementary metric to detect potential structural imbalances, shifting successions, or the disproportionate concentration of numerical abundance by specific opportunistic genera within the investigated coastal ecosystems (Ruthena et al., 2023).

Statistical and Data Analysis

The baseline dataset encompassing plankton density estimates, environmental physico-chemical variables, and the calculated ecological indices (H', E, D) was initially organized and scrutinized through descriptive statistics. The summarized outputs were subsequently illustrated using comparative tables to clarify spatial differences across the monitoring stations.

To explore how the plankton community features align with the fluctuating water quality profiles, we performed multivariate Canonical Correspondence Analysis (CCA). This ordination model was executed via the PAST ecological software package (version 4.03). Within the analysis, the environmental matrix comprising temperature, pH, DO, salinity, transparency, current velocity, nitrate, and phosphate served as the explanatory framework (independent variables), whereas the numerical matrix of plankton genus abundances functioned as the response data (Larasati et al., 2025). The resulting CCA biplot diagram captures the directional arrows of environmental vectors, graphically demonstrating the habitat preferences or vulnerabilities of certain plankton genera toward specific ecological drivers within the Sekotong conservation area.

RESULTS

Environmental Driver Conditions (Water Quality)

The field measurements of physico-chemical parameters as environmental drivers across the 10 observation stations in the coastal waters of Batu Putih Village revealed distinct spatial variations, heavily influenced by specific habitat ecosystem characteristics and local anthropogenic pressure intensities (Table 1). In general, pH values across all sampling sites ranged from 7.7 to 8.2, while water column temperatures remained within a naturally warm baseline ranging from 30.1°C to 30.8°C. Aquatic salinity levels were observed to be highly stable, consistently fluctuating within a narrow range of 33 to 34 ppt. The baseline values of these three primary parameters indicate ideal marine conditions that fall well within the safe threshold of national marine water quality standards for aquatic life, as regulated by Kepmen LH No. 51 of 2004.

Noticeable fluctuations, however, were captured in water transparency, current velocity, and dissolved oxygen (DO) levels. The highest light penetration or transparency occurred in the inner coral reef flat and jetty zone (ST3), reaching a depth of 10.5 meters, closely followed by the pearl oyster aquaculture ecosystem (ST6) at 10.0 meters. Conversely, extreme turbidity was detected in the zone subjected to high anthropogenic activities, specifically the port station (ST10), which recorded a transparency depth of only 0.75 meters, and the dense mangrove forest ecosystem (ST8) at 5.0 meters.

Water mass hydrodynamics, assessed via digital current meter measurements, indicated that the peak current velocity occurred in the sandy lagoon area (ST2) at 0.091 m/s and the jetty vicinity (ST3) at 0.08 m/s. Meanwhile, the most stagnant water movements were documented in the estuary area (ST9) and the port zone (ST10), both recording a constant low value of 0.020 m/s. Dissolved oxygen concentrations fluctuated between 4.4 and 6.3 mg/L; the aquaculture transition site (ST7) yielded the highest oxygen levels (6.3 mg/L), whereas the port area (ST10) fell short of the standard reference baseline, dropping to 4.4 mg/L.

Regarding macro-nutrient content, nitrate concentrations ranged from 0.001 to 0.016 mg/L. The highest accumulation of nitrogen compounds was found at the port station (ST10) at 0.016 mg/L and the pearl oyster aquaculture ecosystem (ST6) at 0.014 mg/L. In contrast, phosphate levels across most stations were remarkably low, falling below the detection limit of the spectrophotometer instrument (<0.01 mg/L), with minor exceptions documented in the sandy lagoon ecosystem ST2 (0.003 mg/L) and the port zone ST10 (0.001 mg/L).

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Table 1. Physico-Chemical Water Quality Parameters Across Various Coastal Ecosystems in Batu Putih Village.

Coastal Ecosystem Group	Station	pH	Temperature (°C)	Current velocity (m/s)	Salinity (ppt)	Transparancy(m)	DO (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)
Coral reef	ST1	7,7	30,1	0,0538	33	9,5	4,5	0,009	<0,01
	ST4	8,2	30,5	0,03	34	8	5	0,005	<0,01
	ST5	7,7	30,4	0,066	34	7	5,6	0,001	<0,01
Sandy lagoon	ST2	8,1	30,2	0,091	33	9	5,6	0,004	0,003
Jetty area	ST3	7,9	30,8	0,088	34	10,5	4,8	0,003	<0,01
Pearl Oyster Culture	ST6	8,1	30,3	0,058	33	10	5,4	0,014	<0,01
	ST7	8,1	30,1	0,062	33	9	6,3	0,013	<0,001
Mangrove	ST8	7,9	30,8	0,078	34	5	5	0,007	<0,01
	ST9	8,1	30,7	0,020	34	7	4,8	0,009	<0,01
Port area	ST10	8	30,8	0,020	33	0,75	4,4	0,016	0,001
Water Quality standard		**7,0-8,5**	**28-32**	**-**	**33-34**	**-**	**>5**	**0,008**	**0,015**

