

Benthic-Pelagic Coupling and Structural Complexity of Coral Reefs in the Northern Bali Strait: Implications for Coastal Ecosystem Resilience

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Abstract. This study examines benthic-pelagic associations in neritic environments by evaluating habitat structural heterogeneity, macrobenthic biodiversity, and pelagic community status at Grand Watudodol (GWD) in the northern Bali Strait. Utilizing Line Intercept Transect (LIT) protocols and volumetric filtration methods alongside in-situ hydro-oceanographic monitoring, community ecological indexes were quantified across biological zones. The empirical results revealed a live hard coral cover of 41.55%, classifying the ecosystem status as moderate. The benthic matrix showed high architectural diversity, with branching *Acropora*, massive corals, soft corals, and sponges. Conversely, the pelagic zone demonstrated a community structure imbalance, suggesting potential environmental enrichment indicated by a high abundance of the diatom *Skeletonema* sp.. Statistical correlation analysis revealed that this pelagic microalgal accumulation was positively associated with vertical water clarity and calm surface current velocities (0.06 m/s), which may prolong the residence time of terrestrial nutrients. While current physicochemical parameters largely meet national environmental standards, chronic pelagic nutrient loading may pose long-term ecological risks of substrate smothering. Ultimately, these findings indicate a potential ecological shift, showing that long-term reef resilience requires expanding beyond localized physical marine protection to a comprehensive ridge-to-reef management framework that can mitigate terrestrial organic inputs.

Keywords: Benthic-pelagic coupling; Coral lifeforms; Diatom bloom; Ecological index; Structural complexity.

I. INTRODUCTION

Coral reef ecosystems represent some of the most productive coastal environments in the marine realm, exerting crucial ecological functions as habitat engineers, spawning grounds, and nursery grounds for a diverse array of aquatic biota. A primary driver determining the exceptionally high biodiversity inherent to these ecosystems is the morphological composition of the coral reef matrix. Habitat structural heterogeneity is collaboratively shaped by a wide variation of coral

lifeforms ranging from branching and massive to encrusting and foliose. From an ecological perspective, elevated heterogeneity expands the availability of architectural crevices and micro-refugia, directly supporting advancements in species richness, abundance, and the long-term community stability of both the benthos and its associated vagile fauna [1,2].

The coastal zone of Grand Watudodol (GWD), situated in the northern corridor of the Bali Strait in Banyuwangi, features highly dynamic hydro-oceanographic characteristics. Functioning as a narrow choke point connecting the Java Sea water masses in the north with the

Indian Ocean in the south, this marine environment is driven by intense and constant semidiurnal tidal currents. The local physicochemical water parameters generally exhibit ideal conditions for scleractinian coral metabolism, characterized by a robust dissolved oxygen concentration reaching 6.5 mg/L, a neutral pH of 7.0, and excellent vertical water clarity extending to depths of 8 meters [3]. While the availability of these optimal environmental conditions serves as a primary catalyst for the establishment of a heterogeneous benthic community across GWD waters, this neritic ecosystem remains vulnerable. Directly adjacent to the mainland, the biological community continuously faces ecological challenges stemming from potential fluctuations in terrestrial organic matter and alluvial sediments from

triggered by terrestrial surface runoff during the rainy season [4–6]. In the long term, such pelagic nutrient loading could impair vertical light penetration dynamics and stimulate the proliferation of macroalgae that compete with corals for space, thereby threatening to alter the underlying benthic community structure.

Despite symptoms of potential nutrient enrichment in the pelagic component, the benthic community in GWD waters retains a compelling structural resilience. Live hard coral cover is dominated by branching *Acropora* (ACB, 6.75%) and massive corals (CM, 6.70%), alongside other structural benthic organisms such as soft corals (12.85%) and sponges (6.15%). These community dynamics reflect a diverse morphological variation that builds a distinctive underwater spatial heterogeneity. Most previous research

