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INFLUENCE OF OCEANOGRAPHIC PATTERN ON HARD CORAL COMMUNITIES IN PULAU BIDONG, SOUTH CHINA SEA

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ABSTRACT

Coral reef assessments are vital for sustainable management, as reef-building corals form the foundation of marine ecosystems. This study examines the spatial distribution of hard coral communities around Pulau Bidong, South China Sea, across different sites, locations, depths, and reef zonation. Video sampling was conducted at seven sites and oceanographic conditions, particularly Horizontal Kinetic Energy (HKE) were considered. Results showed that massive corals mostly occupied the exposed areas where the HKE values are high. Meanwhile, the branching *Acropora* mostly dominated the sheltered area with lower Horizontal Kinetic Energy (HKE) values. Biotic and abiotic components varied significantly across sites, areas, and reef zones (Significance Level < 5%), but not by depth. ST5 (58.14% ± 5.47%) and ST6 (60.18% ± 5.1%) in southwestern reef mainly composed of Coral while ST2 (54.27% ± 3.52%), ST3 (48.31% ± 5.49%), and ST7 (63.62% ± 7.46%) in northeastern reef were dominated by Dead Coral. A total of 41 hard coral genera from 17 families were recorded. Branching corals such as *Acropora* and *Pocillopora* dominated the sheltered southwestern reefs while massive forms like *Porites* and *Diploastrea* were prevalent in the northeastern reefs. These findings highlight the role of oceanographic energy and geomorphological factors in shaping coral distribution and support the need for site-specific conservation strategies.

Introduction

Coral reefs cover 0.2% of the ocean (Souter *et al*., 2021) and provide a variety of ecological functions for humans and marine organisms (Woodhead *et al*., 2019). However, they are exposed to the adverse impact of human activities such as inappropriate sewage discharges (Lachs *et al*., 2019) and uncontrolled tourism (Shokri & Mohammadi, 2021) as well as natural turbulence such as coral predator outbreaks (Bambridge *et al*., 2019), severe tropical storms (Fabricius *et al*., 2008) and rising surface temperatures at sea (Lough, 2012), which contribute to coral reef degradation worldwide. As a result, the global percentage cover of hard corals has decreased by 2.5% in 41 years (Souter *et al*., 2021).

The hard coral complexity is influenced by several factors, including depth, reef zonation, and exposure to wave action (Higuchi *et al*., 2015; Tebbett *et al*., 2022; Abrar *et al*., 2022). A study by Darling *et al*. (2019) discussed the variations in the life history of stony corals that influence the structural complexity of reefs and its resilience to different climatic, social, and ecological factors. For example, massive and encrusting hard corals such as *Porites lobata* are commonly found in deeper reefs, where they can adapt to low-light conditions (Waheed & Hoeksema, 2014; Law & Huang, 2023). The shallow area in Kingman's reefs (William *et al*., 2013) was dominated by branching corals from genus *Acropora* and *Pocillopora* while the deeper area had massive *Porites* and *Favia*.

The South China Sea (SCS) is home to a great diversity of marine life, including coral reefs, which account for 4.7% of the world's reef area (Huang *et al*., 2015). In addition, 571 coral species have been identified in this sea. The southern part of the SCS is located in the western part of the Coral Triangle, a region with the highest coral diversity in the world (Veron *et al*., 2009). Malaysia, Indonesia, Papua New Guinea, Philippines, Solomon Islands, and Timor-Leste are the countries located within the Coral Triangle (Cros *et al*., 2014). It is Malaysia's location that explains the abundance and rich biodiversity of corals in the country, some 450 species of hard corals have been identified (Veron *et al*., 2009).

Although Peninsular Malaysia lies just outside the Coral Triangle, the area ranks second in hard coral species richness among the reefs in the SCS (Huang *et al*., 2015). For instance, Pulau Tioman supports 239 recorded hard coral species, Pulau Redang 128 species (Akmal *et al*., 2019), and the Mersing Islands (261 species) (Lee *et al*., 2022). In addition, Bornean sites within the SCS also exhibit considerable diversity, with Tun Mustapha Park hosting 84 species and the waters off Kota Kinabalu recording 233 species. Pulau Bidong, located off the east coast of Peninsular Malaysia remains uninhabited and experiences limited human intervention (Safuan *et al*., 2021). Currently the island is occasionally used for recreational diving, data collection near the research station as well as visits to the remnants of historical Vietnamese settlements, which serve as cultural attractions. Due to the low frequency and scale of these activities, the impact of direct human activity on the surrounding coral reefs is presently minimal.

However, the reef was severely affected by a tropical storm that caused changes in the predominant coral genera and damage to the coral reef, especially in the shallow areas of the reef (Safuan *et al*., 2020). As Pulau Bidong is an island in the SCS, the wind and current velocity increase during the northeast monsoon season, which affects the hard coral community in the waters of Peninsular Malaysia (Toda *et al*., 2007).

Furthermore, a larger area needs to be studied to obtain a representative estimate of the hard coral community on the island, as previous datasets mostly cover only parts of the coral reef around the island (Reef Check Malaysia, 2022). Therefore, a better understanding of the hard corals under different environmental conditions will help to provide information on the formation of reef-building corals in the coral reef ecosystem. Besides, studies related to corals in Malaysia focus on the coral structures following the coral research by Toda *et al*. (2007). The coral communities on the reefs of Peninsular Malaysia are generally dominated by the genera *Acropora*, *Montipora*, and *Porites*, with hard coral cover exceeding 50% around many of the islands in the region (Akmal *et al*., 2019).

Despite these important findings, providing qualitative and quantitative data on coral reefs is crucial to improving coral reef management in the region (Praveena *et al*., 2012), especially by providing insights into the distribution of hard coral structures through the lens of environmental variability. This is important for coral reef management planning as the effects of environmental factors vary depending on the resilience of coral taxon's (Darling *et al*., 2019).

Given the decline in coral cover globally, the hard corals in Pulau Bidong is considered stable, with a higher-than-average hard coral cover of 33.9% in the Coral Triangle region (Vercammen *et al*., 2019). The percentage of hard coral coverage is in the range of other countries in the East Asian seas (Chan *et al*., 2023). Nevertheless, precautionary measures are needed to prevent a major change in community structure under environmental stress such as prolonged high sea temperatures (Loya *et al*., 2001).

As one of the islands in the South China Sea, the fringing reef of Pulau Bidong is exposed to current movement with variations of speed following the months, particularly during the monsoonal seasons (Daud & Akhir, 2015). The condition surrounding the island showed that the reef situated at the northeastern part of the island is greatly influenced by the current movement, specifically during the southwest monsoon season. In December, the current circulates eastward at the northern tip of the island and then the current speed escalates, causing the current to move southward and surround the northeastern part of the island.

Consequently, the northeastern reef of Pulau Bidong was more affected by the strong winds and high current circulation. This implies that the surrounding condition of the islands is mainly influenced by the oceanographic pattern.

To understand the influence of environmental conditions on coral distribution in Pulau Bidong, this study has two objectives: (1) to compare the biotic and abiotic components of the coral reef between the different factors i.e., namely, areas (southwest and northeast of Pulau Bidong), depth (shallow, mid, and deep), reef zonation (reef flat and reef slope), and (2) to compare hard corals between these factors. Our data would provide insights into the influences of natural parameters on the spatial variation of benthic reef components especially hard corals, which would be helpful for the future development of coral reef management. The available up-to-date data on the coral reef would be beneficial in developing the management plan for the sustainability of the coral reef ecosystem.

Materials and Methods

Study Area

Pulau Bidong (5.6198°, 103.0631°) is an island situated on the east coast of Malaysia. The island previously known as “Hell Isle” was once gazetted as a refugee camp from 1978–1991 for Vietnamese refugees escaping the Vietnam War in 1975 (Rahman *et al*., 2022). Although Pulau Bidong is not gazetted as a marine park, there is relatively minimal human activity compared to nearby marine parks such as Pulau Perhentian Marine Park (coral cover of between = 2.12% and 52.73%), Pulau Redang Marine Park (with coral cover of between 28.2% and 73.5%), and Pulau Tioman Marine Park (with between 37.6% and 55.9%) (Akmal *et al*., 2019; Safuan *et al*., 2022). With an average coral cover of 44%, Pulau Bidong stands out as one of the islands with high coral cover along the east coast of Peninsular Malaysia (Safuan *et al*., 2021). The coastline of the island is mainly composed of rocky shore, particularly from the north towards the south part of the island. Lagoon areas with a white sandy beach can be found in the west and south part of the island.

