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Habitat associations of grouper (Teleostei: Epinephelidae) assemblages across reefs in the Bidong Archipelago, Malaysia

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Abstract. *Afiq-Firdaus AM, Safuan CDM, Abdullah MM, Awalludin EA, Syafruddin RS, Qamarina MFN, Mohamad Y, Bachok Z. 2026. Habitat associations of grouper (Teleostei: Epinephelidae) assemblages across reefs in the Bidong Archipelago, Malaysia. Biodiversitas 27 (4): d270426. https://doi.org/10.13057/biodiv/d270426.* Groupers (Teleostei: Epinephelidae) are important predatory fishes in coral reef ecosystems, yet their relationships with coral habitat remain insufficiently understood. This study aimed to evaluate grouper assemblages are structured by coral genus composition and benthic habitat, including live coral cover, across reefs in the Bidong Archipelago, Malaysia. Surveys were conducted at 18 stations between March and May 2022 using 100 m belt transects (5×100 m). Grouper assemblages were recorded using Underwater Visual Census (UVC) with video support, while benthic composition and coral genera were assessed using Coral Video Transects (CVT). Data were analyzed using canonical correspondence analysis (CCA), non-metric multidimensional scaling (NMDS), PERMANOVA, and Spearman correlation. A total of 388 individuals representing 11 species were recorded. Assemblages were dominated by *Cephalopholis formosa* (27%), *Cephalopholis boenak* (26%), and *Cephalopholis cyanostigma* (24%). NMDS indicated substantial overlap among sites, suggesting weak spatial structuring of assemblages. Coral genus composition explained 48.9% of constrained variation in CCA but was not statistically significant ($p>0.05$), consistent with PERMANOVA results (R^2: 0.492, p: 0.811). Benthic cover explained 36.0% of variation in CCA and showed a marginal effect in PERMANOVA (R^2: 0.434, p: 0.078), with only the “other invertebrates” category showing a significant relationship ($p<0.05$). Spearman correlation analyses revealed no significant relationships between grouper abundance and habitat variables. Grouper assemblages in the Bidong Archipelago showed weak and largely non-significant associations with coral genus composition and benthic habitat variables, indicating that factors other than measured habitat characteristics may play a greater role in structuring these communities.

Keywords: Coral reefs, canonical-correspondence analysis, grouper habitat preferences, Bidong Island, South China Sea

INTRODUCTION

The South China Sea is a highly productive and biologically rich large marine ecosystem that supports diverse marine life, including extensive reef-associated fish assemblages (Matsunuma et al. 2011). More than 2,200 marine fish species have been reported from Malaysian waters, many closely associated with coral reef ecosystems (Ambak et al. 2010). Coral reefs are among the most structurally complex and productive marine habitats, providing food resources, shelter, breeding sites, and nursery areas that sustain highly diverse fish communities (Siqueira et al. 2020; Afiq-Firdaus et al. 2021). The structural heterogeneity of reefs promotes ecological specialization and diverse behavioral adaptations among reef fishes (Kingsford and Battershill 1998; Hemingson et al. 2022).

Groupers, family Epinephelidae, are ecologically and economically important components of coral reef fish assemblages throughout the Indo-Pacific. The family was historically classified as a subfamily Epinephelinae within Serranidae, but is now widely recognized as a distinct family based on morphological and molecular phylogenetic evidence (Craig et al. 2011). Epinephelidae comprises approximately 165-175 valid species distributed across tropical and subtropical seas (Mitcheson and Liu 2022). Groupers occupy a range of coastal habitats, including mangroves, seagrass beds, sandy substrates, and coral reefs, typically at depths of 2-200 m (Ambak et al. 2012; Mehanna et al. 2013). Within reef ecosystems, they function as mesopredators or apex predators and frequently utilize crevices, overhangs, and complex coral structures that provide refuge and ambush sites (Komyakova et al. 2013). Because their abundance and persistence are closely linked to reef structural complexity, groupers are widely regarded as indicators of habitat condition and reef ecosystem integrity (Hackradt et al. 2014).