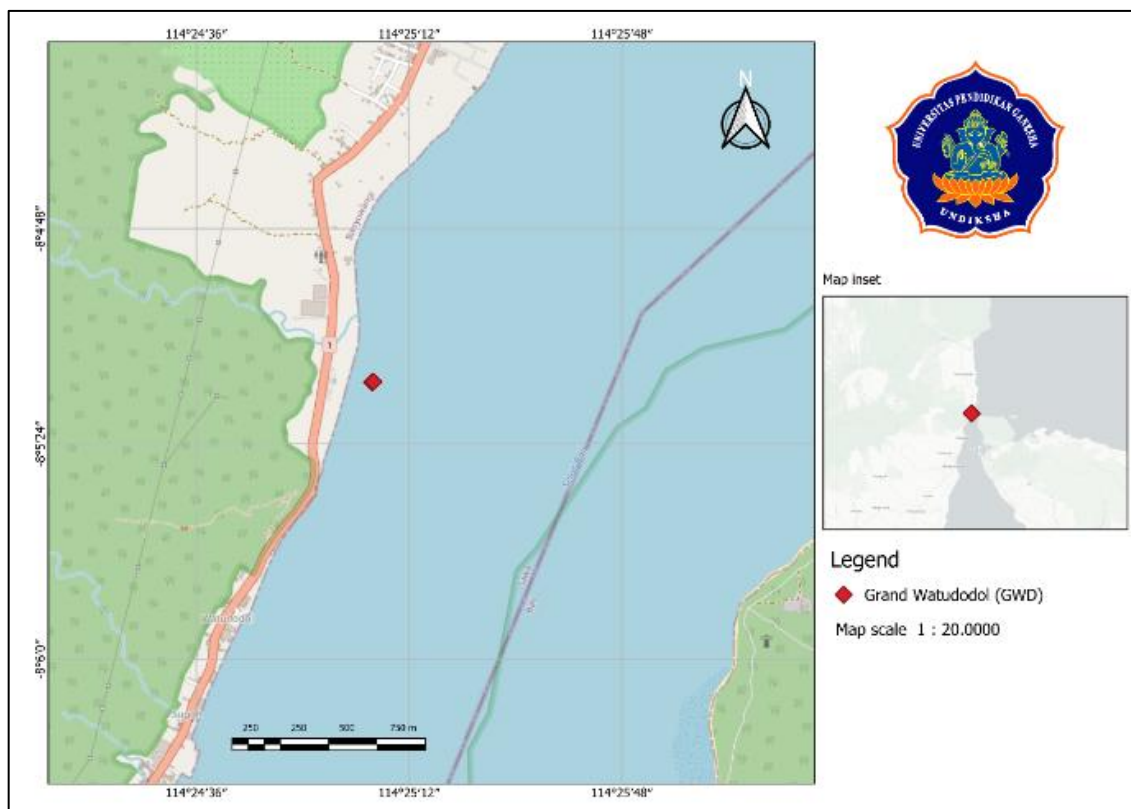


Figure 1. The research location is in the Grand Watudodol area, which is located in the Bali Strait.

coastal runoff.

Signs of environmental shifts within GWD waters are observable in the biological components of the pelagic zone. Plankton community structure data reveal exceptionally high density, reaching a total abundance of 3.4×10^6 cells/m³. This pelagic community exhibits dominance by microalgae belonging to the class *Bacillariophyceae* (diatoms), particularly the genus *Skeletonema* sp., which accounts for 81.95% of the total plankton population, followed by the genus *Chaetoceros* sp.. The high abundance of these micro-diatoms may serve as a bioindicator of potential environmental enrichment

in the northern Bali Strait has been restricted to macro-scale coral cover monitoring utilizing single, descriptive visual methods. Micro-ecological studies that specifically integrate macrobenthic biodiversity quantification, ecological indices, and the morphological composition of coral lifeforms in direct relation to pelagic trophic states remain scarce [1,2,7].

Consequently, this study aims to comprehensively analyze macrobenthic biodiversity, quantify community ecological index parameters, and evaluate the coral lifeform composition within the GWD waters, Banyuwangi. Utilizing an integrative community ecology