Data Collection

In the present study, attempts were made to see the coral distribution at different sites, areas, depths, and reef zonation in May and August 2023. Coral reefs can be found surrounding the island. At the northeastern part of Pulau Bidong, coral reefs can be found extending up to 20 m depth. The island coastline in this area is mainly covered with rocky shore and more exposed to strong currents according to model data by Daud and Akhir (2015).

Three sampling sites (ST1, ST2, and ST3) were chosen in this area. At the opposite sites, the reef in the southwestern part of the island can be found at depths of up to 8 m with a coastline consisting of sandy and rocky areas. In total four sampling sites (ST4, ST5, ST6, and ST7) were chosen in this area represented by a lagoon or sheltered sites that have sandy shorelines and are more protected from the strong current. Data collection at different depths were collected in each survey site. As the reef extension across water depth is inconsistent at the surrounding island, three depth categorisations were used: Shallow (1-5 m), mid (6-10 m), and deep (10-16 m).

Although only specific sites have coral reefs in deeper areas (ST1, ST2, ST3, and ST7), data was also collected to gain a better understanding of coral reef formation around the island at varying depths. The classification of reef zonation also depended on the depth of the survey which was categorised into two reef zonation: Reef flat and reef slope. Reef flat is characterised by the consistency of depth within the area while reef slope is recognised by the increase in the gradient of the sea floor into the deeper water. In total, 18 x 100 m transect lines (total = 1.8 km survey line) were laid out in the study area following the reef contours parallel to the shoreline. Details of the sampling sites are shown in Table 1 and Figure 1.

Coral Video Transect

The data was collected via a Coral Video Transect (Safuan *et al*., 2015) using an underwater camera, Olympus TG-6 enclosed in an underwater camera housing. The camera was set to an Underwater Wide mode on Full High-Definition (1920 x 1080). Prior to recording, a 100 m-transect tape divided into four, 20 m segments with an interval of 5 m was laid out on the reef floor. A photo of dive slate with the information of site was captured with the camera. The depth for each survey site was recorded using the diving computer data. The data was collected via video recording along the transect tape using the underwater camera facing down perpendicularly 0.5 m above the substrate (Safuan *et al*., 2015). A reference bar was attached to establish a consistent distance between the camera and the substrate. To ensure video clarity, the diver swam about 5 m per minute throughout the video recording. Any coral taxa found along the transect line were photographed to assist in identification later.

Image Analysis

The videos were extracted into 50 non-overlapping frames for each segment (20 m) and analysed using Coral Point Count with Excel extension (CPCe) software version 4.1 (Kohler & Gill, 2006) with 50 uniform points per frame as outlined by Safuan *et al*. (2015). Data were categorised as biotic [Coral (C), Algae (ALG), Other Invertebrates (OT)] and abiotic [Dead Coral (DC) and Sand and Rock (SR)] components of coral reef. Hard corals were identified at the genus level following Veron *et al*. (2024) with further verification conducted using the World List of Scleractinia (Hoeksema & Cairns, 2024) from the World Register of Marine Species (WoRMS).

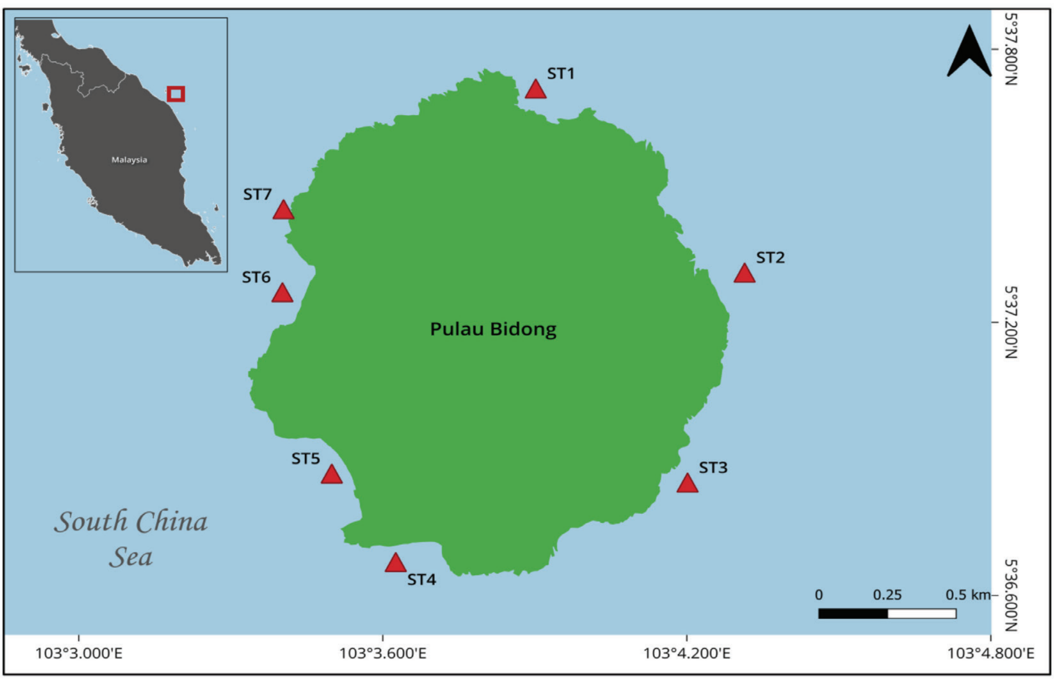

Figure 1: Sampling sites in Pulau Bidong

Table 1: Sampling sites at Pulau Bidong

Site	Site Name	Code	Transect	Latitude	Longitude	Area	Depth	Reef Zonation	Date of Sampling
ST1	Teluk Air	ST1.1	1	5.629318°	103.064278°	Northeast	16	Reef slope	23/5/2023
		ST1.2	2				10	Reef slope	
		ST1.3	3				5	Reef slope	
ST2	Dinding Laut	ST2.1	1	5.621822°	103.071904°	Northeast	14	Reef slope	18/8/2023
		ST2.2	2				10	Reef slope	
ST3	Christmas Garden	ST3.1	1	5.613727°	103.070742°	Northeast	12	Reef slope	18/8/2023
		ST3.2	2				5	Reef slope	
ST4	Pantai Pasir Tenggara	ST4.1	1	5.611225°	103.060426°	Southwest	5	Reef flat	28/5/2023
		ST4.2	2				2	Reef flat	
ST5	Pantai Pasir Pengkalan	ST5.1	1	5.615332°	103.057857°	Southwest	2	Reef flat	3/5/2023
		ST5.2	2				2	Reef flat	
ST6	Pantai Pasir Cina	ST6.1	1	5.621103°	103.056698°	Southwest	6	Reef slope	2/5/2023
		ST6.2	2				6	Reef slope	
		ST6.3	3				2	Reef flat	
		ST6.4	4				2	Reef flat	
ST7	Batu Menangis	ST7.1	1	5.623362°	103.056488°	Southwest	16	Reef slope	24/5/2023
		ST7.2	2				10	Reef slope	
		ST7.3	3				5	Reef slope	

Physical Data Collection

Physical parameters including current speed and direction, temperature, and salinity were collected in August and October 2024. On site data was collected at three depths in the shallow (3 - 5 m) and in deeper waters (10 - 15 m). A 600 kHz ship-mounted Aquadopp Acoustic Doppler and Current Profiler (ADCP) was used to measure currents for 10 minutes at 5 = second intervals. The Aquapro Software was used to fine tune the settings and extract the data from the ADCP. Temperature and salinity data were collected using a Valeport SWiFT SVP profiler. The SWiFT SVP was fitted with Valeport's digital time of flight sound velocity sensors, temperature compensated piezo-resistive pressure transducer, and a PRT temperature sensor. The SVP was gradually lowered into the sea surface until it reached the seafloor to record the data. Data from SVP was downloaded and reviewed wirelessly, via Bluetooth, using the SWiFT App.