Reef structural complexity plays a critical role in shaping fish assemblages by providing microhabitats essential for shelter, feeding, and reproduction (Graham and Nash 2013; Seraphim et al. 2020). Grouper occurrence is typically associated with structurally complex coral habitats that support high prey availability and refuge from predation (Hackradt et al. 2014). However, groupers are particularly vulnerable to environmental disturbance due to life-history traits such as site fidelity, spawning aggregations, slow growth, long lifespans, and late maturity (Mitcheson and Colin 1995; Mitcheson et al. 2013). These characteristics reduce resilience to overfishing and habitat degradation, contributing to documented declines across their range. Emerging evidence further suggests that grouper distribution varies according to species-specific associations with benthic reef features, highlighting the importance of fine-scale habitat characteristics (Sluka 2001; Nanami 2021).

The Bidong Archipelago, located off the Terengganu coast in the southern South China Sea, Malaysia, comprises Bidong Island and adjacent islands, including Karah Island, Gelok Island, and Tengkorak Island (Grismer et al. 2014; Aziz et al. 2019). The area supports diverse coral assemblages, including branching, massive, and encrusting growth forms, as well as rocky reef habitats that support distinct fish communities (Matsunuma et al. 2011). Although previous studies have documented reef fish diversity and trophic structure in the archipelago (Rumeaida et al. 2014; Arai et al. 2015; Afiq-Firdaus et al. 2021, 2023), quantitative evidence linking grouper distribution to coral habitat characteristics remains limited. Consequently, the habitat features structuring grouper assemblages in this reef system remain poorly understood.

Accordingly, this study aims to quantify spatial variation in grouper assemblages across reef stations in the Bidong Archipelago and evaluate the relationships between grouper abundance and composition with key habitat variables, including dominant coral genera and benthic substrate composition. We hypothesize that grouper abundance increases with higher live coral cover, reflecting enhanced habitat complexity and prey availability, and grouper species composition varies with coral genus and growth form, indicating species-specific habitat associations. We further predict that structurally complex habitats (e.g., branching and massive corals) support higher grouper diversity compared to less complex substrates. By identifying habitat features that structure grouper assemblages, this study provides ecologically relevant indicators for reef condition assessment and contributes to improved reef monitoring and management strategies in the southern South China Sea.

MATERIALS AND METHODS

Study area

This study was conducted at Bidong Archipelago, Terengganu, Malaysia (5.6212°N, 103.0616°E), located about 16 km from Merang Jetty (Figure 1). Bidong Island is not designated as a marine park under Marine Parks Malaysia, but has been gazetted as a Malaysian National Heritage site and is used as a recreational island. This management status suggests relatively low formal protection and potentially moderate fishing pressure compared to fully protected marine parks, which may influence reef fish assemblages, including groupers. The island comprises well-developed coral reef ecosystems containing various coral and rocky-reef-associated fishes (Matsunuma et al. 2011; Afiq-Firdaus et al. 2021, 2023). The relatively undisturbed condition and structural complexity of these reefs provide suitable habitats for predatory reef fishes, making the area appropriate for examining habitat-assemblage relationships.