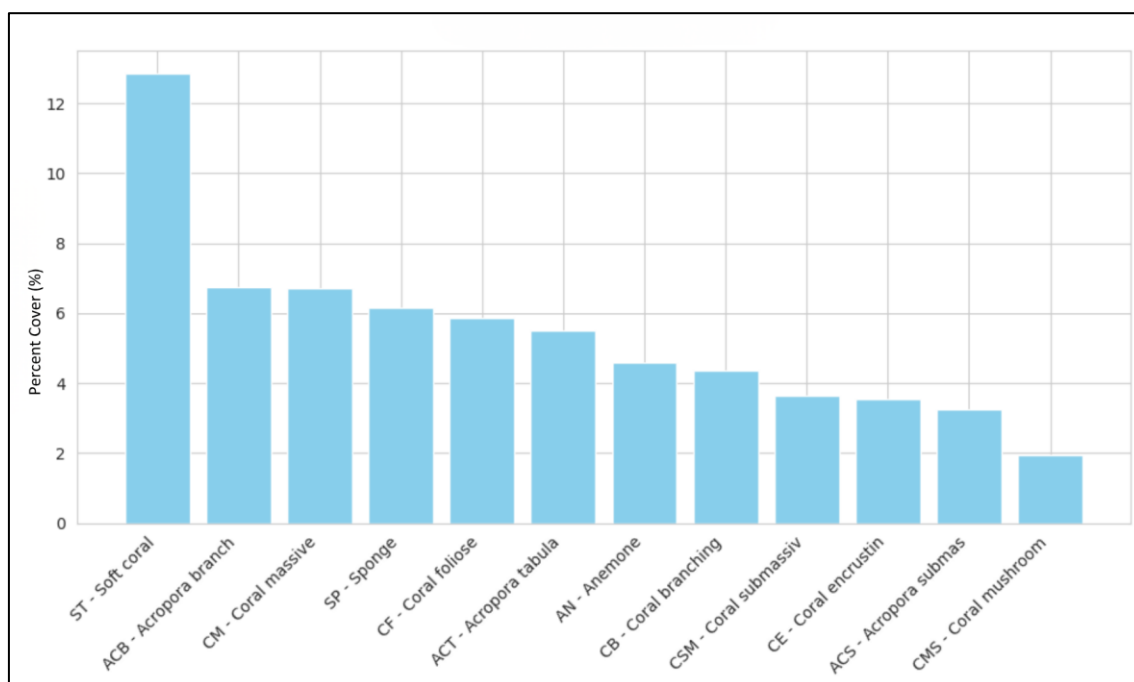


Figure 2. Percentage Composition of Benthic Component Cover and Morphological Variation

approach, this research provides baseline data on the contemporary health status of the benthic ecosystem and its functional association with pelagic dynamics in the Bali Strait. Ultimately, the findings of this study contribute primary scientific data to inform the development of future ecosystem resilience-based management strategies for coral reefs in the region.

II. METHODS

1. Study Time and Location

This study was conducted in the coastal waters of GWD, Wongsorejo District, Banyuwangi Regency, East Java Province, geographically situated along the northern coast of the Bali Strait. Field data collection was executed during a synchronized diurnal tidal cycle, encompassing three independent sampling stations. At each station, three separate 50-meter LIT transects and three independent plankton replicates were surveyed to ensure statistical robustness. We selected this temporal framework to align field sampling with local tidal fluctuations and optimal solar irradiance penetration, ensuring standardized environmental conditions for comparative analysis of pelagic and benthic biota. Monitoring of the marine communities was focused along the shallow benthic corridor of the GWD coast, spanning the spatial transitions across the designated sampling stations (Figure 1).

2. Research Apparatus and Materials

The field apparatus deployed in this study comprised SCUBA diving equipment, a 50-meter transect tape, underwater paper attached to a writing slate, an underwater digital camera, a mesh size 25 plankton net, 100-mL plankton sample bottles, a 1% Lugol's iodine solution, a handheld refractometer, a digital water thermometer, a pH meter, a standard Secchi disk, and a mechanical flowmeter. A Global Positioning System (GPS) receiver was utilized to map the absolute geographical coordinates of each sampling station.

3. Hydro-Oceanographic Parameter Measurements

In-situ monitoring of physicochemical seawater quality parameters was conducted concurrently with the biological sampling at the designated stations. The environmental indicators quantified included seawater temperature (°C), salinity (ppt), pH, vertical water clarity (meters), surface current velocity (m/s), and dissolved oxygen (DO) concentration (mg/L) as critical ecological limiting factors [3].

4. Data Analysis Methods

4.1. Community Ecology Index Analysis

The comparative characteristics of the community structure of benthic macrobenthos and pelagic plankton were quantitatively analyzed using three main ecological index formulas [8,12]:

- Shannon-Wiener Diversity Index (H'):

$$H' = - \sum_{i=1}^8 P_i \ln P_i$$

Where; $P_i = \frac{n_i}{N}$ (n_i represents the abundance/percentage value of the individual taxa i , and N represents

these data with the national standard criteria for coral reef degradation enacted by the Decree of the Minister of State for the Environment No. 4 of 2001 [8].