Statistical Analysis

Statistical analyses were conducted using PRIMER software version 6. Data on benthic categories and coral genera were pooled into four factors, "site", "depth", "reef zonation", and "area". The data then were transformed into square roots with Bray-Curtis similarity and further tested for significance difference with Analysis of Similarities (ANOSIM). Meanwhile, pairwise analysis revealed the differences between the factors. Similarity percentages (SIMPER) were calculated to find the average similarity and dissimilarity between the groups. Multidimensional scaling (MDS) and Principle Component Analysis (PCA) were also conducted to illustrate the differences between the site surveys: Exposed, non-exposed, and semi-exposed with the physical parameters.

Results and Discussion

Physical Parameter

Physical parameters were collected during two different months, August (summer monsoon) and October (monsoon transition period). Table 2 presented the temperature, salinity, zonal, and meridional velocities (u and v or cross-shore ad alongshore), zonal and meridional heat flux, zonal and meridional salt flux, and HKE between August and October. The temperature in August was cooler than in October, with mean temperatures ranging between 29.2 ± 0.18ºC and 30.56 ± 0.07ºC, respectively. The water salinity levels in August were slightly higher than in October, with a mean salinity of 32.46 ± 0.2 psu and 31.6 ± 0.4 psu. Zonal and meridional currents in August showed that the average currents moved westward and northward at a velocity of -0.02 ± 0.05 m/s and 0.003 ± 0.06 m/s, respectively.

In October, the zonal and meridional currents were dominated by westward and southward current movement at velocities of -0.02 ± 0.08 m/s and -0.01 ± 0.09 m/s, respectively. We calculated the Horizontal Kinetic Energy (HKE), cross-shore heat and salt fluxes, and alongshore heat and salt fluxes from the currents, temperature, and salinity data. The HKE in August is much lower than in October, with HKE values of 3.08 ± 3.9 W/m^2 and 7.68 ± 9.3 W/m^2, respectively.

The cross-shore heat and salt fluxes in August and October showed dominant westward movement. The cross-shore heat fluxes in August and October are -0.06 ± 0.2 W/m^2 and -0.08 ± 0.3 W/m^2, respectively. Meanwhile, the cross-shore salt fluxes in August and October are -0.07 ± 0.2 W/m^2 and -0.08 ± 0.3 W/m^2, respectively. The alongshore heat and salt fluxes in August and October showed dominant southward movement. The alongshore heat fluxes in August and October were -0.06 ± 0.3 W/m^2 and -0.05 ± 0.6 W/m^2, respectively. Meanwhile, the alongshore salt fluxes in August and October are -0.07 ± 0.4 W/m^2 and -0.06 ± 0.4 W/m^2, respectively.

The PCA analysis was done to determine the correlation among the type of corals, physical parameters, and geographical conditions (Figure 2). The results showed that

Table 2: Mean values of in-situ physical parameters during August and October 2024

Physical Parameters	August	October
Temperature	29.2 ± 0.18 °C	30.56 ± 0.07 °C
Salinity	32.46 ± 0.2 psu	31.6 ± 0.4 psu
U-component	-0.02 ± 0.05 m/s	-0.02 ± 0.08 m/s
V-component	0.003 ± 0.06 m/s,	-0.01 ± 0.09 m/s
Cross-shore heat fluxes	-0.06 ± 0.2 W/m^2	-0.08 ± 0.3 W/m^2
Cross-shore salt fluxes	-0.07 ± 0.2 W/m^2	-0.08 ± 0.3 W/m^2
Alongshore heat fluxes	-0.06 ± 0.3 W/m^2	-0.05 ± 0.6 W/m^2
Alongshore salt fluxes	-0.07 ± 0.4 W/m	-0.06 ± 0.4 W/m^2
Horizontal Kinetic Energy (HKE)	3.08 ± 3.9 W/m^2	7.68 ± 9.3 W/m^2

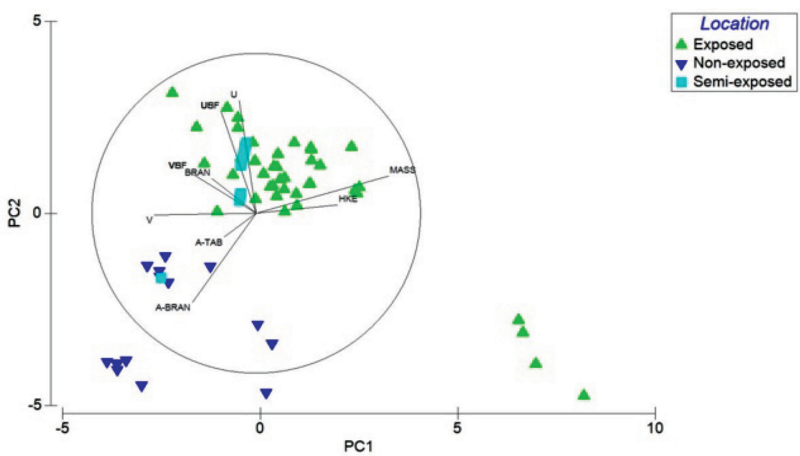

Figure 2: Principal component analysis biplots of geographical area scores and physical parameters and type of coral loadings. PC1 = 28.4% of total variance; PC2 = 23.3% of total variance. Symbols represent different geographical conditions (exposed area = green △; non-exposed area = blue Ñ; semi-exposed area = turquoise □). Vectors represent physical parameters (U = u-component of currents; V = v-component of currents; UHF = cross-shore heat flux; VHF = alongshore heat flux; USF = cross-shore salt flux; VSF = alongshore salt flux; HKE = horizontal kinetic energy), and type of hard corals (BRAN = Branching corals (*Pocillopora*); A-TAB = Tabular *Acropora*; A-BRAN = Branching *Acropora*; MASS = Massive corals (*Porites*)

the first principal component has large positive associations with massive corals (*Porites*) in the exposed area. Meanwhile, the branching type of corals (*Pocillopora*), tabular *Acropora*, and branching *Acropora* have high contributions to the second principal component in the non-exposed and semi-exposed areas. Vectors that point in the same direction correspond to variables that have similar response profiles and can be interpreted as having similar meanings in the context set by the data. The Horizontal Kinetic Energy (HKE) vector is close to the massive corals in the exposed area, indicating a strong positive correlation. In the non-exposed area, HKE is negatively correlated with the tabular and branching *Acropora*, as their axes run in almost exactly the opposite direction (almost 180°). HKE is almost not associated with the distributions of branching corals in the semi-exposed area when the angle between the vectors is almost 90°.

The other physical parameters such as u-components (zonal) of currents, cross-shore heat flux, and cross-shore salt fluxes are the main physical parameters in the semi-exposed area and well-correlated with the branching type of corals. These components have a negative correlation with the domination of tabular and branching *Acropora* in the non-exposed area and are not correlated with the massive corals in the exposed area.

Meanwhile, the v-components (meridional) of currents, alongshore heat flux, and alongshore salt flux are close to the branching corals in the semi-exposed and exposed areas. The alongshore heat and salt fluxes do not correlate with the tabular and branching *Acropora* in the non-exposed area. Only the meridional currents are associated with the distribution of tabular and branching *Acropora* in the non-exposed area. It can be summarised that HKE is the most dominant physical factor influencing the distribution of corals around Bidong Island. Massive types of corals mostly occupied the exposed areas where the HKE values are high.

For the meantime, the tabular and branching corals (*Acropora*) mostly dominated the non-exposed area with lower HKE values. The area with dominant branching corals (*Pocillopora*) that was found in the semi-exposed area (and some of the exposed area) is directly associated with currents and heat and salt fluxes.

