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Elucidating hard coral community in tropical coral reefs of Pulau Bidong and nearby islands, South China Sea

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Abstract. *Qamarina MFN, Wee HB, Yu HP, Bachok Z, Safuan CDM. 2025. Elucidating hard coral community in tropical coral reefs of Pulau Bidong and nearby islands, South China Sea. Biodiversitas 26: 444-457.* This study investigates the intricate dynamics of hard coral communities within the tropical coral reefs of the South China Sea, a region renowned for its high marine biodiversity. Data were collected through video sampling to assess the hard coral composition around Pulau Bidong and nearby islands, analyzing variations of hard coral communities across different variables such as island, depth, habitat, and exposure. In total, 40 hard coral genera from 15 families were identified in the study area. Overall, *Acropora* (22.41% ± 22.17) emerged as the most prominent genus, followed by *Porites* (5.8% ± 10.27). *Acropora* dominated in leeward reefs (28.70% ± 22.84) and sandy habitats (29.11% ± 23.89), both sheltered from intense winds and currents. *Porites* were abundant in exposed reefs (13.69% ± 16.4) with submerged habitats (35.64% ± 8.42) and windward reefs (9.33% ± 10.47) with rocky habitats (8.17% ± 9.46), both of which are subject to higher physical disturbances. Varying local conditions significantly influence the composition of hard coral communities in these tropical reefs. These findings underscore the urgent need for conservation in disturbed reefs, as they should be protected from intense human activities to preserve hard coral diversity. The recommendation that sheltered areas, such as leeward reefs, may be more suitable for water activities and controlled human development supports the responsible utilization of Pulau Bidong and nearby islands while ensuring the long-term sustainability of the marine ecosystem. Overall, this study provides a foundational understanding of how local environmental variables affect hard coral communities in the South China Sea, a crucial insight for developing effective coral reef management strategies amid increasing pressures from climate change.

Keywords: Coral reef management, hard coral, hard coral community, South China Sea, tropical coral reef

INTRODUCTION

Insights into hard coral communities have become crucial for their conservation, given the growing threats to coral reefs from both natural and human influences (Mujahidah et al. 2023; Isdianto et al. 2024). Research into the intricate relationships within these ecosystems is essential for preserving reef biodiversity. Hard corals serve as foundational elements of coral reefs, forming the structural basis that supports various ecological functions (Wulandari et al. 2022; Razak et al. 2024). Their complex structures provide a habitat for reef fish and shelter for juvenile marine life (Rivera et al. 2020). However, it is important to note that humans, which heavily rely on coral reef ecosystems for fisheries resources and tourism income, also play a significant role in their destruction (Grafeld et al. 2017; Rivera et al. 2020). Coastal regions benefit from healthy coral reefs, as reefs absorb and dissipate wave energy, reducing the impact of rough sea conditions before the waves reach the shoreline (Shimokawa et al. 2014; Carlot et al. 2023). Moreover, the aesthetic appeal of underwater landscapes attracts tourists, supporting various water-based activities in coral reef areas (Khodzori et al. 2019).

The significance of coral reefs stems largely from the complex organization of hard corals. Different forms of hard corals contribute to the structural complexity of reefs (Graham and Nash 2013). The structure of reef ecosystems varies depending on local variables such as depth, reef zonation, hydrodynamic patterns, and temperature (Zhao et al. 2016; Angkotasan et al. 2023; Law and Huang 2023). For instance, studies at remote atoll reefs in the Pacific Ocean have found that hard corals in different reef zones exhibit distinct community patterns, with some species being more abundant in certain zones and others showing a preference for different environmental conditions (Williams et al. 2013). Reef exposure to open ocean conditions also influences community structure; hard corals with higher tolerance levels predominantly occupy exposed areas (Shimokawa et al. 2014; Waheed and Hoeksema 2014). Additionally, depth—closely linked to temperature and light intensity—affects the distribution of hard corals (Higuchi et al. 2015; Chow et al. 2019). These factors underscore that the distribution of hard corals depends on the specific environmental conditions in which they thrive.

Malaysia is among the countries in a region of high marine biodiversity, particularly within the South China Sea (SCS) (Huang et al. 2015) and is home to Pulau Bidong. Situated on the east coast of Peninsular Malaysia facing the

SCS, Pulau Bidong is recognized as one of the healthier reefs in the area. Although the island is not designated as a Marine Protected Area (MPA), it harbors a higher proportion of live coral cover than some MPAs, such as Pulau Kapas and Pulau Perhentian, largely due to minimal human interference (Safuan et al. 2021). A survey by Reef Check Malaysia (2023) revealed that the reef around Pulau Bidong is in good condition, with coral cover among the highest in Malaysia, estimated at 15% higher than the national average. However, in 2019, tropical storm Pabuk generated strong currents (>1 ms^{-1}) and large wave heights (>4 m), causing significant changes to the reefs, particularly in shallow water areas (Safuan et al. 2020). Studies indicate that disturbances, whether natural or anthropogenic, influence coral structure complexity (Darling et al. 2019). Malaysia also experiences seasonal monsoons—the northeast monsoon (November-February) and the southwest monsoon (June-September) (Daud and Akhir 2015)—which bring heavy rain, intense winds, and currents. Physical oceanography likely shapes coral communities in this region (Toda et al. 2007); however, the influence of ocean dynamics on coral communities in Malaysia remains under-researched, presenting an exciting opportunity for future studies.

This collaborative study aims to determine the spatial distribution of hard corals around Pulau Bidong and nearby islands and to examine hard coral communities in relation to local variables. Insights from this research will enhance understanding of hard corals and the factors influencing them, providing valuable guidance for coral reef stakeholders. By considering these external variables, stakeholders can develop effective measures to maintain the desirable condition of coral reefs in this area.

MATERIALS AND METHODS

Study area

The Bidong Archipelago, located in the SCS, includes Pulau Bidong, Pulau Gelok, and Pulau Tengkorak, while Karang Tengah is considered separately due to its unique submerged reef characteristics (Figure 1). Pulau Bidong, historically a refuge for Vietnamese migrants, has transformed into a research station and tourist destination, attracting visitors for diving and snorkeling due to its exceptional reef landscape. Recognizing its biodiversity, the state government recently designated Pulau Bidong as part of the Terengganu State Park, although it does not have MPA status. Human activities on the island remain minimal, contributing to its relatively undisturbed condition despite seasonal hydrodynamic changes influenced by the monsoon season (Daud and Akhir 2015). Given the healthy condition of the reefs and the limited human impact observed in previous assessments (Safuan et al. 2021; Reef Check Malaysia 2023), this area is ideal for studying the spatial distribution of coral reef communities and evaluating the influence of local conditions on their patterns.