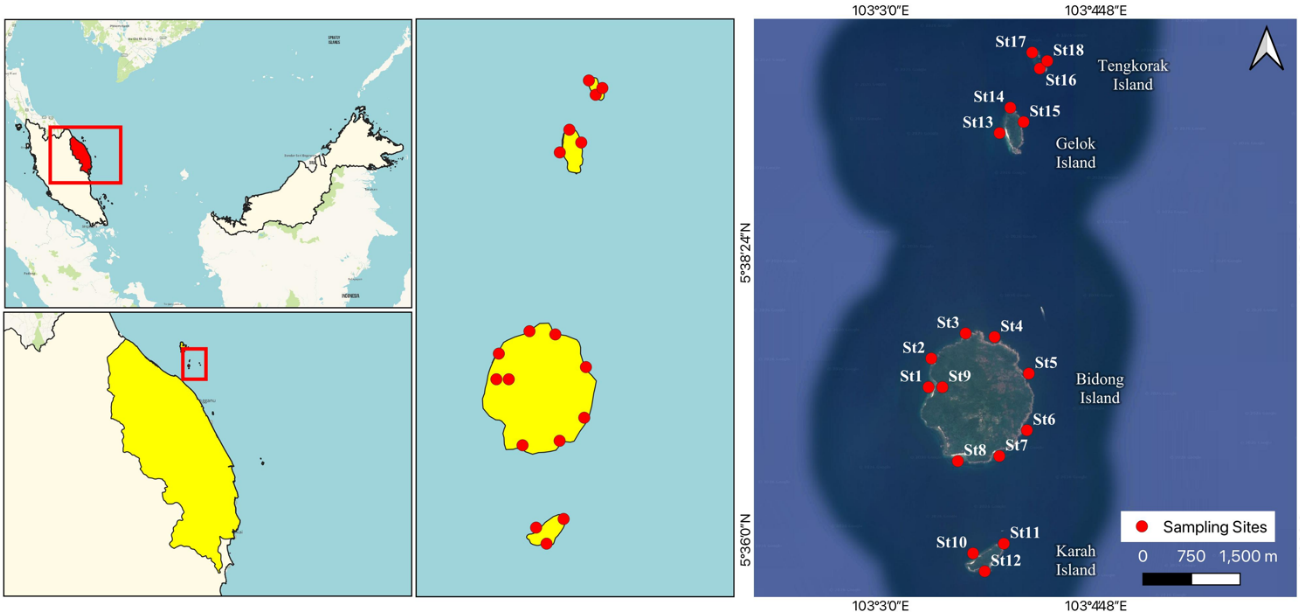


Figure 1. A map of sampling locations in Bidong Archipelago, Terengganu, Malaysia

A total of 18 sampling stations were selected across Bidong Island and the nearby islands of Karah Island, Gelok Island, and Tengkorak Island (Figure 1). Depths at the sampling sites ranged from 5 to 16 m, depending on the location. The inclusion of multiple islands and depth ranges allows comparison across spatial gradients that may reflect differences in exposure, habitat structure, and potential anthropogenic influence.

The condition of the reefs across all sites varied from fair to excellent, with details on percent coral cover, reef health, and dominant hard coral genera listed in Table 1. Bidong Island (St1-9), Karah Island (St10-12), Gelok Island (St13-15), and Tengkorak Island (St16-18) (Table 1 and Figure 1) were characterized by branching or digitate corals, and some sites featured massive corals such as *Acropora*, *Fungia*, *Porites*, and *Diploastrea*, with coral cover ranging from 11.8% to 78.32%. Variation in coral cover and dominant growth forms among stations represents differences in habitat quality and structural complexity, which are key drivers of reef fish distribution and were therefore incorporated into subsequent analyses.

Similarly, the stations at Karah Island (St10, St11, and St12), Gelok Island (St13, St14, and St15), and Tengkorak Island (St16, St17, and St18) were predominantly dominated by species from the *Acropora* and *Porites* genera. Stations differed in their level of exposure to wave action and human activities, with some sites being more sheltered while others were more exposed, potentially leading to variation in disturbance regimes that may influence coral composition and associated fish assemblages.

Fish survey

A reef fish survey was conducted to document grouper assemblages within coral reef habitats using a modified underwater visual census (UVC) method adapted from English et al. (1997), in which diver observations were supplemented and verified using a forward-facing underwater video camera (Olympus TG-5). Continuous video recording improved detectability and enabled post-survey verification of species identification and counts. Fish counts were recorded in situ by the observer during transect progression, and video footage was subsequently reviewed to confirm identifications and resolve uncertainties rather than to independently generate primary counts, ensuring consistency with standard UVC protocols.