Biotic and Abiotic Components in Coral Reef

The percentage cover of biotic and abiotic components was significantly different between sites (Significance level = 0.1%, R = 0.517), location (Significance level = 0.1%, R = 0.163), and reef zonation (Significance level = 0.1%, R = 0.316). However, depth does not significantly (Significance level = 19.5%, R = 0.031) influence the major components in the coral reef (Figure 3). Overall, Coral (Mean ± Standard Error = 39.97% ± 2.93) and Dead Coral (39.77% ± 2.7%) dominated the reef with a high percentage cover within the study area except for ST4 (Figure 4) as indicated by SIMPER analysis (Appendix 3). Among all sites, only ST4 was dominated by Other Invertebrates (90.37% ± 1.97%) and is highly colonised with zoanthids [Figure 4 (a)]. Based on the pairwise test (Appendix 1), the variation in percentage cover of biotic and abiotic components can be clearly seen between several sites while the differences between northeast (16.03% ± 1.82%) and southwest (2.65% ± 0.61%) reefs are primarily due to the differences in sand and rock cover. The higher cover of Coral and Dead Coral in the reef slope (Coral = 42.08% ± 3.36%, Dead Coral = 44.13% ± 3.38%), compared to the reef flat (Coral = 34.45% ± 5.57%, Dead Coral = 31.78% ± 4.07%) signifies the differences in the reef zonation.

Located in the South China Sea, Pulau Bidong is situated in a region with great diversity of hard coral (Veron *et al*., 2009). Our findings indicate that the biotic and abiotic components between sites varied although the reef encircles the same island. Factors "site" and "area" were discussed simultaneously as they are interrelated. The HKE (August = 3.08 ± 3.9 W/m^2) was lower during the southwest monsoon (Table 3). According to Daud and Akhir (2015), the southward currents moved towards the island with the highest intensity on the eastern part in December. The in-situ parameters also revealed higher HKE (October = 7.68 ± 9.3 W/m^2) as the northeast monsoon got closer. This parameter was highly associated with the exposed area mostly affecting the northeastern reef. Therefore, influences the differences in Coral and Dead Coral coverage between both sides of Pulau Bidong.

The northeastern reefs (Coral = 40.15% ± 2.76%, Dead Coral = 41.46% ± 3.4%) have higher Coral and Dead Coral coverage than the southwestern reefs (Coral = 39.85% ± 4.48%, Dead Coral = 38.69% ± 3.87%) of Pulau Bidong. High Coral cover was found in ST5 (58.14% ± 5.47%) and ST6 (60.18% ± 5.1%) in the southwest area. These shallow, non-exposed reefs are negatively associated with the HKE. Similar findings were also found in Puerto Galera, Philippines, and Chagos Archipelago in Indian Ocean, where Coral coverage is the most abundant in the sheltered stations (Lange *et al*., 2021; Lalas *et al*., 2023).

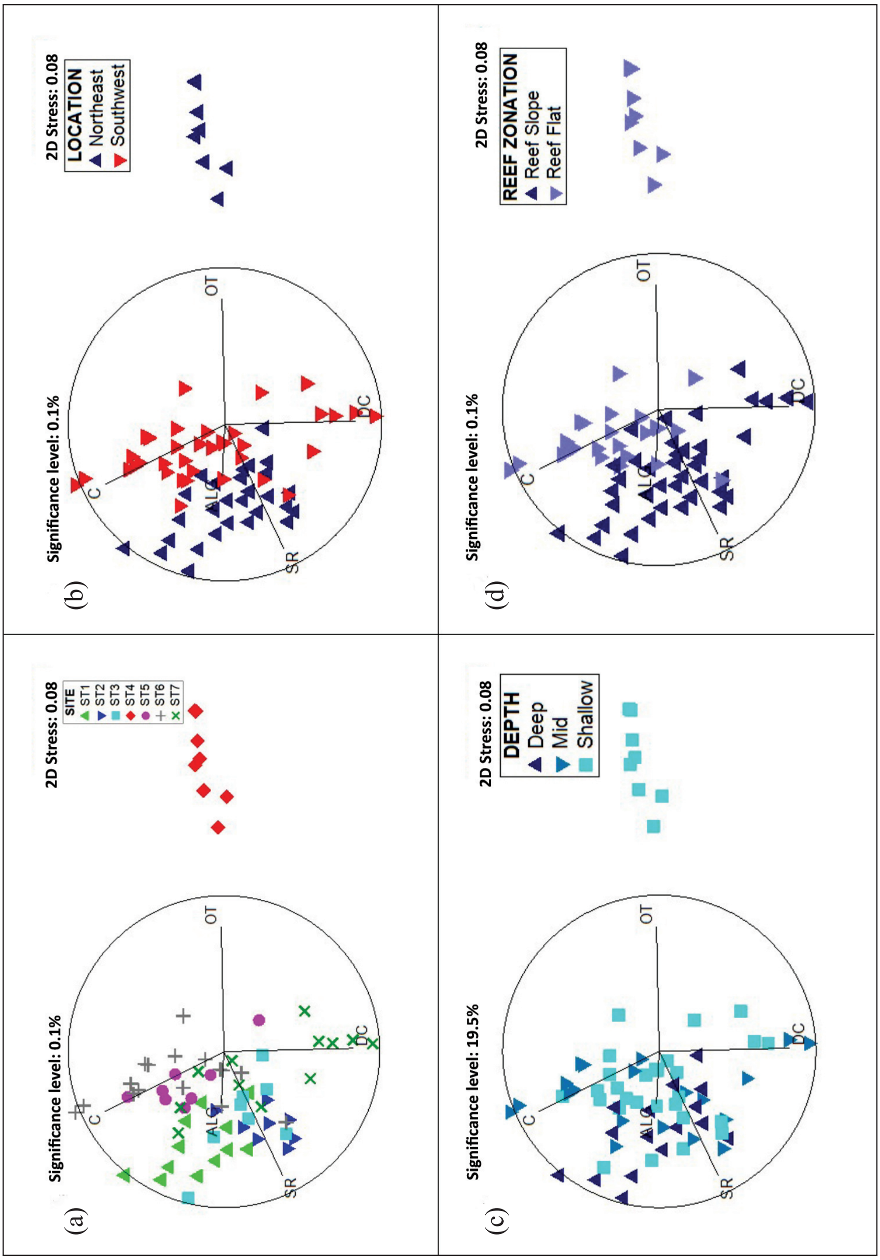

Figure 3: Non-metric multidimensional scaling (MDS) plot of biotic and abiotic components between (a) site, (b) area, (c) depth, and (d) reef zonation based on Bray-Curtis similarity. Each point represents a sample, with distances between points reflecting the dissimilarity in community composition. Vectors represent biotic and abiotic components (C = Coral, ALG = Algae, OT = Other Invertebrates, DC = Dead Coral, SR = Sand and Rock) with significant Spearman correlations, indicating their directional influence on the reef components