Struktur Komunitas Plankton di Berbagai Ekosistem Pesisir

The quantitative features of the plankton community structure encompassing total individual abundance estimates alongside the calculated ecological metrics (H', E, D) are presented comparatively in Table 2.

Table 2. Abundance and Ecological Index Values of Plankton Communities Across Various Coastal Ecosystem Groups.

Ecological Parameters	ST 1	ST 2	ST 3	ST 4	ST 5	ST 6	ST 7	ST 8	ST 9	ST 10
Phytoplankton										
Abundance(ind/L)	35	42	40	33	27	42	59	136	77	139
Number of Taxa (S)	17	15	11	12	14	15	18	20	20	23
Diversity Index (H')	2.63	2.63	2.10	2.31	2.33	2.51	2.59	2.11	2.46	2.77
Evennes Index (E)	0.93	0.97	0.88	0.93	0.88	0.92	0.89	0.43	0.82	0.88
Dominance Index (D)	0.09	0.07	0.14	0.11	0.08	0.09	0.09	0.20	0.10	0.12
Zooplankton										
Abundance(ind/L)	5	19	41	24	24	24	11	86	11	22

Ecological Parameters	ST 1	ST 2	ST 3	ST 4	ST 5	ST 6	ST 7	ST 8	ST 9	ST 10
Number of Taxa (S)	3	8	10	9	8	10	5	14	5	7
Diversity Index (H')	1.05	1.97	1.80	1.74	1.55	1.92	1.36	1.06	1.46	1.67
Evennes Index (E)	0.96	0.94	0.78	0.79	0.74	0.83	0.84	0.40	0.91	0.86
Dominance Index (D)	0.36	0.15	0.22	0.25	0.32	0.20	0.30	0.61	0.25	0.23

Phytoplankton Abundance and Community Structure

The population density of the phytoplankton community across the coastal waters of Batu Putih Village ranged from 27 to 139 ind/L. The abundance gradient revealed a significant increasing trend in zonations positioned closer to the mainland and areas under anthropogenic influence. The highest cell densities were discovered in the port zone (ST10) at 139 ind/L and the dense mangrove ecosystem (ST8) at 136 ind/L. Conversely, the lowest phytoplankton density was encountered on the reef slope (ST5) at only 27 ind/L, followed by the intertidal coral reef zone (ST4) at 33 ind/L.

Phytoplankton taxonomic richness fluctuated between 11 and 23 genera. The highest number of genera was documented in the port area (ST10) with 23 taxa, while the lowest was found in the jetty zone (ST3) with 11 taxa. Ecological index evaluations demonstrated that phytoplankton diversity values (H') across the entire area ranged from 2.10 to 2.77, indicating a moderate level of community heterogeneity.

Phytoplankton evenness index values (E) were generally high (>0.80), showing a well-balanced individual distribution among species. However, a sharp community structure anomaly occurred specifically within the dense mangrove ecosystem (ST8), characterized by a drop in the evenness value to its lowest point at 0.43. This dramatic decline in evenness at ST8 was directly proportional to a peak in the Simpson dominance index (D), resulting from space and nutrient monopolization by a specific opportunistic phytoplankton genus belonging to the diatom class (Bacillariophyceae).

Zooplankton Abundance and Community Structure

The abundance of the zooplankton community as secondary consumers exhibited lower ranges compared to phytoplankton, varying between 5 and 86 ind/L. The spatial distribution of zooplankton demonstrated a massive population concentration within the dense mangrove ecosystem (ST8), reaching a peak abundance of 86 ind/L, followed by the jetty zone (ST3) at 41 ind/L. In contrast, the site with the lowest zooplankton population was the outer reef zone (ST1), which only recorded a density of 5 ind/L.

Zooplankton diversity index values (H') ranged from 1.05 to 1.97, with the highest heterogeneity levels discovered in the sandy lagoon ecosystem (ST2) at 1.97 and pearl oyster aquaculture (ST6) at 1.92, while the lowest value resided in the outer reef zone (ST1) at 1.05. Zooplankton individual evenness characteristics were mostly high, with evenness index values (E) ranging between 0.75 and 0.96.