4.3. Integrative Analysis of Benthic-Pelagic Interactions

The co-occurrence of benthic morphological diversity

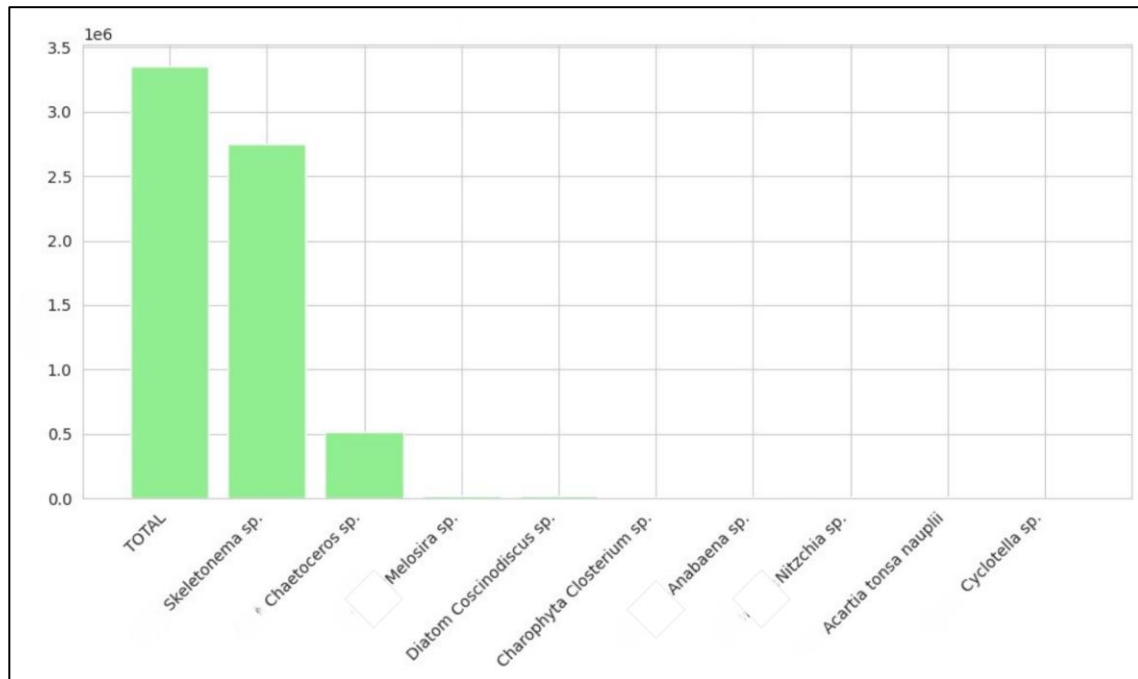


Figure 3. Relative Abundance Structure and Dominance of Plankton Genus in the Neritic Pelagic Zone of GWD.

the total abundance/percentage of all taxa in the community).

- Pielou Evenness Index (E):

$$E = \frac{H'}{\ln S}$$

Where S is the total number of identified genera or taxa in a community.

- Simpson's Dominance Index (D):

$$D = \sum_{i=1}^8 \left(\frac{n_i}{N} \right)^2$$

Plankton density is calculated by standardizing sweep volume in the SRCC and is expressed in cells/m³.

4.2. Analysis of Structural Complexity and Coral Reef Status

The morphological heterogeneity of the coral reefs was analyzed based on lifeform diversity and its relative contribution to the provision of underwater architectural space. The total percentage of live coral cover was determined by calculating the cumulative percentage of all hard coral lifeforms. The ecological status of the reef condition was subsequently classified by cross-referencing

and pelagic status was evaluated using a descriptive-analytical approach. Biological correlations were examined by comparing the diversity and dominance indices of the plankton community against the percentage cover and morphological growth diversity of corals at GWD.