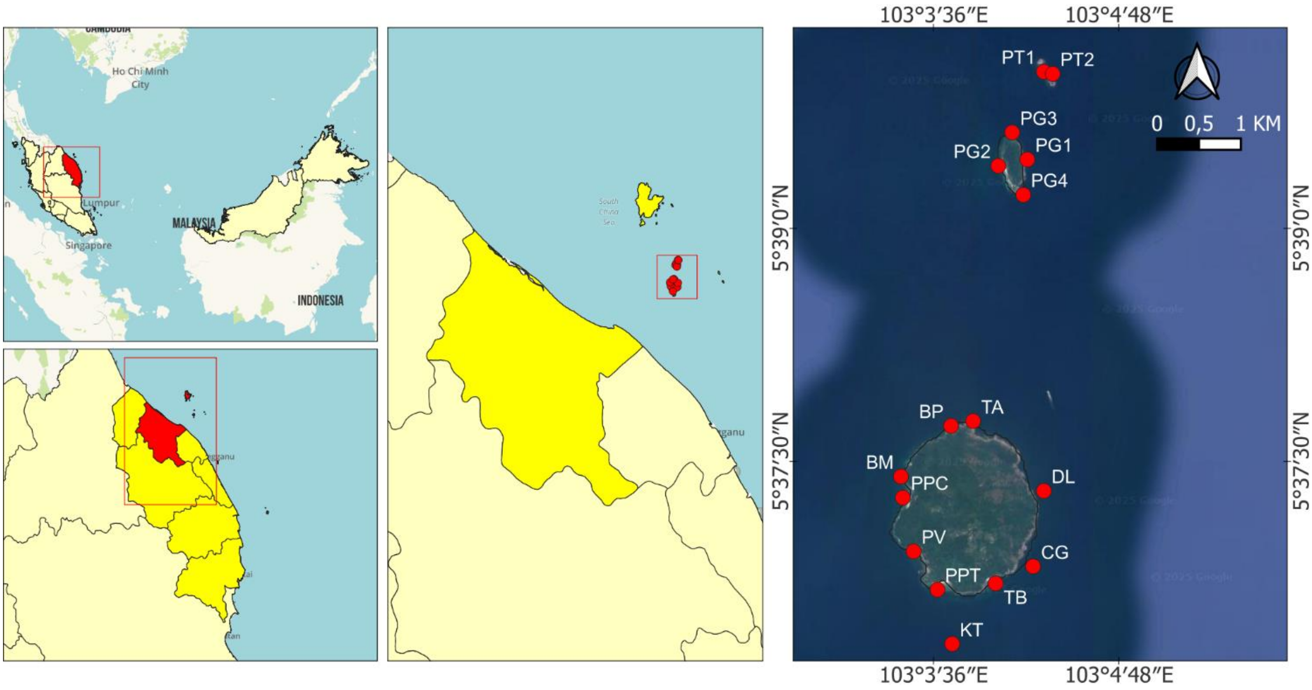

Figure 1. Map shows location of study area. Pulau Tengkorak (PT1: Pulau Tengkorak1; PT2: Pulau Tengkorak2). Pulau Gelok (PG1: Pulau Gelok1; PG2: Pulau Gelok2; PG3: Pulau Gelok3; PG4: Pulau Gelok4). Pulau Bidong (TA: Teluk Air; DL: Dinding Laut; CG: Christmas Garden; TB: Teluk Belanga; PPT: Pantai Pasir Tenggara; PV2: Pantai Vietnam2; PV1: Pantai Vietnam1; PPC: Pantai Pasir Cina; BM: Batu Menangis; BP: Batu Payung). KT: Karang Tengah

Table 1. Sampling sites at Pulau Bidong, Pulau Gelok, Pulau Tengkorak and Karang Tengah, South China Sea

Island	Site	Depth (m)	Coordinates	Description	Date
Pulau Bidong	PPC	2.0-8.0	5.621103°, 103.056698°	Leeward reef with a sandy beach shoreline, sheltered from high exposure to physical forces.	August 2016, May 2023
	PPT	7.7	5.611225°, 103.060426°	Leeward reef with a sandy beach shoreline, sheltered from high exposure to physical forces.	September 2017
	TB	11.5	5.611900°, 103.066700°	Windward reef with a rocky shoreline, exposed to physical forces.	August 2017
	PV	5.6-6.6	5.615332°, 103.057857°	Leeward reef with a sandy beach shoreline, sheltered from high exposure to physical forces.	July 2017, September 2017
	BM	6.3	5.623362°, 103.056488°	Leeward reef with a rocky shoreline, sheltered from high exposure to physical forces.	August 2017
	TA	12.0	5.629318°, 103.064278°	Windward reef with a rocky shoreline, exposed to physical forces.	August 2017
	CG	5.8	5.613727°, 103.070742°	Windward reef with a rocky shoreline, exposed to physical forces.	August 2017
	DL	15.2	5.621822°, 103.071904°	Windward reef with a rocky shoreline, exposed to physical forces.	August 2017
	BP	10.8	5.628800°, 103.061900°	Leeward reef with a rocky shoreline, sheltered from high exposure to physical forces.	July 2017
Karang Tengah	KT	12.0	5.605411°, 103.062017°	Submerged reef highly exposed to physical forces.	August 2016
Pulau Gelok	PG1	7.6	5.657380°, 103.070126°	Windward reef with a rocky shoreline, exposed to physical forces.	August 2017
	PG2	12.2	5.656701°, 103.066997°	Leeward reef with a rocky shoreline, sheltered from high exposure to physical forces.	August 2017
	PG3	12.8	5.660290°, 103.068486°	Windward reef with a rocky shoreline, exposed to physical forces.	August 2017
	PG4	7.4	5.653590°, 103.069693°	Leeward reef with a rocky shoreline, sheltered from high exposure to physical forces.	August 2017
Pulau Tengkorak	PT1	13.4	5.666800°, 103.071900°	Reef with a rocky shoreline, highly exposed to physical forces.	August 2017
	PT2	11.8	5.666572°, 103.072858°	Reef with a rocky shoreline, highly exposed to physical forces.	August 2017

Procedures

Sampling design

Data collection was conducted in August 2016, July, and September 2017, as well as May 2023 at a total of 20 sites (Table 1) ranging in depth from 2 m to 15 m in Bidong Archipelago (5.6198° N, 103.0631° E). Data was collected along 20x100 m transect lines (total: 2 km survey line) at the designated sites. The sites were grouped by islands within the study area, including Pulau Bidong, Pulau Gelok, Pulau Tengkorak and Karang Tengah. Since hard coral cover extends approximately to a depth of 15 m, reefs were categorized by depth ranges into 3-5 m, 5-10 m and 10-15 m. Additionally, reefs were classified as Rocky, Sandy or Submerged based on shoreline structure and the reef habitat characteristics. Given the influence of varying physical patterns, reefs were further categorized as Windward, Leeward, or Exposed according to the spatial characteristics of each reef.