At each station, a single 100 m transect line was deployed, and fish were recorded within a fixed belt transect extending 2.5 m on each side of the line (total width: 5 m). Observations were limited to a standardized vertical observation height of 0.7 m above the substrate, corresponding to the effective visual detection range of the observer-camera system under prevailing underwater visibility conditions. Preliminary underwater calibration indicated that reliable species identification and size discrimination were consistent within this range; individuals beyond this height could not be identified. The vertical limit, therefore, represents the effective detection envelope rather than the full vertical distribution of fish. Based on these dimensions, each transect encompassed a surveyed volume of 350 m^3 (100×5×0.7 m), standardizing detectability among stations.

Table 1. Spatial and ecological characteristics of coral reef survey stations in the Bidong Archipelago. The table includes geographic coordinates (°N, °E), site names, depth (m), percentage of live coral cover, reef condition classification, and dominant coral genera (>5%) recorded at each station

Island	Station	Coordinates (°N, °E)	Site name	Depth (m)	Coral cover (%)	Coral condition	Dominant genera (>5%)
Bidong Island	St1	5.6213 N, 103.056683 E	Pantai Pasir Cina	8.0	57.03	Excellent	*Acropora*, *Fungia*
	St2	5.6253 N, 103.057066 E	Batu Menangis	6.3	33.09	Fair	*Acropora*
	St3	5.6288 N, 103.061850 E	Batu Payung	10.8	26.98	Fair	*Acropora*, *Porites*
	St4	5.6283 N, 103.065883 E	Teluk Air	12.0	56.10	Good	*Porites*, *Diploastrea*
	St5	5.6232 N, 103.070666 E	Dinding Laut	15.2	25.78	Poor	*Diploastrea*
	St6	5.6153 N, 103.070400 E	Christmas Garden	5.8	57.86	Good	*Acropora*, *Montipora, Porites*
	St7	5.6117 N, 103.066554 E	Teluk Belanga	11.5	12.07	Poor	*Acropora*
	St8	5.6110 N, 103.060766 E	Pantai Pasir Tenggara	7.7	11.84	Poor	*Acropora*
	St9	5.6213 N, 103.058616 E	Pantai Pasir Pengkalan	6.6	43.57	Fair	*Acropora*, *Pocillopora*
Karah Island	St10	5.59815 N, 103.062883 E	Pantai Karah	12.0	80.65	Excellent	*Acropora*, *Diploastrea*
	St11	5.5995 N, 103.067180 E	Terumbu Tenggiri	8.0	61.23	Good	*Acropora*, *Diploastrea*
	St12	5.595643 N, 103.064514 E	Terumbu Kerisi	7.0	47.58	Fair	*Acropora*, *Fungia*
Gelok Island	St13	5.6567 N, 103.066583 E	Gelok West	12.2	29.84	Fair	*Pocillopora*
	St14	5.660245 N, 103.068080 E	Gelok North	12.8	17.75	Poor	*Acropora*, *Porites*
	St15	5.65825 N, 103.069933 E	Gelok East	7.6	38.33	Fair	*Acropora*, *Fungia*
Tengkorak Island	St16	5.6657 N, 103.072183 E	Tengkorak West	13.4	55.05	Good	*Acropora*
	St17	5.667932 N, 103.071122 E	Tengkorak North	15.1	26.20	Fair	*Porites*, *Pocillopora, Montipora*
	St18	5.66675 N, 103.073233 E	Tengkorak East	11.8	41.77	Fair	*Montipora*, *Porites*

Each 100 m transect was subdivided into four consecutive 20 m segments to capture fine-scale variability in grouper distribution. Fish counts were recorded separately for each segment prior to progressing forward. Although segments were contiguous, surveys proceeded in a single forward direction, and individuals moving behind the observer were excluded to minimize repeat counts. The 20 m segment length exceeds the typical grouper territory size, reducing recounting. However, because segments are not spatially independent, they were not used as independent replicates in inferential analyses. Instead, segment-level counts (n: 72) were aggregated to derive station-level abundance (n: 18), which represents the primary unit of analysis. Segment-level data were used only for descriptive purposes.

Station-level abundance was calculated as the sum of counts across segments (segment → station). Abundance was expressed as density per unit volume (individuals per 350 m^3), corresponding to the standardized detection envelope. This approach was adopted because observations were constrained within a fixed vertical range (0.7 m), and thus volume-based density more accurately represents the effective sampled space than area-based estimates, which assume full vertical detectability. Equivalent area-based density (individuals per 500 m^2) can be derived for comparison, but was not used for primary inference.