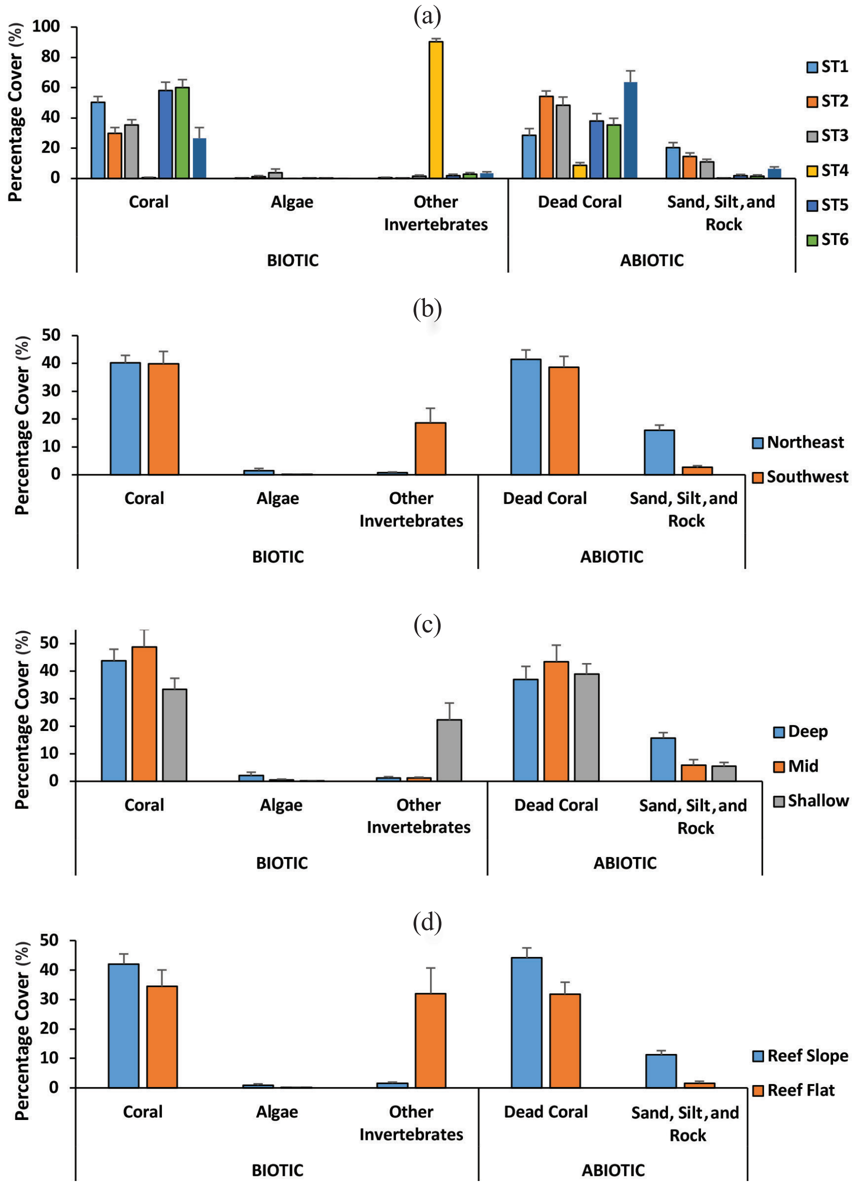

Figure 4: Relative percentage cover of biotic and abiotic components between different (a) site, (b) area, (c) depth, and (d) reef zonation

On the other hand, Dead Coral mainly characterised the northeastern reefs (41.46% ± 3.4%) such as ST2 (54.27% ± 3.52%), ST3 (48.31% ± 5.49%), and ST7 (63.62% ± 7.46%). These exposed areas were shown to have a positive correlation with HKE, indicating the reefs in this area received the impact of intense currents. Similar scenarios were observed in previous studies where the variation in the reef composition is potentially caused by physical variables (Shimokawa *et al.*, 2014; Comfort *et al.*, 2019; Medina-Valmaseda *et al.*, 2022). Calcified organisms including hard corals showed a decline in coverage as wave energy increased as studied by Williams *et al.* (2013). This would explain the lower Coral

Table 3: Average percentage cover of hard coral families in this study

Family	Average Percentage Cover (%)
Acroporidae	4.769
Poritidae	3.964
Diploastraeidae	3.518
Pocilloporidae	0.943
Merulinidae	0.236
Lobophyllidae	0.236
Fungiidae	0.220
Agariciidae	0.180
Euphyllidae	0.125
Dendrophylliidae	0.120
Pachyseridae	0.103
Oulastreidae	0.042
Helioporidae	0.011
Montastraeidae	0.010
Plerogyridae	0.006
Coscinaraeidae	0.004
Astrocoeniidae	0.001

cover on the exposed northeastern reef of the island. The exposure to the higher energy in the northeastern reed might be stressing hard corals thus contributing to the high Dead Coral cover (Kim *et al*., 2022; Medina-Valmaseda *et al*., 2022).

There are variations of biotic and abiotic components between reef zonation and depth which are interdependent variables in this study. It is noted that exposure to current, wave, and light can be suggested as the factors influencing the distribution of biotic and abiotic components, considering depth and reef zonation contributing to the differences. The average depth of reef flat and reef slope around Pulau Bidong is 2.58 m and 8.98 m, respectively. The percentage cover of Coral (42.08% ± 3.36%) and Dead Coral (44.13% ± 3.38%) is higher towards the reef slope because of the exposure to high energy similar to the reef in Weno Island and Kingman Reefs (Williams *et al*., 2013; Kim *et al*., 2022). The reef slope is mainly associated with Dead Coral (44.13% ± 3.38%) and Sand and Rock (11.20% ± 1.43) while Coral (34.45% ± 5.57) makes up the structure of the reef flat. Survey conducted by Kim *et al*. (2022) in Micronesia shows that the benthic composition varies according to the zonation.

Following the findings based on pooled data for factor depth, the Coral and Dead Coral coverage increased with depth up to 10 m and started declining after 11 m. Gove *et al*. (2015) also discovered the Coral cover decreases with increasing depth. Similar trend was observed in Pulau Lang Tengah, South China Sea where Coral cover gets higher at 12 m depth, then decreases when the depth is more than 15 m (Bernard *et al*., 2023). Water visibility would explain the decrement trend in hard coral cover over a certain depth. Light may play a role in the benthic reef composition as depth increases with the increasing reef slope gradient.

As the water visibility decreases at deeper depths, the growth of the hard coral is also affected by this condition. Coral relies on the mutualistic relationship with symbiotic algae in the coral tissue, which require light for photosynthesis to provide nutrients as algae receive shelter from the corals (Al-Hammady *et al*., 2022). Therefore, hard corals must receive optimum light for survival and growth (Chow *et al*., 2019; Law & Huang, 2023). This also influences the huge decline of coral coverage in deeper water because light accessibility decreases and limits photosynthesis (Chow *et al*., 2019). Nevertheless, water visibility driven by light accessibility is crucial for the abundance and diversity of hard corals across depth gradients (Law & Huang, 2023).

Hard Coral Community in Pulau Bidong

In total, 17 families of hard coral comprising 41 genera were recorded during the survey at Pulau Bidong. Overall, the hard coral cover was dominated by Acroporidae (4.769%), Poritidae (3.964%), and Diploastreidae (3.518%). Other families constitute less than 1% of the total hard coral cover when all sites are combined.

There is a significant difference in coral genera cover between sites (Significance Level = 0.1%, R = 0.673), locations (Significance Level = 0.1%, R = 0.467), depths (Significance Level = 0.1%, R = 0.237), and reef zonation (Significance Level = 0.1%, R = 0.576) (Appendix 2). Based on the MDS plot, the differences between area, depth, and reef zonation can be seen contributed by six different genera: *Acropora*, *Pocillopora*, *Fungia*, *Porites*, *Diploastrea*, and *Favites*. *Acropora*, *Pocillopora*, and *Fungia* are mainly found at Southwest of Pulau Bidong, at shallow to mid water depth and the reef flat. Both massive types of coral namely *Porites* and *Diploastrea* and encrusting coral *Favites* can be found dominating the Northeast part of the island, at mid to deep water depth, and at the reef slope.

Based on Table 4, other genera show a pattern of their distribution. *Montipora* can be found mostly in the Northeast of the island in the shallow to mid water depth, along the reef flat. Meanwhile, *Favites* mostly found in the Northeast part of the island in the mid water area along the reef slope. These indicate that factors such as area, depth, and reef zonation influenced the distribution of hard coral genera in Pulau Bidong.

Hard coral communities in Pulau Bidong differ significantly between sites and areas. Lalas *et al*. (2023) suggest a similar trend where site-specific condition has a significant role in the variation of coral communities. Branching *Acropora* and branching *Pocillopora* mainly covered the southwestern area while massive coral such as *Porites* and *Diploastrea* dominated the northeastern area of this island. As oceanographic patterns are different between the areas under review, coral taxa particularly the massive type are more tolerant towards an area with a stronger HKE while branching *Acropora* is adapted in the non-exposed area with low influence of HKE. As the northeastern reefs are highly exposed to the current intensity, hard corals are prone to breakage (*Acropora* branching) would not withstand surviving in this area, leaving stress-tolerant corals with massive forms (*Porites* and *Diploastrea*) to dominate (Edinger & Risk, 2000).