Coral video transect

Data were acquired via SCUBA diving using the Coral Video Transect (CVT) method, following the technique described by Safuan et al. (2015). The data collector recorded video with an Olympus TG-6 underwater camera, encased in a waterproof housing and configured to Underwater Wide mode at Full High-Definition resolution (1920x1080) and 60 frames per second. A 100 m transect tape, divided into four 20 m segments, was laid parallel to the shoreline along the reef contour in the study area. Before recording, the data collector photographed a dive slate displaying complete site information. Depth at each survey site was recorded using a dive computer. At the start of each transect, the data collector recorded a 360° video overview of the reef to document the reef conditions. They then recorded along the transect line with the camera facing down perpendicularly, using a reference bar (0.5 m) to maintain a consistent distance above the substrate (Safuan et al. 2015). To ensure video clarity, the data collector swam at approximately 5 m per minute throughout the recording. Coral taxa observed along the transect line were thoroughly photographed for later identification.

Image analysis

Each video was extracted into 50 non-overlapping frames for 20 m segment. Each frame was analyzed using Coral Point Count with Excel extension (CPCe) software version 4.1 (Kohler and Gill 2006), with an overlay of 50 points per frame (Safuan et al. 2015). Hard corals were identified at the genus level, utilizing Veron (2000) and the World List of Scleractinia (Hoeksema and Cairns 2024) as references. The percentage cover of hard coral genus was calculated to assess the hard coral community of Pulau Bidong and nearby islands. Genera with a percentage cover lower than 0.5% were grouped under Others for further analysis. As a result, hard coral genera were divided into ten groups: *Acropora*, *Porites*, *Fungia*, *Pocillopora*, *Diploastrea*, *Montipora*, *Favites*, *Pavona*, *Goniopor*a and Others.

Data analysis

The analyzed data were compiled and imported into the R Statistic Program (R Core Team 2024) via RStudio (R Studio Team 2024). Each sampling transect was designated with factors (Island, Depth, Exposure and Habitat) and followed by the percentage cover of each coral genera recorded. The composition of the hard coral genera was ordinated via the Bray-Curtis dissimilarity matrix. Permutation ANOVA (PERMANOVA, permutation: 999) was conducted to examine the composition differences with the interactions of the factors (Oksanen et al. 2013). This is followed by a post-hoc pairwise test (pairwise adonis: Arbizu 2017) on each factor driving the composition of the coral genera. Similarity Percentage (SIMPER) analyses were conducted to distinguish important hard coral genera, which drove the differences within each factor (Island, Depth, Exposure and Habitat). Non-parametric Multi-Dimensional Scaling (nMDS) graphs (stress: 0.167) were constructed using the ordinated data and represented the distance of dissimilarities between data points, while grouped based on significant factors.

RESULTS AND DISCUSSION

Hard coral community

The survey recorded a percentage cover of hard coral at 42.35% covering the reef in the study area. The hard coral comprised of 38 genera from 16 families across all transects in the study area (Table 2). *Acropora* was the most common genus (22.41% ± 22.17), followed by *Porites* (5.80% ± 10.27), *Fungia* (3.49% ± 9.09), *Pocillopora* (1.50% ± 3.03), *Diploastrea* (1.62% ± 5.12), *Montipora* (2.67% ± 6.05), *Favites* (0.92% ± 1.43), *Pavona* (0.61% ± 2.17) and *Goniopora* (0.52% ± 1.26) (Table 3). The remaining genera were grouped under Others (2.81% ± 3.71).

The hard coral community (Table 4) based on exposure revealed that *Acropora* is the dominant hard coral genus cover for all Exposures: Leeward (28.70%), Exposed (24.04%), and Windward (9.64%) reefs (Figure 2.A). This is followed by *Porites* at Exposed (13.69%), Windward (9.33%) and Leeward (1.99%). Other special attention genera were *Fungia* and *Diploastrea*, which were more common at Leeward reef (6.03%) and Windward reef (4.56%), respectively. The Others, which made up the 31 lesser Hard Coral genera in the Bidong Archipelago, recorded higher at Exposed (18.44%) and Windward (12.16%) reefs.

The percentage cover of *Acropora* declined as depth increased (Figure 2.B), from 2-5m (38.46%), 5-10m (28.27%) and 10-15m (12.47%). *Montipora* recorded the highest cover at 2-5m (12.07%), but negligible (<2%) at deeper Depths. *Fungia* showed a notable percentage cover at 5-10m (6.11%), with lesser at shallower (2-5m: 2.73%) and deeper (10-15m: 0.91%). In contrast, *Porites* have a substantial influence at 10-15m (10.44%) and least cover at shallower depths of 2-5m (0.21%). Other coverage increases with depth, being lowest at 2-5m (0.88%) and highest at 10-15m (3.52%). In general, the shallow depth (2-5m) was dominated by *Acropora*, while *Fungia* had the highest cover at 5-10m. The deeper depth (10-15m) was highly covered with *Porites*, followed by other hard corals.

Sandy (29.11%) reefs were majorly covered by *Acropora* (Figure 2.C) followed by Submerged (16.29%) and Rocky (15.29%) reefs. *Porites* were highly prevalent in Submerged (35.64%) reefs, followed by Rocky (8.17%) reefs. Additionally, *Fungia* (5.82%), *Pocillopora* (1.94%), *Montipora* (3.17%) and *Pavona* (0.67%) were more common at Sandy reef. Meanwhile, *Diploastrea* was only present in Rocky reefs (3.73%). Finally, Others have a high influence in the Submerged reefs with a percentage cover of 36.97%. Overall, *Acropora* was dominant in Sandy and Rocky reefs and *Porites* are more abundant in Submerged reefs. Other than these two genera, *Fungia* has higher cover in Sandy reefs while *Diploastrea* in Rocky reefs.

Acropora (Figure 2.D) was the dominant hard coral genus in the reef of Pulau Bidong (23.65%), Pulau Tengkorak (27.91%) and Pulau Gelok (17.29%) whereas *Porites* for Karang Tengah (35.64%). *Fungia* (4.87%) and *Diploastrea* (2.72%) were recorded at Pulau Bidong, whereas *Pocillopora* (1.92%), *Favites* (1.90%), and *Goniopora* (1.83%) were mainly recorded at Pulau Gelok. Pulau Tengkorak reefs have a high coverage of *Montipora* (4.91%) and *Pavona* (2.07%). The percentage cover of Others (genera) in Pulau Tengkorak (9.18%) and Pulau Gelok (7.18%) were higher than in Pulau Bidong (2.07%) and Karang Tengah (1.34%). Across the study area, *Acropora* has high coverage in the reef of Pulau Bidong, Pulau Tengkorak and Pulau Gelok and *Porites* were the most abundant in Karang Tengah.