Mirroring the pattern observed in their primary producers, the zooplankton community in the mangrove ecosystem (ST8) once again displayed a prominent structural anomaly, marked by the lowest evenness value at 0.40. This community instability phenomenon at the ST8 mangrove site was further substantiated by a high Simpson dominance index (D), which surged to 0.61. This score reflects an absolute dominance by specific taxa from the Copepoda group that monopolized the water column within that mangrove ecosystem.

Plankton Distribution Preferences Toward Environmental Drivers

The functional relationships and specific distribution preferences of plankton genera in response to physico-chemical water quality variables were analyzed using a Canonical Correspondence Analysis (CCA) ordination diagram presented in Figure 3. The biplot visualization confirms the clustering of plankton taxa characteristics responding to environmental vectors spatially across different coastal ecosystem types within the Sekotong conservation area.

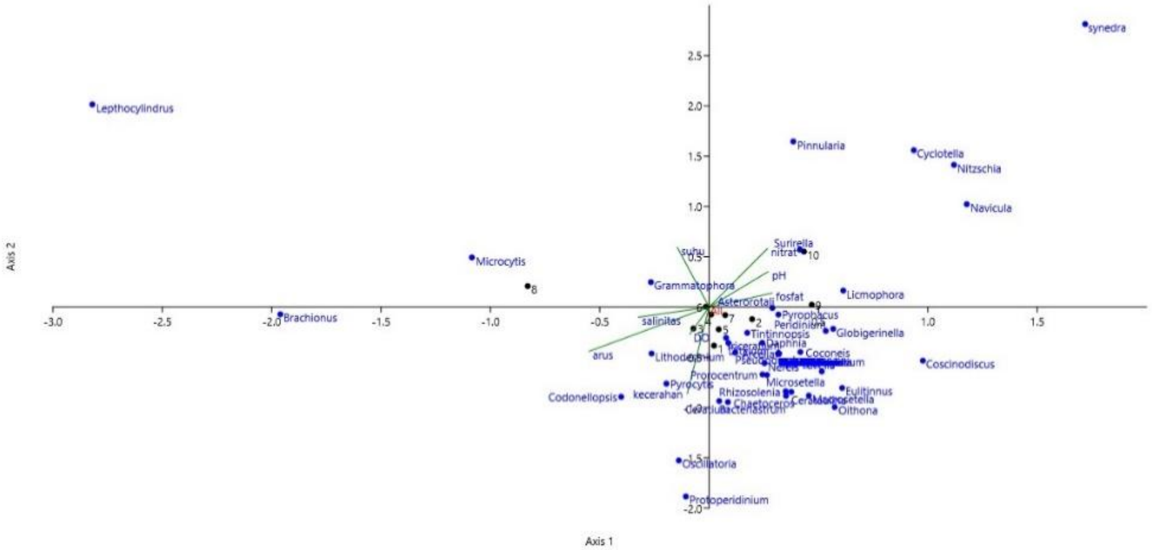

Figure 2. Canonical Correspondence Analysis (CCA) ordination biplot diagram demonstrating the relationship between water quality parameters (environmental drivers) and the spatial distribution of plankton genera across various coastal stations in Batu Putih Village.

The ecosystem zonations of the outer reef (ST1), intertidal coral reef (ST4), reef slope (ST5), and the sandy lagoon area (ST2) clustered closely near the center of the ordination coordinates. Environmental conditions within these baseline habitats tend to be ecologically stable without extreme single-parameter pressures, and are characterized by the continuous presence and strong affinity of marine diatom genera such as *Navicula*, *Cyclotella*, *Coscinodiscus*, and *Nitzschia*.

The subsequent station cluster, which encompasses the jetty zone (ST3), the pearl oyster aquaculture site (ST6), and the aquaculture transition area (ST7), displayed close vector orientations or direct preferences toward water temperature, pH, and water column transparency parameters. This dynamic zone serves as an ideal supporting habitat for the resilience and existence of dinoflagellate groups, notably the genera *Peridinium* and *Pyrophacus*.

Meanwhile, the coastal cluster formed by the dense mangrove ecosystem (ST8), the estuary/river mouth area (ST9), and the port zone (ST10) exhibited a highly powerful linear correlation with slow water current velocity vectors and elevated macro-nutrient concentrations (nitrate and phosphate). These nutrient-rich aquatic characteristics in the mangrove and port environments control taxonomic succession, stimulate growth rates, and ultimately trigger localized massive blooms of specific opportunistic plankton genera such as *Microcystis* and *Brachionus*.