III. RESULTS AND DISCUSSION

RESULT

1. Coral Reef Community Structure and Benthic Structural Complexity

Based on the empirical analysis of benthic datasets collected within GWD waters, the cumulative hard coral cover was quantified at 41.55%. Pursuant to the State Minister for the Environment Decree No. 4/2001, the ecological status of the coral reef condition in this region is classified as moderate. The spatial heterogeneity at the study site is fundamentally underpinned by the morphological predominance of branching *Acropora* (ACB) at 6.75% and massive corals (CM) at 6.70%, closely followed by foliose corals (CF) at 5.85% and tabulate *Acropora* (ACT) at 5.50%. This micro-

environmental substrate heterogeneity is further augmented by a substantial coverage of non-scleractinian components, including soft corals (12.85%), sponges (6.15%), and sea anemones (4.60%) (Figure 2).

dominance by specific benthic taxa. This structural equilibrium is further corroborated by a notably low Simpson Dominance Index ($D = 0.11$).

2. Pelagic Plankton Community Structure

Table 1. Physical-Chemical Parameters of Seawater Quality in GWD.

Water Quality Parameters	Measurable Value	Quality Standards (PP 22/2021)	Remarks
Temperature (°C)	29.7	28 – 32	Conform
Salinity (ppt)	32.5	33 – 34	Sub-optimal
pH	7.0	7.0 - 8.5	Conform
Visibility (m)	8.0	> 5	Excellent

The Shannon-Wiener Diversity Index (H') for the benthic community was calculated at 2.38, indicating a moderate level of biodiversity accompanied by a relatively robust community stability. Furthermore, the Pielou Evenness Index (E) reached 0.91, demonstrating an equitable distribution of individuals across the identified lifeforms without any pronounced monospecific

Analysis of the pelagic zone reveals a high total plankton abundance, quantified at 3.4×10^6 cells/m³, with a cumulative enumeration of 2,233 individual organisms across identified taxa. The pelagic zone exhibits a dominance driven by the diatom assemblage. The genus *Skeletonema* sp. achieved the highest density, reaching 2.7×10^6 cells/m³ and accounting for 81.95% of the total

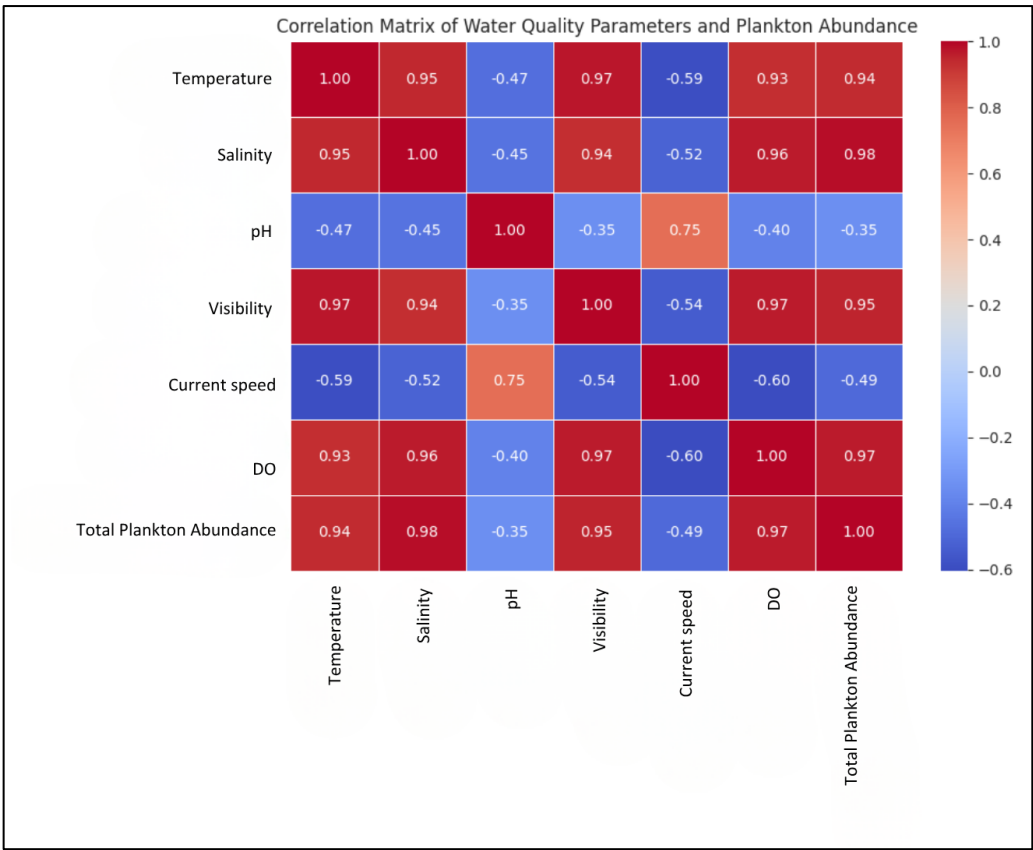


Figure 4. Pearson Correlation Matrix (Heatmap) Between Physical-Chemical Parameters of Water and Plankton Community Structure.