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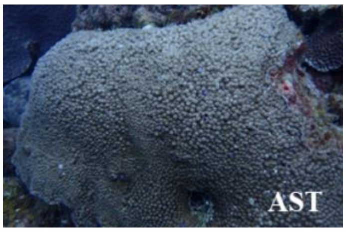
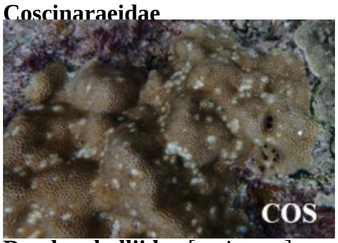
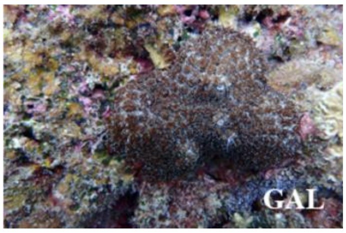
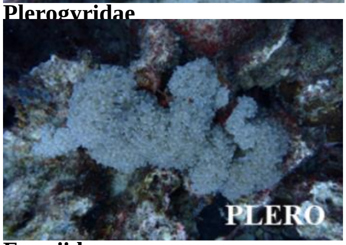
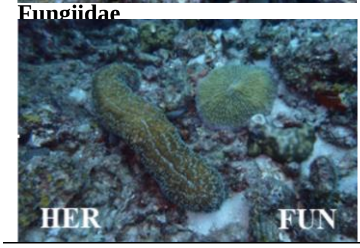
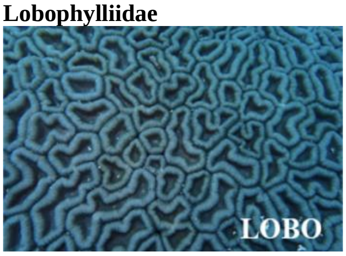
Table 2. Family and genus classification

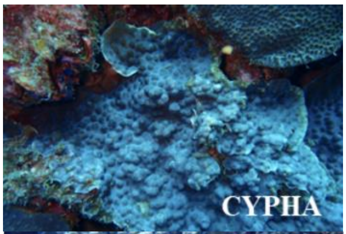
Family	Genus
Acroporidae   	*Acropora* (ACP) *Astreopora* (AST) *Montipora* (MON)
Agariciidae 	*Gardineroseris* (GAR) *Leptoseris* (LEP) *Pavona* (PAV)
Caryophylliidae [no image]	*Distichopora* (DIS)
Coscinaraeidae 	*Coscinaraea* (COS)
Dendrophylliidae [no image]	*Turbinaria* (TURBI)
Diploastreidae 	*Diploastrea* (DIPLO)
Euphylliidae  	*Euphyllia* (EUP) *Galaxea* (GAL)
Plerogyridae 	*Plerogyra* (PLERO)
Fungiidae  	*Ctenactis* (CTENA) *Fungia* (FUN) *Halomitra* (HALO) *Heliofungia* (HELIO) *Herpolitha* (HER) *Polyphyllia* (POLY)

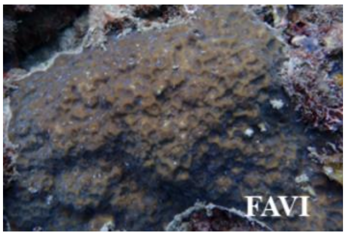
Lobophylliidae

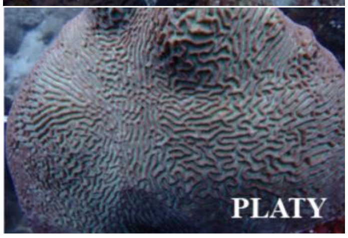


Acanthastrea (ACANT)
Lobophyllia (LOBO)

Merulinidae







Cyphastrea (CYPHA)
Dipsastraea (DIP)
Echinopora (ECHI)
Favites (FAVI)
Goniastrea (GON)
Hydnophora (HYDNO)
Merulina (MERU)
Montastrea (MONTA)
Oulophyllia (OULOP)
Pectinia (PEC)
Platygyra (PLATY)

Poritidae

Goniopora (GONIO)
Porites (PORI)

Pocilloporidae

Pocillopora (POCL)

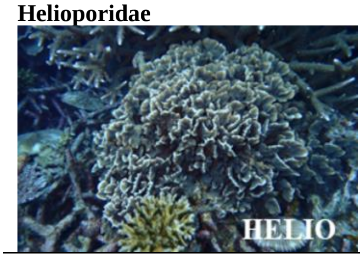
Pachyseriidae

Pachyseris (PACHY)

Psammocoridae [no image]

Psammocora (PSAM)

Helioporidae



Heliopora (HELIO)

Table 3. The mean percentage covers with standard deviation and median of each genus in Pulau Bidong and nearby islands, South China Sea

Genus	Mean	Standard Deviation	Median
Acropora	22.41	22.17	12.25
Porites	5.80	10.27	1.06
Fungia	3.49	9.09	0.12
Others	2.81	3.71	1.45
Montipora	2.67	6.05	0.08
Diploastrea	1.62	5.12	0.00
Pocillopora	1.50	3.03	0.36
Favites	0.92	1.43	0.10
Pavona	0.61	2.17	0.00
Goniopora	0.52	1.26	0.00

Sandy (29.11%) reefs were majorly covered by *Acropora* (Figure 2.C) followed by Submerged (16.29%) and Rocky (15.29%) reefs. *Porites* were highly prevalent in Submerged (35.64%) reefs, followed by Rocky (8.17%) reefs. Additionally, *Fungia* (5.82%), *Pocillopora* (1.94%), *Montipora* (3.17%) and *Pavona* (0.67%) were more common at Sandy reef. Meanwhile, *Diploastrea* was only present in Rocky reefs (3.73%). Finally, Others have a high influence in the Submerged reefs with a percentage cover of 36.97%. Overall, *Acropora* was dominant in Sandy and Rocky reefs and *Porites* are more abundant in Submerged reefs. Other than these two genera, *Fungia* has higher cover in Sandy reefs while *Diploastrea* in Rocky reefs.