Transects were surveyed in a single continuous pass at a constant swimming speed. Only fish observed ahead of the observer were recorded, and individuals re-entering the transect were excluded. Given the relatively sedentary behavior of groupers, repeated observations were considered unlikely. Surveys were conducted between March and May 2022 during daylight hours (09:00-14:00 h) under comparable sea state and underwater visibility conditions (>4 m). Each station was surveyed once; surveys conducted on separate days reflect logistical constraints rather than temporal replication, and the design represents a spatial comparison among stations.

All surveys were conducted by the same trained observer to minimize inter-observer variability. Video footage and photographs were reviewed post-survey to verify counts and species identifications; discrepancies between in situ observations and video records were cross-checked to ensure consistency, and no systematic differences in abundance estimates were detected during validation. Fish were identified to the lowest possible taxonomic level using published photographic field guides (Allen et al. 2003; Matsunuma et al. 2011; Allen and Erdmann 2012). Detectability may vary with fish size, behavior, and habitat complexity; therefore, small cryptic species or individuals concealed within reef structure may be under-represented.

Coral reef benthic habitat survey

Benthic habitat composition was assessed using the Coral Video Transect (CVT) method following established protocols (Reef Check 2014; Safuan et al. 2015). The CVT was conducted along the same 100 m transect line, depth contour, and reef zone used for the fish surveys to ensure direct spatial correspondence between benthic habitat and fish observations.

The 100 m transect was divided into four consecutive 20 m segments to maintain consistency with the fish survey sampling structure and to ensure systematic spatial coverage along the reef. Video footage was recorded using an underwater camera positioned approximately 0.5 m above the substrate while the diver swam at a constant speed of ~5 m min^{-1} to maintain consistent image scale and sampling effort. A reference bar attached to the camera housing was used to maintain vertical alignment and minimize variation in camera height and field of view.

The CVT was recorded immediately after completion of the fish survey along the same transect to minimize temporal variability and diver disturbance. Close-up photographs were taken of cryptic or morphologically similar coral taxa encountered along the transect to improve taxonomic accuracy during post-processing. Video footage and photographs were later reviewed frame-by-frame to identify benthic categories and estimate percent cover. Percent cover of benthic categories, including live coral cover, was quantified using CPCe (Coral Point Count with Excel extensions) software through a standardized point-count workflow applied to all transects. These CPCe-derived values were used consistently for all analyses and tables (Table 1, Table 5 and Table 6), ensuring a single authoritative coral cover dataset and avoiding duplication with field-based estimates.

Data analysis

Fish image analysis

Fish identification was verified and followed standard taxonomic references, including FishBase (Froese and Pauly 2018), Reef Fish Identification: Tropical Pacific (Allen et al. 2003), regional field guides (Lim et al. 2018), and South China Sea Reference and Repository Center (INOS, Universiti Malaysia Terengganu), which provided supplementary regional records for verification. All video footage was processed in the laboratory and converted into image frames using Video Images Master Pro V1.2.8. To ensure representative coverage and improve counting accuracy, footage from each 20 m transect segment was subsampled by extracting 50 non-overlapping frames. This produced a total of 200 frames per 100 m transect. Extracted frames were saved in JPEG format and analyzed using DotDotGoose software (Version 1.5.1; Ersts 2020; Afiq-Firdaus et al. 2023). All fish visible within each frame were manually counted and recorded. Frame extraction provided analytical subsamples to improve detection and reduce observer bias; frames were not treated as independent ecological replicates. To ensure clarity and consistency, three assemblage metrics were calculated. Relative abundance (%) was defined as the proportion of individuals of each species relative to the total number of Epinephelidae individuals recorded. Density was expressed as the number of individuals per cubic meter (ind m^{-3}) based on the surveyed transect volume. Occurrence (%) represented the proportion of sampling stations at which each species was recorded.