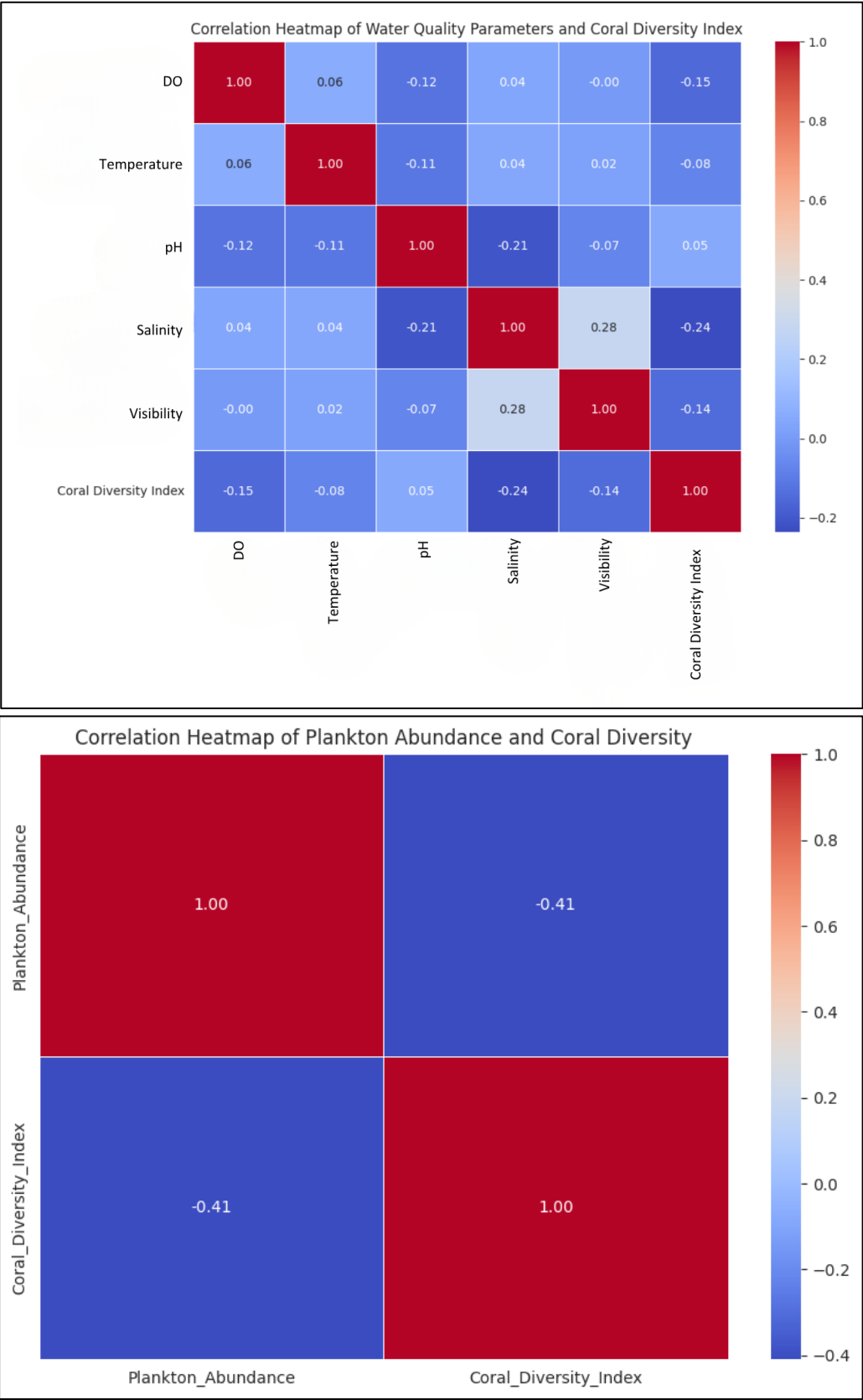


Figure 5. Linear Regression Graph of the Influence of DO Parameters and Physical Limiting Factors on Community Ecological Index.