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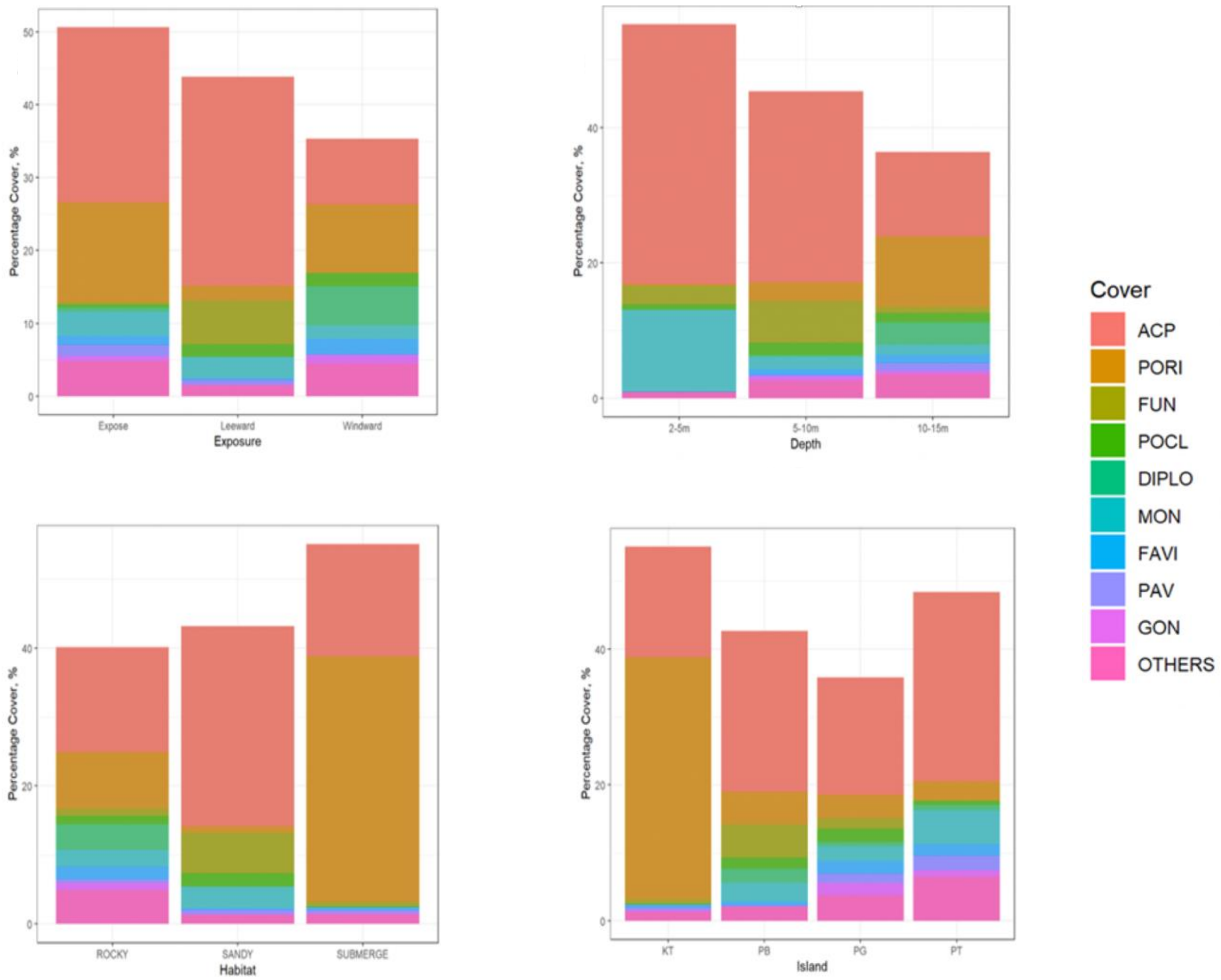

Figure 2. Bar graph percentage cover of hard coral genera for all factors; A. Exposure; B. Depth; C. Habitat; D. Island

Table 4. Average percentage cover of hard coral genera at different islands, habitats, exposures, depths and sites

Parameters	ACP	PORI	FUN	POCL	DIPLO	MON	FAVI	PAV	GON	Others	Number of genus
Island											
Pulau Bidong	23.69	4.76	4.87	1.64	2.16	2.72	0.53	0.15	0.06	2.07	33
Karang Tengah	16.29	35.64	0.66	0.11	-	0.03	0.38	0.48	0.16	1.34	18
Pulau Gelok	17.29	3.43	1.55	1.92	0.72	2.08	1.90	1.35	1.83	7.18	25
Pulau Tengkorak	27.91	2.72	0.16	0.56	0.90	4.91	1.72	2.07	1.02	9.18	22
Depth											
2-5m	38.46	0.21	2.73	0.79	-	12.07	-	0.11	-	0.88	13
5-10m	28.27	2.79	6.11	1.81	0.37	1.71	0.88	0.22	0.62	2.60	30
10-15m	12.47	10.44	0.91	1.35	3.34	1.49	1.19	1.14	0.54	3.52	32
Habitat											
Rocky	15.29	8.17	1.09	1.15	3.73	2.41	1.86	0.55	1.06	4.84	30
Sandy	29.11	0.92	5.82	1.94	-	3.17	0.19	0.67	0.10	1.26	16
Submerged	16.29	35.64	0.66	0.11	-	0.03	0.38	0.48	0.16	36.97	19
Exposure											
Exposed	24.04	13.69	0.32	0.41	0.60	3.28	1.27	1.54	0.73	18.44	27
Leeward	28.70	1.99	6.03	1.70	0.03	2.92	0.22	0.61	0.14	1.49	29
Windward	9.64	9.33	1.05	1.74	4.56	1.63	1.87	0.84	1.01	12.16	32
Batu Menangis	22.43	0.06	8.22	2.35	-	-	-	0.03	-	0.06	5
Batu Payung	9.51	13.77	0.01	-	0.28	0.50	0.62	0.05	0.52	3.93	15
Christmas Garden	31.92	9.62	-	0.59	0.53	5.56	3.48	-	-	15.68	17
Dinding Laut	-	4.30	-	-	16.01	-	0.85	0.06	0.30	8.14	14
Karang Tengah	16.29	35.64	0.66	0.11	-	0.03	0.38	0.48	0.16	36.97	20
Pulau Gelok1	6.35	8.70	0.07	0.45	2.83	2.69	3.01	0.44	4.62	17.74	21
Pulau Gelok2	13.05	0.93	5.98	1.88	-	0.43	0.27	4.95	0.02	3.26	15
Pulau Gelok3	2.51	1.96	0.17	4.57	0.05	0.85	3.25	0.03	1.71	4.62	17
Pulau Gelok4	47.25	2.14	-	0.76	-	4.37	1.07	-	0.97	3.08	11
Pantai Pasir Cina1	19.15	0.11	0.07	0.52	-	21.01	-	-	-	-	5
Pantai Pasir Cina2	58.57	-	5.62	1.30	-	0.05	-	0.72	-	1.81	11
Pantai Pasir Cina3	57.78	0.32	5.39	1.05	-	3.14	-	0.22	-	2.08	12
Pantai Pasir Cina4	11.87	0.39	35.61	3.76	-	2.65	0.03	0.79	-	2.30	12
Pantai Pasir Tenggara	5.14	0.14	4.64	1.39	-	-	0.01	-	-	0.59	12
Pulau Tengkorak1	53.38	0.16	0.18	0.14	-	0.78	0.03	0.04	0.06	0.44	10
Pulau Tengkorak2	2.45	5.27	0.13	0.97	1.79	9.04	3.40	4.09	1.97	17.93	22
Pantai Vietnam1	37.03	0.67	0.04	5.68	-	0.03	-	-	-	0.67	5
Pantai Vietnam2	33.87	3.42	0.76	-	-	-	0.37	-	-	6.58	12
Teluk Air	1.39	27.76	0.51	0.72	18.23	1.07	1.58	-	0.02	32.38	16
Teluk Belanga	7.42	1.11	0.07	3.08	-	-	0.13	-	0.02	1.29	7

Note: ACP: *Acropora*; PORI: *Porites*; FUN: *Fungia*; POCL: *Pocillopora*; DIPLO: *Diploastrea*; MON: *Montipora*; FAVI: *Favites*; PAV: *Pavona*; GON: *Goniopor*