Coral image analysis

Footage from the Coral Video Transect (CVT) surveys was analyzed using Coral Point Count with Excel extensions (CPCe) software version 4.1 to quantify benthic cover (Kohler and Gill 2006). Each transect video was subsampled into 50 non-overlapping frames for analysis. For each frame, 50 randomly distributed points were overlaid, yielding 2,500 points per transect. Points were arranged in a grid (5 rows × 10 columns) to ensure uniform spatial coverage and avoid clustering, with each frame representing approximately 0.6 m^2 of benthic area. Substrate beneath each point was visually classified into standard CPCe categories: coral (C), algae (ALG), other invertebrates (OT), dead coral (DC), and sand/silt/rock (SR). Biotic components were identified to the lowest possible taxonomic level where feasible. Percentage hard coral cover was used to categorize reef condition following the ASEAN-Australia Living Coastal Resources Project criteria: excellent (>75%), good (50-75%), fair (25-50%), and poor (<25%) (Chou et al. 1994).

Statistical analysis

In this study, the Shapiro-Wilk test was applied to assess the normality of ecological variables, including grouper abundance, coral cover, and benthic habitat composition, prior to subsequent statistical analyses (Shapiro and Wilk 1965). This test was selected due to the relatively small sample size and to guide the use of appropriate non-parametric methods when assumptions of normality were not met. Given the small sample size (n: 18) and the non-normal distribution of most variables ($p<0.05$), non-parametric methods were consistently applied throughout to ensure robust inference.

Canonical correspondence analysis was employed to examine relationships between grouper assemblages and environmental variables (Prodon and Lebreton 1994). The species matrix consisted of grouper abundance data across sampling stations, while the environmental matrix included coral genus composition and benthic habitat categories. Grouper abundance data were square-root transformed to reduce the influence of dominant species, and environmental variables were standardized prior to analysis. Rare species (singletons) were down-weighted to reduce their disproportionate influence on ordination results, and a sensitivity analysis confirmed that their inclusion did not substantially alter the overall patterns observed.

The statistical significance of the CCA model and its canonical axes was evaluated using permutation tests with 999 permutations. Non-metric multidimensional scaling based on Bray-Curtis dissimilarity was used to visualize patterns in grouper assemblage structure across sampling sites (Field et al. 1982; Somerfield 2008). The NMDS analysis was run with two dimensions (k: 2) and multiple random starts to ensure convergence on a stable solution. Stress values were used to assess the goodness-of-fit of the ordination (Field et al. 1982). Permutational multivariate analysis of variance was applied to test for differences in grouper community composition in relation to environmental variables (Anderson 2001). The analysis was performed using 999 permutations based on Bray-Curtis dissimilarity. The proportion of variance explained (R^2), pseudo-F statistics, and associated p-values were used to evaluate the significance of environmental effects (Anderson 2001).

To further quantify relationships between grouper assemblages and ecological parameters, Spearman's rank correlation analysis was applied consistently, as the data did not meet normality assumptions. Correlation coefficients were visualized using heatmaps to facilitate interpretation of the strength and direction of associations between grouper metrics and coral-related variables. All statistical analyses were conducted using R (version 4.3.3) (R Development Core Team 2014).

The integration of multivariate ordination, hypothesis testing, and non-parametric correlation analysis provides a robust and coherent framework for identifying key habitat features and understanding the ecological dynamics governing grouper distribution and habitat associations. All analyses were conducted at the station level (n: 18), using abundance standardized per survey volume. Where data were initially recorded at the segment level, values were aggregated (segment → station) prior to analysis to avoid pseudo-replication and ensure independence of sampling units (Bart et al. 1998).