According to Williams *et al*. (2013), the coverage of hard corals at remote Pacific reefs, including the *Acropora* genus decreased as wave strength increased. Another study implies *Porites* can withstand high wave pressure (Kim *et al*., 2022). Hence, the variation of hard corals in Pulau Bidong is influenced by the differences in physical parameters particularly the HKE surrounding the island. After considering the condition of the reef ecosystem, the southwest area of Pulau Bidong was recommended as a publicly accessible area. In this area, recreational activities and minor development are allowed within a regulated level (Great Barrier Reef Marine Park Authority, 2003). Coral restoration could be initiated in this area with a calm reef environment. This would enhance the immediate recovery of damaged reefs after incidents like the Pabuk storm. In contrast, restricted management approach including the establishment of a Marine Protected Area (MPA) had a positive

Table 4: Relative percentage cover of hard coral genera at different site, location, depth, and reef zonation

Family	Genus	Site							Location		Depth			Reef Zonation	
		ST1	ST2	ST3	ST4	ST5	ST6	ST7	Northeast	Southwest	Shallow	Mid	Deep	Reef Flat	Reef Slope
Acroporidae	*Acropora*	2.09	0.24	6.83	0.02	50.24	50.04	8.99	0.76	-	0.03	0.37	0.79	-	0.44
	Alveopora	0.18	-	-	-	-	-	-	2.91	29.79	20.57	27.49	6.38	27.76	15.13
	Astreopora	-	0.70	0.25	-	-	-	0.04	0.08	-	-	0.05	0.07	-	0.05
	Montipora	3.73	1.12	3.43	-	0.28	5.36	0.01	0.27	0.01	0.01	0.12	0.33	-	0.17
Agariciidae	*Gardineroseris*	0.86	-	-	-	-	-	-	0.00	-	0.00	-	-	-	0.00
	Pavona	0.55	0.02	0.15	-	0.02	0.64	0.31	0.16	0.06	0.04	0.21	0.07	0.03	0.13
Astrocoeniidae	*Palauastrea*	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.01
Coscinaraeidae	*Coscinaraea*	-	-	0.03	-	-	-	-	0.01	-	-	-	0.01	-	0.00
Dendrophyllidae	*Turbinaria*	0.04	0.28	0.50	-	-	0.02	-	-	0.39	0.04	0.73	0.05	0.07	0.32
Diploastraeidae	*Diploastrea*	13.00	8.48	3.15	-	-	-	-	0.01	-	-	0.02	-	-	0.01
Euphyllidae	*Euphyllia*	0.01	0.06	0.09	-	-	0.00	0.01	8.89	-	0.03	1.48	13.65	-	5.19
	Galaxea	0.08	0.23	1.26	-	-	0.02	-	-	0.01	-	0.01	-	-	0.01
Fungiidae	*Ctenactis*	-	-	-	0.14	-	0.67	0.42	0.11	0.11	0.05	0.14	0.20	0.03	0.15
	Fungia	0.01	-	0.18	0.02	0.13	2.24	1.97	0.05	0.00	-	0.00	0.09	-	0.03
	Halomitra	-	-	-	-	-	0.17	-	1.49	0.06	0.44	0.53	1.12	0.01	0.92
	Herpolitha	-	-	0.02	-	-	-	0.20	2.72	0.08	0.50	2.08	1.24	-	1.66
Helioporidae	*Heliopora*	-	-	0.08	-	-	0.01	-	0.05	1.38	0.06	2.69	0.40	0.09	1.25
Lobophyllidae	*Acanthastrea*	0.40	1.39	0.66	-	-	-	-	0.46	0.01	0.17	0.08	0.34	-	0.27
	Echinophyllia	-	-	-	-	-	0.02	-	0.37	-	0.00	0.51	-	-	0.21
	Lobophyllia	0.39	0.44	1.53	-	0.00	-	0.11	1.33	0.01	0.66	0.37	0.42	0.01	0.78

Family	Genus	Site							Location		Depth			Reef Zonation	
		ST1	ST2	ST3	ST4	ST5	ST6	ST7	Northeast	Southwest	Shallow	Mid	Deep	Reef Flat	Reef Slope
Merulinidae	*Australogyra*	-	-	0.02	-	0.00	-	0.00	0.00	0.00	0.00	-	0.01	-	0.01
	Caulastraea	0.34	-	0.04	-	0.08	-	0.15	-	0.06	-	0.14	-	-	0.06
	Cyphastrea	0.03	-	-	-	0.00	-	-	0.00	0.06	-	0.08	0.07	-	0.05
	Dipsastraea	0.09	0.05	0.21	-	0.09	0.15	0.14	-	0.00	0.00	-	-	0.01	-
	Echinopora	2.51	0.60	0.86	-	0.03	0.01	0.19	0.02	-	-	-	0.03	-	0.01
	Favites	1.45	5.16	2.18	-	0.00	0.00	0.28	0.73	0.03	0.08	0.23	0.90	-	0.45
	Goniastrea	1.40	1.08	1.49	-	0.01	0.02	0.02	0.01	-	-	-	0.03	-	0.01
	Hydonophora	-	-	-	-	0.00	0.01	-	2.90	2.00	3.73	1.26	0.61	3.62	1.72
	Leptoria	0.04	-	-	-	0.00	-	-	0.12	-	-	0.13	0.04	-	0.07
	Merulina	-	-	0.05	-	0.00	-	-	0.80	0.03	0.20	0.43	0.49	-	0.50
	Oulophyllia	0.46	1.40	0.71	-	0.00	-	0.12	0.18	0.06	0.00	0.15	0.29	-	0.16
	Pectinia	0.07	0.00	0.00	-	0.00	-	0.05	0.00	-	-	-	0.01	-	0.00
	Platygyra	0.18	0.86	0.48	-	0.02	-	0.07	0.28	0.32	0.19	0.67	0.09	0.02	0.44
	Trachyphyllia	0.03	-	-	-	0.00	-	-	0.03	0.01	-	-	0.09	-	0.03
Oulastreidae	*Oulastrea*	0.22	0.07	-	-	0.00	-	-	0.01	0.00	0.01	0.00	0.01	-	0.01
Pachyseridae	*Pachyseris*	0.27	0.10	0.14	-	0.00	0.01	0.20	0.46	0.02	0.11	0.15	0.43	0.01	0.28
Plerogyridae	*Physogyra*	0.02	-	-	-	0.00	0.00	0.01	0.01	0.00	-	-	0.03	-	0.01
	Plerogyra	0.00	-	0.04	-	0.00	-	0.02	0.51	1.33	0.78	1.91	0.39	0.74	1.14
Pocilloporidae	*Pocillopora*	0.84	-	0.51	0.46	1.37	0.65	2.78	14.07	4.00	5.59	6.71	14.65	2.06	10.84
Poritidae	*Goniopora*	0.01	-	-	-	-	-	0.01	0.01	-	-	0.01	0.02	-	0.01
	Porites	20.68	7.62	10.59	0.04	5.89	0.13	10.52	0.24	0.01	0.00	0.01	0.42	-	0.15
Number of Genus		**31**	**21**	**29**	**6**	**26**	**21**	**25**	**37**	**29**	**27**	**32**	**35**	**14**	**40**