Drivers of hard coral community

Overall, the hard coral communities were significantly different among the groups within each factor (Table 5): Exposure (PERMANOVA: R2: 0.058, p ≤ 0.001), Depth (R2: 0.138, p ≤ 0.001), Habitat (R2: 0.033, p = 0.005) and Island (R2: 0.111, p ≤ 0.001). Pairwise comparisons between exposure exhibited clear differences between Leeward with Windward (R2: 0.152, p = 0.003) and Exposed (R2: 0.058, p = 0.024). Further SIMPER analysis (Table 5) revealed hard coral genus that contributes to the differences between Leeward and Windward was *Diploastrea* (8.5%, higher in Windward) while between Leeward and Exposed is *Fungia* (8.8%, higher Leeward). Non-parametric Multidimensional Scaling (nMDS: Figure 3) illustrates the slight separation between all exposures. In addition, the plot also agrees with the data where the hard coral community is more influential in specific exposure. For example, *Diploastrea* was found within the Windward groups while *Fungia* was shown among the Leeward sites (Figure 3).

The composition of hard coral in Sandy reefs is highly distinctive from the other two habitats, Rocky (R2: 0.121, p = 0.003) and Submerged (R2: 0.117, p = 0.003). Table 5 shows *Fungia* has high contribution to the differences in the hard coral community in Sandy and Rocky reefs based on the SIMPER analysis. On the other hand, the differences between Sandy and Submerged reefs were highly influenced by the high contribution of *Acropora* (30.5%, higher in Sandy reefs). Figure 3 shows a distinction between the Sandy group with Rocky and Submerged following the results from SIMPER analysis.

The pairwise analysis between Depths in Table 5 revealed 10-15m has a substantial difference with 2-5m (R2: 0.130, p = 0.006). Further analysis revealed that the difference was contributed by the high percentage cover of *Acropora* (45.7%) in 2-5m. Furthermore, the clear difference between 10-15m with 5-10m (R2: 0.099, p = 0.003) was due to the high *Fungia* cover at the shallower depth, 5-10m. SIMPER analysis further supports where *Fungia* has the highest percentage contribution (10.8%) to the dissimilarities after *Acropora* and *Porites* at this Depth (Table 5). Nonetheless, Figure 4 shows the hard coral genera at 10-15m have high variation, while at 2-5m, the hard coral community was shown to be influenced by *Acropora*, *Montipora*, and *Fungia*.

Among the islands in the Bidong Archipelago, only Pulau Gelok shows a significant difference with Pulau Bidong (R2: 0.0594, p = 0.025) and Karang Tengah (R2: 0.207, p = 0.024). According to the result of SIMPER analysis in Table 5, hard coral genera contributing to the differences between Pulau Gelok and Pulau Bidong were *Acropora* (43.1%), *Porites* (11.5%) and *Fungia* (9.9%). Also, *Porites* (50.7%) and *Acropora* (28.3%) played a significant role in the different hard coral communities between Pulau Gelok and Karang Tengah. The nMDS plot in Figure 4 agrees *Porites* abundantly covered the reef of Karang Tengah.

Table 5. PERMANOVA results with pairwise analysis for factors ‘Island,’ ‘Depth’, ‘Exposure’ and ‘Habitat’. SIMPER analysis shows cumulative contributions (up to 70%) of most hard coral genera contribute to the dissimilarities within the factors

Groups	Permanova			Simper (% contribution)					
	P	R2	DF	ACP	PORI	FUN	DIPLO	MON	Others
Island	0.001**	0.111	3						
PB vs KT	0.06	0.063	1	0.283	0.499				
PB vs PG	0.025*	0.059	1	0.431	0.115	0.099			
PB vs PT	0.272	0.029	1	0.451	0.093			0.104	0.116
KT vs PG	0.024*	0.207	1	0.283	0.507				
KT vs PT	0.06	0.311	1	0.328	0.429				
PG vs PT	0.272	0.056	1	0.492				0.095	0.126
Depth	0.001**	0.138	2						
2-5m vs 5-10m	0.026*	0.056	1	0.477				0.233	
2-5m vs 10-15m	0.006**	0.130	1	0.457	0.137			0.199	
5-10m vs 10-15m	0.003**	0.099	1	0.427	0.170	0.108			
Exposure	0.001**	0.058	1						
Leeward vs Windward	0.003**	0.152	1	0.405	0.147	0.100	0.085		
Leeward vs Exposed	0.024*	0.058	1	0.413	0.220	0.088			
Windward vs Exposed	0.073	0.063	1	0.376	0.243				0.098
Habitat	0.005 *	0.033	1						
Sandy vs Rocky	0.003**	0.121	1	0.416	0.135	0.101			0.082
Sandy vs Submerged	0.003**	0.117	1	0.305	0.509				
Rocky vs Submerged	0.016*	0.081	1	0.266	0.471				

Note: ** indicate p ≤ 0.001; * indicate p < 0.05; ACP: *Acropora*; PORI: *Porites*; FUN: *Fungia*; POCL: *Pocillopora*; DIPLO: *Diploastrea*; MON: *Montipora*; FAVI: *Favites*; PAV: *Pavona*; GON: *Goniopora*

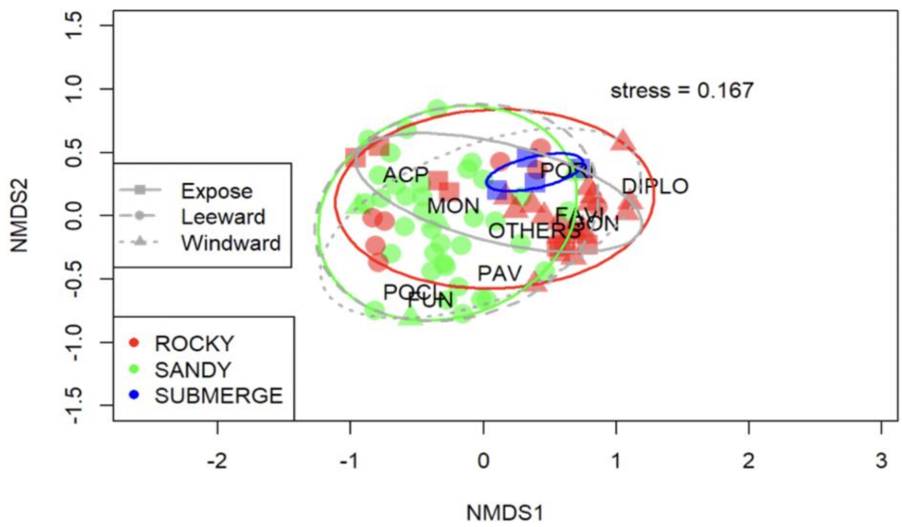

Figure 3. NMDS plot illustrates the distribution of hard coral genera based on Exposure and Habitat. Each point represents a site, differentiated into specific shapes and colors based on their characteristics. Groupings show distinct clusters corresponding to different exposures and habitats. ACP: *Acropora*; PORI: *Porites*; FUN: *Fungia*; POCL: *Pocillopora*; DIPLO: *Diploastrea*; MON: *Montipora*; FAVI: *Favites*; PAV: *Pavona*; GON: *Goniopora*