plankton abundance, followed by the genus *Chaetoceros* sp. at 5.1×10^5 cells/m³ (15.36%). As a consequence of this dominance by the diatom group, the ecological indices

of the plankton community in GWD waters exhibit a pronounced imbalance. The plankton Shannon-Wiener Diversity Index (*H'*) falls within the low-to-moderate

category (1.24), the Pielou Evenness Index (E) stands at 0.38, and the Simpson Dominance Index (D) is 0.69. This elevated dominance value indicates that the pelagic water mass may be experiencing organic nutrient enrichment.

3. Physicochemical Environmental Parameters

correlation with the high accumulation density of the diatom *Skeletonema* sp. within the coastal zone. Such calm water conditions are associated with a prolonged residence time of organic nutrients within the upper water column.

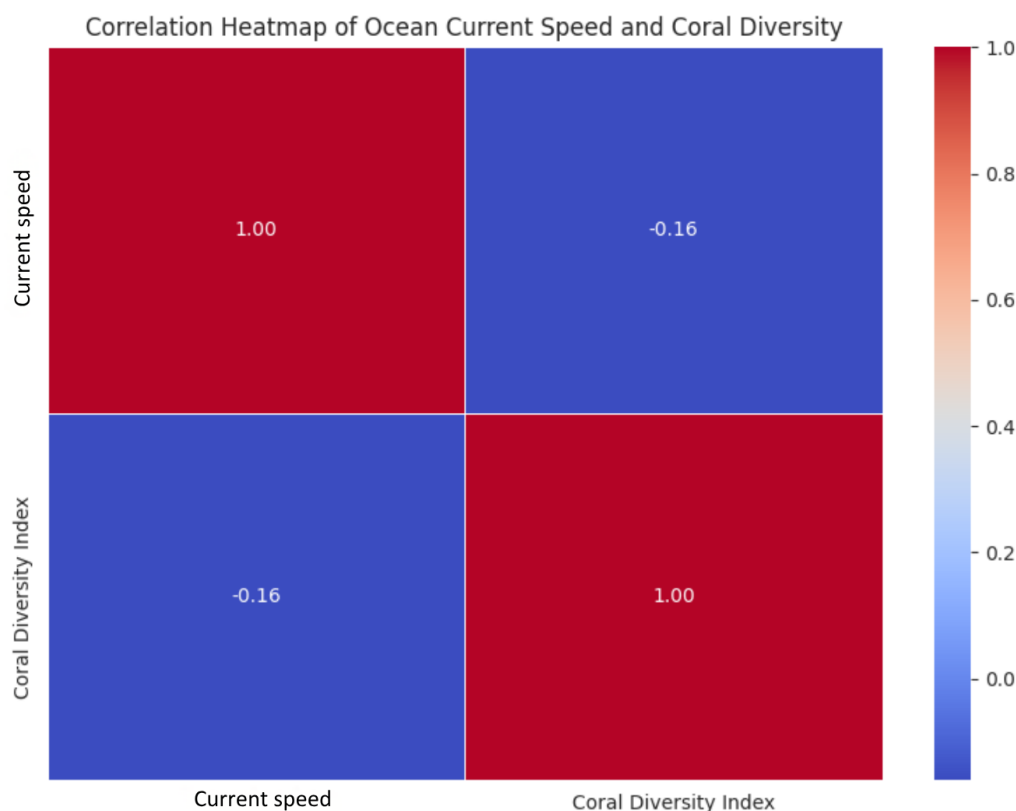


Figure 6. Logarithmic and linear relationship patterns between local current velocity and Pelagic Plankton Density Distribution.

In-situ environmental monitoring indicates that GWD waters exhibit hydro-oceanographic characteristics highly conducive to supporting marine life. Table 1 presents the quantified environmental parameters.