DISCUSSION

Characteristics of Environmetal Drivers in the Conservation Area

The spatial variation of physico-chemical water quality parameters in the coastal waters of Batu Putih Village confirms the profound influence of habitat types and local anthropogenic activities in configuring the hydro-oceanographic conditions of the Gita Nada Marine Protected Area (MPA). Fundamental parameters such as temperature, pH, and salinity exhibited relatively stable homogeneity across all sampling sites, reflecting the dynamic water mass mixing properties characteristic of tropical coastal zones. The stability of salinity levels within 33–34 ppt and pH values above 7.7 indicates that the carrying capacity of the waters generally remains within an ideal physiological tolerance range for marine life, aligning with environmental quality standards regulated in Kepmen LH No. 51 of 2004.

However, significant water quality degradation was detected within the port zone (ST10), marked by an extreme drop in light penetration (transparency) to 0.75 meters and a decline in dissolved oxygen (DO) levels to 4.4 mg/L. This DO condition, which falls below the minimum reference standard threshold (>5 mg/L), is caused by the heavy accumulation of organic matter derived from domestic waste and marine transport operations at the port. The decomposition process of organic materials by heterotrophic microorganisms consumes dissolved oxygen excessively within the water column (Effendi, 2023). This condition is exacerbated by slow current velocities (0.020 m/s) at ST10 and the estuary site ST9, which restricts water mass flushing times and mixing, thereby promoting localized nutrient retention and heavy turbidity.

The stagnant hydrodynamics in the port and estuary zones stand in stark contrast to the high nutrient inputs. The elevated nitrate concentrations at the port ST10 (0.016 mg/L) and the aquaculture area ST6 (0.014 mg/L) indicate anthropogenic inputs from land via surface runoff. These nutrients act as limiting stimulants that trigger biological responses from primary producers in those environments.

Plankton Community Dynamics and Structure Across Ecosystems

Plankton abundance distribution patterns demonstrated a clear gradient, where population densities increased at stations positioned closer to land or zones experiencing nutrient enrichment (eutrophication). The highest phytoplankton abundance peaks at the port ST10 (139 ind/L) and the mangrove ecosystem ST8 (136 ind/L) were driven by the abundant availability of nitrate compounds. In nutrient-rich ecosystems, the diatom class (*Bacillariophyceae*) exhibits exceptionally high specific growth rates due to efficient nutrient absorption mechanisms and adaptive silica cell wall architectures (Salwa et al., 2024). Conversely, the low phytoplankton abundance on the reef slope ST5 (27 ind/L) is attributed to the oligotrophic (nutrient-poor) nature of open-sea waters, despite high light transparency supporting photosynthesis at that site.

Ecological index analysis unveiled a highly pronounced structural community anomaly within the dense mangrove ecosystem (ST8). While phytoplankton diversity (H') at other sites was categorized as moderate with high evenness (E>0.80), evenness at ST8 plummeted sharply to 0.43. This phenomenon coincided with a surge in the Simpson dominance index (D=0.20), signifying monospecific dominance. Based on ecosystem traits, mangrove environments provide abundant supplies of suspended organic materials but feature harsh environmental fluctuations. This induces natural selection where only opportunistic phytoplankton taxa can proliferate massively, suppressing the presence of more sensitive taxa (Santika et al., 2022).

This community anomaly in the mangrove ecosystem ST8 was also strongly reflected in its primary consumers, where zooplankton abundance surged drastically to a peak of 86 ind/L. This elevated abundance was not accompanied by a healthy species evenness, as evidenced by the drop in zooplankton evenness to its lowest point (E=0.40) and a massive dominance index spike (D=0.61). The zooplankton community structure at ST8 was fully dominated by taxa from the Copepoda group. This phenomenon represents a trophic adaptation, where herbivorous zooplankton abundance is directly stimulated by phytoplankton abundance as their primary food source (grazing pressure), combined with a wealth of mangrove litter acting as organic detritus supporting additional food webs (Nurmalitasari and Sudarsono, 2023; Wulandari et al., 2025).