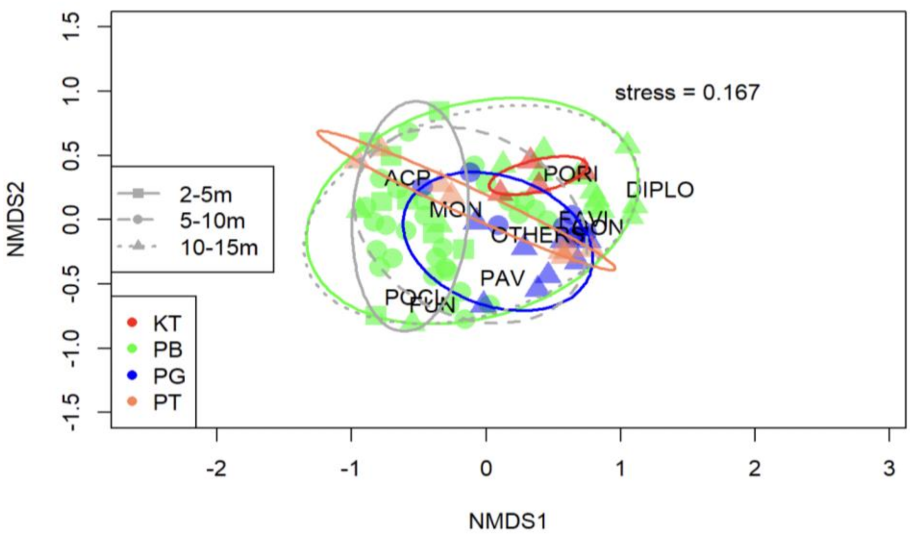

Figure 4. NMDS plot illustrates the distribution of hard coral genera based on Depth and Island. Each point represents a site, differentiated into specific shapes and colors based on their characteristics. Groupings show distinct clusters corresponding to different depths and islands. ACP: *Acropora*; PORI: *Porites*; FUN: *Fungia*; POCL: *Pocillopora*; DIPLO: *Diploastrea*; MON: *Montipora*; FAVI: *Favites*; PAV: *Pavona*; GON: *Goniopora*

Discussion

Distribution of hard coral community

Acropora is the most influential genus, with about 23% coverage of the hard coral community in the Bidong Archipelago. The dominance of *Acropora* around Pulau Bidong and nearby islands has previously been observed along the east coast of Peninsular Malaysia, including Pulau Redang, Pulau Tioman and Balok (Shahbudin et al. 2017; Akmal et al. 2019; Hanapiah et al. 2019), whereas *Porites* was primarily dominant on the west coast of Peninsular Malaysia (Safuan et al. 2016). The significant presence of *Acropora* extends beyond the reefs of Peninsular Malaysia, with notable records in the Philippines, Ryukyu Archipelago in Japan, southern Vietnam, and Aceh Province in Indonesia (Utama and Hadi 2014; Vo et al. 2014; Licuanan et al. 2019).

Understanding the dynamics of coral communities is crucial for effective management planning. In comparison with other tropical reef areas, Singapore's turbid waters support a high contribution of *Porites* to the hard coral community (Heery et al. 2018; Ng et al. 2021). Stress-tolerant corals from the families Merulinidae and Poritidae are abundant, likely due to sedimentation from the proximity of these reefs to the coastal cities (Heery et al. 2018). *Porites* were dominant in Guangdong Province, particularly in areas with high sedimentation, except in remote coral reefs where *Acropora* coverage was more prominent (Zhao et al. 2022). Additionally, a recent survey on benthic community structure in Puerto Galera, Philippines, found changes in dominant taxa where massive *Porites* have replaced the previously dominating *Acropora* in the study area due to natural disturbances (Lalas et al. 2023). These studies suggest that differences in hard coral communities among reefs respond to varying levels of disturbances either from natural or human sources. These known responses of hard coral communities can be considered to accommodate the management planning of coral reefs.

Windward reefs are associated with the Rocky habitat, while the Leeward reefs are with the Sandy habitat. In contrast, Exposed reefs are closely associated with the Submerged habitat. The study area experiences an annual monsoon phenomenon where the wind and current speed are more intense during the northeast monsoon (Daud and Akhir 2015). This phenomenon alters ocean circulation at the archipelagic level, impacting both Windward and Leeward reefs. Windward reefs are highly exposed to fast currents encircling the archipelago as opposed to the protected Leeward reef.

Findings revealed that *Acropora* is abundant in Leeward reefs and Sandy habitat, an area that is sheltered from the strong wind and current. Hence, this reef is preferable for branching *Acropora* especially with their fast-growing ability (Darling et al. 2019). Moreover, Leeward reefs and Sandy habitats are relatively affected by the sedimentation, with the reefs facing the mainland of Peninsular Malaysia, in addition to the lower rate of ocean circulation compared to Windward reefs and Rocky habitats. The higher rugosity of the *Acropora* branching form was able to tolerate the sediment settlement and avoid being smothered (Duckworth et al. 2017). This attribute enables their growth and survival in sheltered conditions. Despite this preference, *Acropora* was also observed in Windward and Exposed reefs, suggesting a wide distribution across areas with varying exposure levels. This distribution may result from enhanced larval dispersal in regions with intense oceanographic activity, such as Windward and Exposed reefs (Lowe and Falter 2015). The increased larval dispersal into these reefs, along with their high growth rate, helps explain the high coverage of *Acropora*. Besides, Edinger and Risk (2000) classified them as ruderal coral due to their traits in adapting to disturbances easily over time. This explains the presence of *Acropora* in reefs with higher exposure to physical conditions such as the Windward reef.

Meanwhile, *Porites* was observed to be abundant in Exposed reefs with Submerged habitats and Windward reefs with Rocky habitats, both affected by the higher impact of the oceanographic condition surrounding the archipelago. As these reefs were situated in the pathway of higher ocean circulation, the current may bring along the water with higher salinity and nutrients to the reefs, which contributes to the higher diversity of hard coral genera in these reefs (Kok et al. 2022). Hard corals with massive and encrusting forms which are frequently from the genera *Porites* and *Diploastrea*, demonstrate a high tolerance to stressors and may shift the hard coral community structure in response to progressive climate change impacts (Reverter et al. 2022). *Fungia* has notable coverage in Bidong Archipelago, especially in Sandy habitats which aligns with findings from Siboni et al. (2008). Fungiid coral exhibits a free-living life form, allowing movement to other preferred locations, particularly in the presence of overgrown *Acropora* or coral fragments (Ohara et al. 2021). Hence, the abundance of *Fungia* at 5-10m in this study.