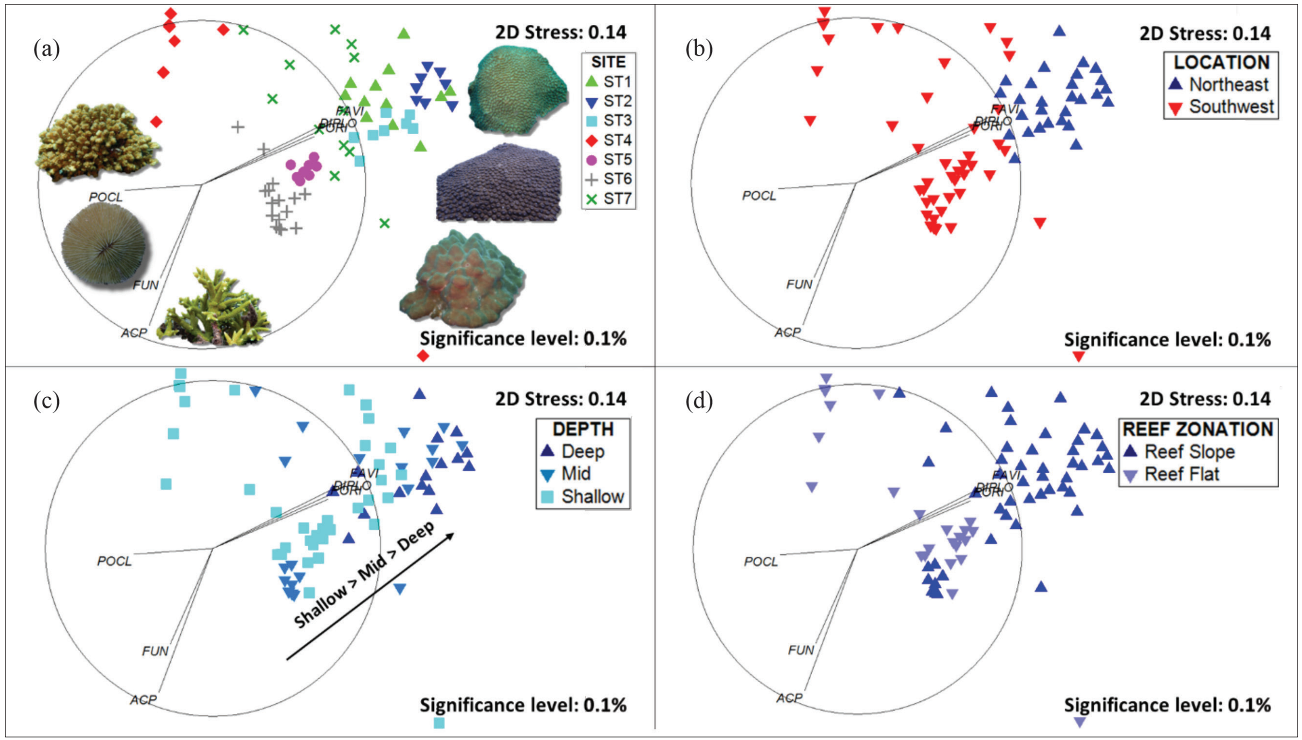

Figure 5: Non-metric multidimensional scaling (MDS) plot of hard coral genera between (a) site, (b) area, (c) depth, and (d) reef zonation based on Bray-Curtis similarity. Each point represents a sample, with distances between points reflecting the dissimilarity in community composition. Vectors represent hard coral genera (ACP = *Acropora*, DIPLO = *Diploastrea*, FAVI = *Favites*, FUN = *Fungia*, POCL = *Pocillopora*, PORI = *Porites*) with Spearman correlations, indicating their directional influence on hard coral communities

influence on the hard coral cover and stress-tolerant corals (Darling *et al*., 2019).

Therefore, it was recommended that actions that might adversely affect the northeastern reefs be prohibited to maintain the reef's long-term condition (Great Barrier Reef Marine Park Authority, 2003). Overall, the pattern of hard coral community structure must be understood to transport insight into strategic reef management, which then improves decision-making for the benefit of the ecosystem.

Different depths and reef zonation play a role in the hard coral community of Pulau Bidong. Toda *et al*. (2007) reported that coral community structure varied across the geographical regions of Peninsular Malaysia, with massive *Porites* species dominating the west coast while various forms of *Montipora* and *Acropora* were more common on the east coast. Although specific studies on depth-related coral zonation in Malaysia are limited, observed patterns in Pulau Bidong suggest that the depth and reef zonation are likely to influence coral form and distribution, consistent with Angkotasan *et al*. (2023). The number of hard coral genera increases as the depth increases from the reef flat towards the reef slope. In Pulau Bidong, branching *Acropora* has the highest contribution to the community in both reef flats and shallow water.

Meanwhile, massive *Porites* and *Diploastrea* are the prominent genera in reef slopes within the mid and deep depths. Angkotasan *et al*. (2023) reported the hard coral diversity where coverage of branching *Acropora* and massive coral varied between depths. Light attenuation may serve as an important influence across depths possibly constraining their energy acquisition and impeding the growth of hard corals within the coral reef ecosystem (Strahl *et al*., 2019). Optimum light intensity in shallow areas exposed to more directional light may promote a higher growth rate for fast-growing corals like *Acropora* (Kaniewska *et al*., 2009). In contrast, light reduction by depth and/or turbidity is known to be a suitable habitat for slow-growing species such as massive *Porites* (Fabricius, 2005).

An experimental study by Juhi *et al*. (2021) indicated that turbid water coral such as *Porites lutea*, *Turbinaria mesenterina*, and *Goniopora cellulose* exhibit photoinactivation under low light stress to adapt to such conditions. Furthermore, Ali *et al*. (2020) learned that *Porites* can survive in the turbid water of Sindh Coast, Pakistan because of the small corallite features of the genera. According to Price *et al*. (2021), *Porites* are adaptive in low water visibility because this coral genus can utilise the heterotrophic mechanism for nutrients and respiration. Insight on mesophotic coral reefs also indicates that the percentage cover of massive and encrusting corals increases as the depth increases while branching coral decreases (Kramer *et al*., 2020). This explains the capability of massive *Porites* and *Diploastrea* to adapt in deeper water thus, the higher coverage of both taxa in water more than 10 m.

The domination of *Acropora* in reef flat and massive *Porites* and *Diploastrea* in reef slope can also be explained by their ability to withstand different wave action. Apart from being differentiated by areas, variables like depth and reef zonation also play a role in determining the wave energy impacting the sea floor. The findings in this study coincide with Kim *et al*. (2022), where *Acropora* mainly covered the shallow back reef with lower wave action while *Porites* in the deeper reef slope. Previous studies showed that the genus *Acropora* is abundant in shallow water while *Porites* dominated the reef at deeper depths (Williams *et al*., 2013).

The different distribution of hard coral genera is due to the various intensities of natural conditions across reef zonation and depth (Zhao *et al*., 2016). The percentage cover of *Acropora* negatively correlated with the wave energy in Kingman Reef (Williams *et al*., 2013). Therefore, *Acropora* is adapted to areas with low wave energy in the shallow reef flats in Pulau Bidong. Besides, the massive degradation of *Acropora* coral in Pulau Bidong during the 2019 Pabuk coincides with the vulnerability of this branching coral to intense energy by tropical storms (Safuan *et al.*, 2020). Hence, the complexity of hard coral with various morphological forms determines their distribution in the coral reef ecosystem. Nevertheless, future research could include hard and dead coral morphology for further insights into the coral assemblage structure of the reef.

Conclusions

The findings in this study indicated that coral reef distribution around Pulau Bidong was influenced by local variation in depth, reef zonation, and oceanographic conditions, particularly Horizontal Kinetic Energy (HKE). Deeper reef slopes with higher HKE intensity, predominantly in the northeastern part of the island were characterised by a higher proportion of abiotic components such as dead coral as well as sand and rock. These exposed and hydrodynamically active environments were typically dominated by stress-tolerant massive corals such as *Porites* and *Diploastrea*.

By comparison, the shallow reef flats in the southwestern region, where HKE intensity was lower, supported high contribution of Coral cover, dominated by structurally complex branching corals such as *Acropora*. These patterns suggest that hydrodynamic forces and depth are key drivers shaping the spatial distribution of coral communities in Pulau Bidong. Moreover, future research should have standardisation of the variables across the study area to provide a comprehensive finding on the influence of local variables on the hard coral communities. Our findings found that the island is dominated by the *Acropora – Porites* community though their distribution varied between site, area, depth, and reef zonation.