4. Analysis of Environmental Interactive Correlation to Biota Communities

Based on the graphical analysis of linear correlations, distinct spatial association patterns were elucidated within the GWD ecosystem:

- Water Quality and Biodiversity: The benthic diversity index (H'benthic) exhibits a positive correlation with both dissolved oxygen (DO) and water clarity parameters. This suggests that a dissolved oxygen concentration of 6.5 mg/L and solar irradiance penetration down to a depth of 8 meters are associated with the ecological resilience of hard coral reefs and macrobenthos at GWD.
- Hydrodynamic Regimes and Plankton Dominance: The low surface current velocity recorded during sampling (0.06 m/s) exhibits a strong positive

DISCUSSION

1. Reef Communities Amidst Benthic Component Heterogeneity

The finding of a live hard coral cover of 41.55%, which falls within the fair category, indicates that the scleractinian community in GWD waters exhibits a relatively high capacity for resilience and adaptation. The spatial heterogeneity in this region is strongly underpinned by highly varied colony architectures. The co-predominance of branching *Acropora* and massive corals indicates an efficient ecological niche partitioning between fast-recruiting, physically vulnerable coral taxa and slow-growing, stress-resistant functional groups. From a community ecology perspective, the elevated Shannon-Wiener Diversity Index ($H' = 2.38$) and Pielou Evenness Index ($E = 0.91$) demonstrate that the benthic zone of GWD maintains a structural equilibrium. The seafloor community structure is further enriched by significant non-scleractinian components, notably soft corals and sponges.

The proportional presence of sponges and soft corals functions as an organic matter sink via dissolved organic carbon uptake and serves to stabilize the reef flat substrate [13–16].

2. Plankton Community Imbalance and Indicators of Partial Eutrophication

A distinct contrast is observed in the neritic pelagic zone of GWD, where the plankton assemblage exhibits a structural imbalance characterized by a low Evenness Index ($E = 0.38$) and an elevated Simpson Dominance Index ($D=0.69$). The proliferation in total plankton abundance, dominated by the diatom *Skeletonema* sp. (81.95%), serves as an ecological signal of potential organic nutrient loading in the water column. *Skeletonema* sp. is an r-strategist that allows it to respond rapidly to surges in ambient nitrate and phosphate concentrations.

The Pearson correlation matrix shows that total plankton abundance displays strong positive correlations with salinity, dissolved oxygen, water clarity, and temperature. The positive correlation with a vertical water clarity of up to 8 meters aligns with optimal solar radiation penetration supporting diatom photosynthetic activity. Concurrently, the low surface current velocity recorded during sampling correlated with pelagic biomass accumulation. This nutrient influx is hypothesized to stem from terrestrial surface runoff transporting organic domestic waste from adjacent catchments.

3. Benthic-Pelagic Interactions: Trophic Implications for Ecosystem Conservation

The high density of pelagic microalgae correlates with the physiological state of the underlying coral reef communities. On one hand, high pelagic plankton abundance functions as an exogenous natural food source for scleractinians and associated filter-feeding organisms. This trophic linkage may explain why non-scleractinian macrobenthic assemblages thrive within GWD waters. On the other hand, recurrent plankton blooms pose a potential risk to scleractinian environmental quality.

Excessive pelagic microalgal density can attenuate vertical solar irradiance penetration, which over long periods limits the photosynthetic efficiency of endosymbiotic Zooxanthellae. Although vertical clarity remained excellent during this sampling campaign, the risk of substrate smothering via organic sedimentation from decaying planktonic biomass should be monitored. Protected area conservation efforts could benefit from an integrated ridge-to-reef management framework, focusing on managing terrestrial nutrient loading into the Bali Strait.

IV. CONCLUSION

The coastal waters of Grand Watudodol remain in relatively stable ecological condition, with 41.55% live hard coral cover and high benthic diversity ($H' = 2.38$; $E = 0.91$). However, the pelagic community was strongly dominated by *Skeletonema* sp. (81.95%), associated with high water clarity and low surface current velocity. Although current physicochemical parameters remain within optimal ranges, potential risks from plankton biomass decomposition and terrestrial organic inputs warrant attention. Therefore, a ridge-to-reef management approach is recommended to support the long-term sustainability of the Grand Watudodol ecosystem.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the research, authorship, or publication of this manuscript. No financial, personal, political, or professional relationships exist with any individuals or organizations that could inappropriately influence, bias, or compromise the objectivity of the methodology, data analysis, interpretations, or conclusions presented in this study.

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