In general, *Acropora* remains the highest contributor to the hard coral community at all depths. However, the declining percentage cover as the depth increases implies that *Acropora* prefers shallow water. Previous studies in Singapore have shown similar findings, attributed to limited light in deeper water (Chow et al. 2019). In contrast, *Porites* has the opposite trend indicating that this genus can thrive in deeper water. Law and Huang (2023) revealed that light plays a critical role in the hard coral distribution across depths. With the increase in depth, light attenuation becomes more significant. Therefore, *Porites* can adopt a heterotrophic feeding mechanism, capturing plankton and particulate matter using tentacles for nutrients (Price et al. 2021). Furthermore, prior research has shown that *Porites* have a high tolerance to multiple stressors, including physical and chemical factors, allowing survival in critical environments (Ali et al. 2020).

Between the islands, Pulau Bidong, Pulau Gelok and Pulau Tengkorak are mainly covered by *Acropora*, whereas *Porites* highly cover Karang Tengah. Nevertheless, these two genera are the highest contributors to the hard coral communities in Bidong Archipelago. The significant difference between the islands indicates that there are variations in the hard coral distribution even within the archipelago. This is similar to research by Lalas et al. (2023) in the Philippines, where the survey revealed different hard coral distributions at an island-specific scale. This further supports those local drivers, such as exposure to physical disturbance, light attenuation, and sedimentation impact the composition of hard coral communities within an area (Junjie et al. 2014; Chow et al. 2019; Safuan et al. 2020). Therefore, these factors should be prioritized in coral reef management, especially in selecting sites for coral restoration initiatives.

Implication to coral reef management

Understanding the hard coral community is essential for effective coral reef management in the study area (Darling et al. 2019). Hard coral serves as an indicator of both potential threats and coral reef resilience (Thompson et al. 2020). Present findings show that Windward reefs have a higher diversity of hard coral genera and the dominance of stress-tolerant and slow-growing genera such as *Porites* and *Diploastrea*. Thus, protecting the reef from human disturbances is essential to maintaining the current state of the hard coral community. More disturbance to these reefs would harm the hard coral diversity in the long term with the addition of the increasing global threat of climate change. Additionally, both taxa are key framework-building species, forming large and structurally complex coral colonies

(Darling et al. 2019). A study by Wang et al. (2021) found that slow-growing corals, such as *Porites*, can recover within one to three years after bleaching events in the northern South China Sea. However, a slower recovery of *Porites* was observed in restoration sites in Indonesia, where fast-growing corals tended to dominate the hard coral composition (Lange et al. 2024). The author also discussed that the restoration site would progressively have lower coral diversity compared to the natural reef which would then potentially affect the ecological aspect of the reef. If this study area is developed for tourism, minimal human development and water activities are recommended in Windward reefs, following Habitat Protection Zone guidelines outlined in the zoning plans by Great Barrier Reef Marine Park Authority (2004) and Razak et al. (2024).

Leeward reefs, in contrast, are mainly covered by the competitive *Acropora*, a fast-growing genus that is also sensitive to multiple disturbances (Darling et al. 2019). Reefs with lower physical disturbance, such as Leeward reefs could be designated as a General Use zone. This zone can be accessed by the public for recreation purposes while simultaneously, being selected as a coral restoration site (Safuan et al. 2022). As for the selection of corals, the most preferred genus is usually *Acropora*, as this genus is widely known for its fast growth rate which is reasonable for coral reef recovery in a degraded area (Boström-Einarsson et al. 2020; Lange et al. 2024). A coral restoration project located in the Andaman Sea found success with about half of the transplanted *Acropora* corals growing significantly within just two years (Putchim et al. 2008). Nevertheless, the restoration effort would compensate for the human intervention caused within the same zone, thus preserving the coral reef eventually. Overall, these protected reefs are suitable for public use and conducive to fast coral growth and settlement. After considering all aspects, it is clear that the insights of the hard coral community are not just crucial but integral in identifying the potential variables affecting the coral reef ecosystem. The knowledge and experience will be invaluable in helping authorities determine the necessity and extent of management intervention in the area. Although Pulau Bidong and the nearby islands are currently underdeveloped for tourism purposes, the interest in the coral reef in this archipelago has increased in recent years as they remain uncharted by coral reef enthusiasts. Therefore, developing an operative reef management plan for Bidong Archipelago is recommended before the increased human activity begins to impact the area.

The findings from this study provide a valuable foundation for understanding the status of the hard coral community in tropical coral reefs, specifically in Pulau Bidong and nearby islands. This study highlights the complex relationship between the hard coral community and local drivers, offering important insights into the state of the ecosystem. The results underscore the need for targeted coral reef management strategies that can address local challenges and ensure the long-term sustainability of these ecosystems. In comparison to other reefs affected by various influences, a study by Xiao et al. (2022) found that the reefs in the Xisha Islands were significantly impacted by high sea surface temperatures and outbreaks of coral predators. These multiple stressors induced coral bleaching events in the region. However, the reefs exhibited a high coral recruitment rate, which facilitated recovery after disturbances. The hard coral communities in the Halmahera Islands were influenced by different local parameters, such as temperature and water visibility (Angkotasan et al. 2023). These variations in local conditions affected the hard coral cover and diversity in the study region. Coral reefs in Japan, particularly in the Ryukyu Archipelago (Afzal et al. 2023), are influenced by outbreaks of coral predators, coral bleaching, and typhoons. These recurrent natural disturbances significantly impact the hard coral taxa in the region. Although there is potential for recovery, more effective management strategies should be implemented to prevent future coral reef deterioration. This study serves as a valuable reference for understanding the future conditions of hard coral communities, particularly in relation to physical disturbances. By comprehensively understanding the differences in local environmental conditions, we can develop and implement targeted management strategies tailored to the specific needs of each region. Based on current findings, it is recommended to focus preservation efforts on the Exposed and Windward reefs, which are subject to the physical disturbances of the South China Sea and are particularly vulnerable to intense human activities. These reefs exhibit a high diversity of hard coral communities, making them critical to preserve. On the other hand, the Leeward reefs, which are more accessible from the mainland of Peninsular Malaysia, could be considered for controlled water activities and regulated human development. Furthermore, the protected nature of these reefs allows for conservation efforts, such as coral restoration activities. This balanced approach would allow for the sustainable use of marine resources while protecting the biodiversity of the coral reef ecosystem within the Bidong Archipelago.

Additionally, future coral reef studies must continue to be integrated into management plans to contribute to the protection of this valuable ecosystem. By expanding research on the factors affecting hard coral communities in tropical reefs, particularly in the South China Sea, we can deepen our understanding of these ecosystems. This will provide essential information for adapting management strategies in response to climate change and other threats, ensuring effective long-term conservation. In conclusion, ongoing studies on coral reefs are crucial for enhancing our knowledge and improving coral reef management. It is hoped that this research will contribute to the development of more robust strategies for the protection and sustainability of coral reefs, particularly in the face of global climate change.

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