RESULTS AND DISCUSSION

Biodiversity of Epinephelidae families

A total of 11 reef fish species from four genera within the family Epinephelidae were recorded across 18 sampling stations around Bidong Island and nearby islands (Table 2). In total, 388 Epinephelidae individuals were observed during the survey. Species composition varied among stations. When expressed as the proportional contribution of individuals recorded at each station relative to the total Epinephelidae abundance across all stations, station-level contributions ranged from 3.26% to 8.70% (Figure 2.A). Three species, *Cephalopholis boenak*, *C. cyanostigma*, and *C. formosa*, were recorded at all sampling stations (Table 3), indicating their widespread distribution and dominance within the study area. Abundance was standardized per station to a surveyed volume of 350 m^3. Higher abundances were observed at stations with relatively greater live coral cover and diverse coral assemblages, although structural complexity was not directly quantified in this study. The assemblage was dominated by *C. formosa* (27%), *C. boenak* (26%), and *C. cyanostigma* (24%) (Figure 2.B). In contrast, *Cephalopholis microprion*, *Epinephelus merra*, *Chromileptes altivelis*, *E. areolatus*, *E. corallicola*, and *E. malabaricus* each accounted for less than 5% of total Epinephelidae abundance. In terms of conservation status, ten recorded species are classified as Least Concern (LC) by the International Union for Conservation of Nature (IUCN), indicating relatively stable population trends. One species, *Chromileptes altivelis*, is categorized as Data Deficient (DD), reflecting insufficient information to adequately assess its conservation status (Table 2).

Table 2. Fishes list of family Epinephelidae observed in Bidong Archipelago, and grouped according to their IUCN status

Species	Fish images	Common name	IUCN status
Cephalopholis boenak (Bloch, 1790)		Chocolate hind	LC
Cephalopholis cyanostigma (Valenciennes, 1828)		Bluespotted hind	LC
Cephalopholis formosa (Shaw, 1812)		Bluelined hind	LC
Cephalopholis microprion (Bleeker, 1852)		Freckled hind	LC
Chromileptes altivelis (Valenciennes, 1828)		Humpback grouper	DD
Epinephelus areolatus (Forsskål, 1775)		Areolate grouper	LC
Epinephelus corallicola (Valenciennes, 1828)		Coral grouper	LC
Epinephelus fasciatus (Forsskål, 1775)		Blacktip grouper	LC
Epinephelus malabaricus (Bloch & Schneider, 1801)		Malabar grouper	LC
Epinephelus merra (Bloch, 1793)		Honeycomb grouper	LC
Plectropomus maculatus (Bloch, 1790)		Spotted coral grouper	LC

Note: EN: Endangered, NT: Near Threatened, VU: Vulnerable, LC: Least Concern, DD: Data Deficient, NE: Not Evaluated

Table 3. Occurrence (presence/absence) of grouper species (family: Epinephelidae) across 18 sampling stations at Bidong Archipelago

Fish species	Bidong Island									Karah Island			Gelok Island			Tengkorak Island		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Cephalopholis boenak	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Cephalopholis cyanostigma	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Cephalopholis formosa	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
Cephalopholis microprion	/	/	-	-	-	-	/	/	-	-	/	-	-	/	/	-	-	-
Chromileptes altivelis	-	-	/	-	/	-	-	-	-	-	-	-	-	-	-	-	-	-
Epinephelus areolatus	-	/	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Epinephelus corallicola	-	-	-	-	-	-	/	-	-	-	-	-	-	-	-	-	-	-
Epinephelus fasciatus	/	/	/	/	/	-	/	-	-	-	/	/	/	/	-	-	/	/
Epinephelus malabaricus	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	/
Epinephelus merra	-	-	-	-	-	-	/	-	-	-	-	/	-	-	/	-	-	-
Plectropomus maculatus	/	/	/	-	/	/	/	-	-	/	-	-	-	/	/	-	/	/

Note: Presence is indicated by "/" and absence by "-"

Among the recorded species, *C. formosa* was the most abundant (104 individuals), followed by *C. boenak* (101 individuals) and *C. cyanostigma* (88 individuals). The least abundant species were *E. areolatus*, *E. corallicola*, and *E. malabaricus*, each represented by only a single individual. Bidong Island exhibited the highest overall grouper density (0.176 ind/m^{-3}) compared to Karah Island (0.058 ind/m^{-3}), Gelok Island (0.055 ind/m^{-3}), and Tengkorak Island (0.062 ind/m^{3}). Across all islands, *C. formosa* contributed the greatest proportion of the total density (0.049 ind/m^{-3} at Bidong Island), whereas large-bodied species such as *C. altivelis*, *E. areolatus*, and *E. corallicola* were rarely encountered (Table 4). The distribution of species was not uniform among islands, with Bidong Island showing consistently higher densities for most species, particularly within the genus *Cephalopholis*. In contrast, low densities were recorded for several species across Karah Island, Gelok Island, and Tengkorak Island, indicating potential site-specific habitat preferences.