Interactions Between Plankton Communities and Environmental Drivers

Visualized ordinations using Canonical Correspondence Analysis (CCA) reinforce the role of physico-chemical water parameters as the primary environmental drivers separating plankton community characteristics into specific ecosystem clusters. The grouping of coral reef stations (ST1, ST4, ST5) and sandy lagoons (ST2) near the center of the ordination coordinates represents stable environmental conditions with minimal parameter fluctuations. Coral reef habitats are characterized by high light penetration and moderate current velocities, which serve as ideal limiting factors for the growth of pure marine diatom communities like *Navicula*, *Cyclotella*, and *Coscinodiscus*. This alignment corresponds with findings by Larasati *et al.* (2015, 2025a), which assert that true marine diatom genera exhibit high ecological preferences toward stable-current waters with optimal transparency.

Shifts in environmental vector directions were highly visible in the cluster comprising the jetty zone (ST3) and pearl oyster aquaculture sites (ST6 and ST7), which aligned toward more dynamic temperature and pH parameters. Micro-temperature increases from anthropogenic structures trigger taxonomic composition shifts toward dinoflagellate groups like *Peridinium* and *Pyrophacus*, which possess wider thermal tolerances than sensitive diatoms.

The most evident impact of anthropogenic pressure was shown by the ecosystem cluster of mangroves (ST8), estuaries (ST9), and ports (ST10), which correlated linearly and strongly with nitrate, phosphate, and slow current vectors. Environments featuring rich nutrients but minimal water mass movement trigger community succession toward opportunistic plankton genera such as *Microcystis* and *Brachionus*. The massive growth of these genera in nutrient-rich zones serves as a robust bioindicator of secondary organic enrichment (eutrophication) symptoms in coastal waters. These findings corroborate a study by Larasati et al. (2025b) in Bima Bay, which states that coastal water zones connected to settlements and ports experience shifts in environmental drivers toward nitrogen nutrient dominance, radically restructuring microscopic food webs through reductions in biotic evenness.

Ecologically, the presence of community structure anomalies and signs of water quality degradation (DO < 4.5 mg/L) in several specific zones of the Gita Nada MPA provides an early warning for conservation area management. Although the core and tourism utilization zones (coral reefs and seagrass) currently appear stable, nutrient leakage from port activities and land-based domestic waste has proven to alter biological structures at the lowest trophic levels in mangrove and estuary ecosystems. If these environmental driver fluctuations are not mitigated through regular water quality monitoring and waste discharge regulations, ecological destabilization could potentially spread to surrounding sensitive ecosystems, threatening long-term biodiversity sustainability in the Sekotong Marine Protected Area.

CONCLUSSION

Water quality in the coastal area of Batu Putih Village, Sekotong Marine Protected Area (MPA), generally remains in a good state capable of sustaining marine life in compliance with the environmental quality standards of Kepmen LH No. 51 of 2004. Nevertheless, fairly sharp physico-chemical parameter fluctuations were detected spatially across ecosystems, with water quality degradation in the form of heavy turbidity and dissolved oxygen (DO) declines below the minimum threshold most prominently encountered in the port zone (ST10). Plankton communities in these waters were absolutely dominated by the diatom group (*Bacillariophyceae*) at the primary producer level and the Copepoda group at the secondary consumer level. At a macro level, ecological indices indicated that the plankton community structure was within a moderate diversity level with high individual evenness, reflecting a relatively stable ecosystem condition. However, a prominent structural anomaly featuring a drop in evenness and a surge in the Simpson dominance index occurred specifically inside the dense mangrove ecosystem (ST8) due to space monopolization by certain opportunistic taxa responding to high organic matter availability from mangrove litter. Plankton quantitative abundance also exhibited uneven distributions, with phytoplankton densities peaking in the port zone ST10 (139 ind/L) and zooplankton populations concentrating massively in the mangrove ecosystem ST8 (86 ind/L), while open oligotrophic areas on the reef slope (ST5) recorded the lowest density. Through multivariate Canonical Correspondence Analysis (CCA) modeling, it was confirmed that nutrient compounds consisting of nitrate and phosphate, alongside temperature, pH, and dissolved oxygen (DO), act as the primary environmental drivers strongly controlling spatial distribution patterns and plankton taxonomic succession within the Gita Nada MPA.

As a follow-up measure to these findings, it is recommended to implement regular water quality monitoring programs and structured regulations for domestic waste disposal as well as marine transport operations, particularly within the Sekotong port zone. These mitigation steps are highly crucial to control excessive nitrogen and phosphate nutrient inputs into the sea, minimize secondary organic enrichment (eutrophication) risks, and protect microscopic food web stability across surrounding sensitive ecosystems like coral reefs and seagrass beds to guarantee the long-term functional sustainability of the Sekotong Marine Protected Area.

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