The characteristics of hard coral itself such as the strength or tolerance to disturbance influence their distribution. Overall, it can be concluded that environmental variation makes up the community structure of coral reefs, which affects the spatial distribution of biotic and abiotic components of coral reefs and hard coral communities in Pulau Bidong. Further insight into the coral reef community in particular, hard coral distribution provides information on the life history of the reef, which will be valuable in deciding the effective strategic management to sustain the reef over time.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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Appendices

Appendix 1: Result of ANOSIM with pairwise analysis of biotic and abiotic components in coral reef for factors "Site", "Depth", "Location", and "Reef Zonation". Significance level of less than 5% indicates significant differences and is marked as bold. Significance level for pairwise test is less than 0.238% and marked as bold

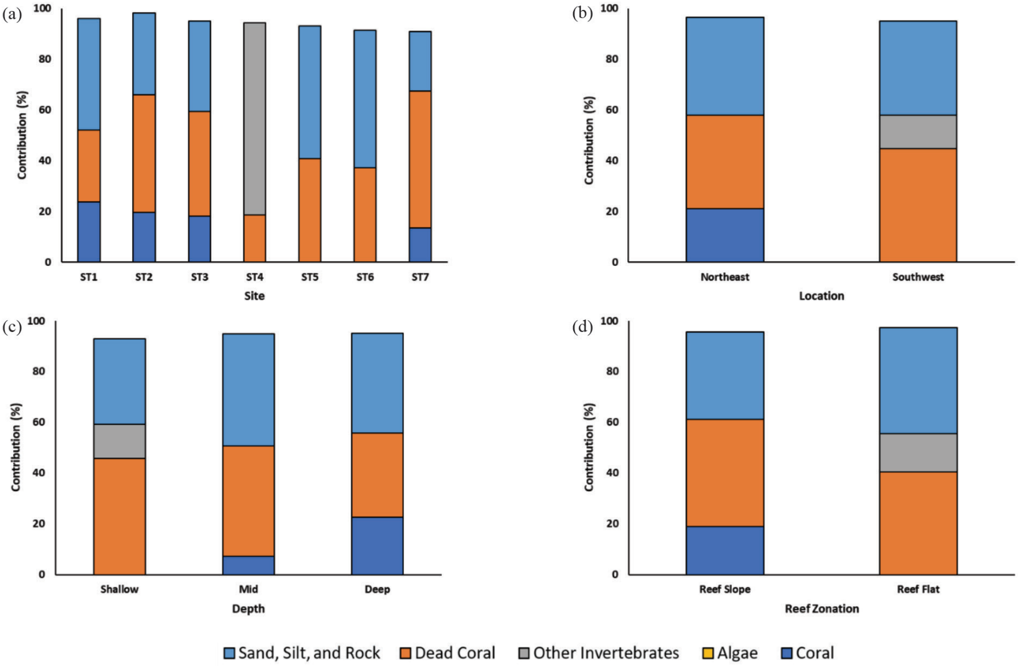
Factor	Global R	Significance Level (%)
Site	0.517	**0.1**
Depth	0.031	19.5
Location	0.163	**0.1**
Reef zonation	0.316	**0.1**

Pairwise Test (Site)

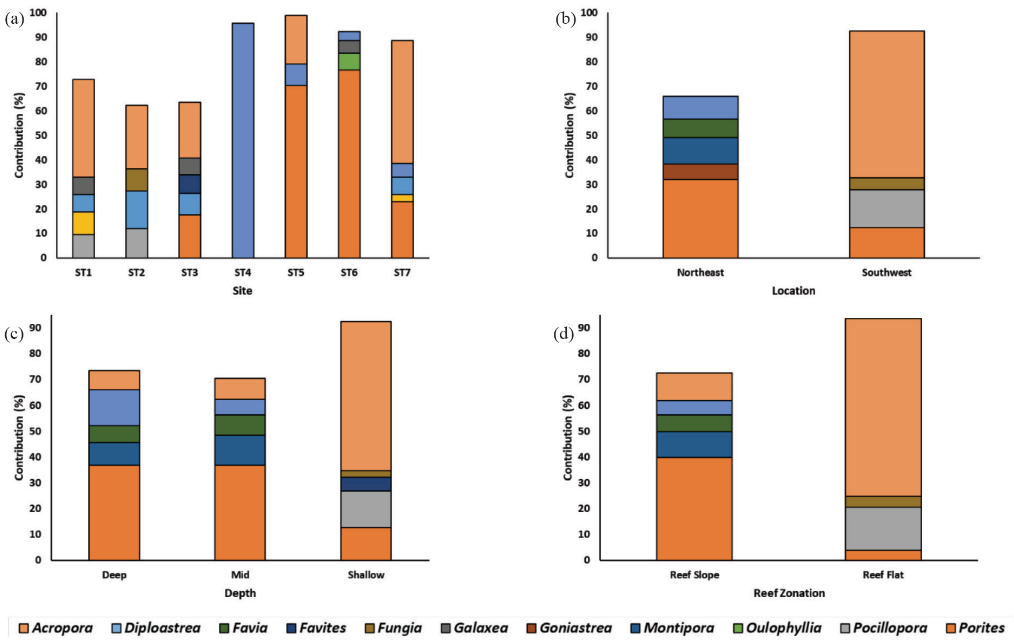
Group	R	Significance Level (%)	Actual Permutations
ST1, ST2	0.33	0.6	999
ST1, ST3	0.29	0.7	999
ST1, ST4	1.00	**0.1**	999
ST1, ST5	0.48	**0.1**	999
ST1, ST6	0.50	**0.1**	999
ST1, ST7	0.42	**0.1**	999
ST2, ST3	-0.08	91.9	999
ST2, ST4	1.00	**0.1**	999
ST2, ST5	0.69	**0.2**	999
ST2, ST6	0.48	**0.2**	999
ST2, ST7	0.23	1.7	999
ST3, ST4	1.00	**0.1**	999
ST3, ST5	0.50	**0.2**	999
ST3, ST6	0.40	**0.2**	999
ST3, ST7	0.11	9.7	999
ST4, ST5	1.00	**0.2**	999
ST4, ST6	1.00	**0.1**	999
ST4, ST7	0.99	**0.1**	999
ST5, ST6	-0.06	73.4	999
ST5, ST7	0.31	0.9	999
ST6, ST7	0.36	**0.1**	999

Appendix 2: Result of ANOSIM test with pairwise analysis of coral genera. Significance level less than 5% indicates significant differences and marked as bold. Significance level for pairwise test is less than 0.238% and marked as bold

ANOSIM (Coral Genera)			
Factor	**Global R**	**Significance Level (%)**	
Site	0.673	**0.1**	
Depth	0.237	**0.1**	
Location	0.467	**0.1**	
Reef zonation	0.576	**0.1**	
Pairwise Test (Site)			
Groups	**R**	**Significance Level (%)**	**Actual Permutations**
ST1, ST2	0.393	**0.1**	999
ST1, ST3	0.199	3.0	999
ST1, ST4	0.871	**0.1**	999
ST1, ST5	0.889	**0.1**	999
ST1, ST6	0.947	**0.1**	999
ST1, ST7	0.386	**0.1**	999
ST2, ST3	0.489	**0.1**	999
ST2, ST4	0.854	**0.1**	999
ST2, ST5	1.000	**0.2**	999
ST2, ST6	0.996	**0.1**	999
ST2, ST7	0.503	**0.2**	999
ST3, ST4	0.779	**0.1**	999
ST3, ST5	0.926	**0.1**	999
ST3, ST6	0.874	**0.1**	999
ST3, ST7	0.282	0.5	999
ST4, ST5	0.737	**0.1**	999
ST4, ST6	0.902	**0.1**	999
ST4, ST7	0.739	**0.1**	999
ST5, ST6	0.252	1.6	999
ST5, ST7	0.164	4.3	999
ST6, ST7	0.647	**0.1**	999
Pairwise Test (Depth)			
Deep, Mid	0.152	2.4	999
Deep, Shallow	0.280	**0.2**	999
Mid, Shallow	0.243	0.9	999



Appendix 3: Result of SIMPER analysis of biotic and abiotic components at different (a) site, (b) location, (c) depth, and (d) reef zonation



Appendix 4: Result of SIMPER analysis of coral genera at different (a) site, (b) location, (c) depth, and (d) reef zonation