Coral community structure

Bidong Island and nearby islands are rich in diverse coral reef ecosystems (Figure 3 and Table 5). There are as many as ten dominant coral genera that have been identified on Bidong Island and its surroundings. Among them, *Acropora* appeared as the most abundant genus, accounting for more than 46% of the total coral cover in the area. In contrast, *Goniastrea* exhibited the lowest coverage at just 0.7% among the ten selected dominant coral genera, as shown in Table 5. In addition, all ten identified coral genera were present at specific sites, particularly at Gelok Island (stations St14 and St15) and Tengkorak Island (station St18). Research findings reveal that the *Acropora* is the most dominant genus and its ecological relevance in the coral community of Bidong Island and the archipelago. Furthermore, *Acropora* dominance can improve the structure and function of coral reef ecosystems and has the potential to alter biodiversity and habitat availability for associated marine life.

Relative abundance (%) of dominant coral genera across sampling stations in the Bidong Archipelago, including Bidong Island, Gelok Island, Karah Island, and Tengkorak Island. Each stacked bar represents the proportional contribution of coral genera at individual stations (St1-St18). The most dominant genera include *Acropora*, *Porites*, *Pocillopora*, *Favia*, and *Montipora*, with noticeable spatial variation among islands and stations.

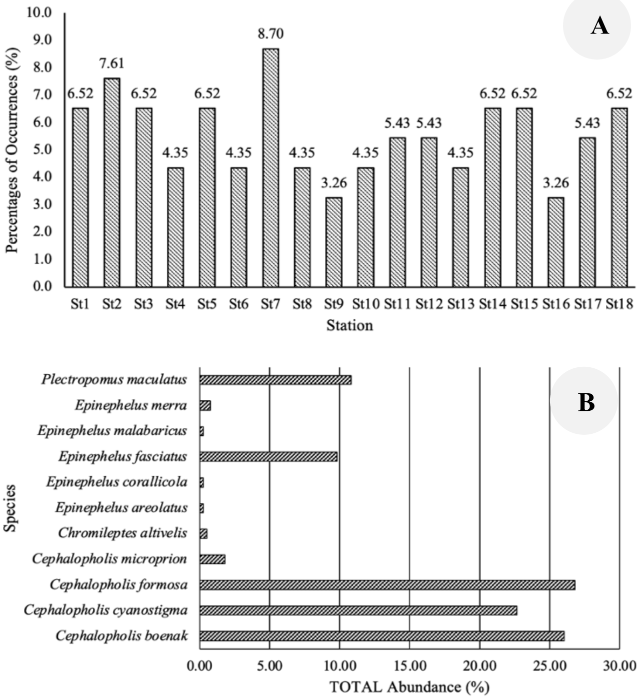


Figure 2. A. Percentages of occurrences (%), B. Percentages of abundance (%) of grouper species among stations

Table 4. Number of species and abundance, density (ind.m^{-3}) of Epinephelidae family in Bidong Archipelago

Species	Total abundance	Bidong Island (9 stations)	Karah Island (3 stations)	Gelok Island (3 stations)	Tengkorak Island (3 stations)
Cephalopholis boenak	101	0.043	0.017	0.013	0.017
Cephalopholis cyanostigma	88	0.038	0.014	0.015	0.011
Cephalopholis formosa	104	0.049	0.013	0.014	0.017
Cephalopholis microprion	7	0.004	0.001	0.002	0.000
Chromileptes altivelis	2	0.002	0.000	0.000	0.000
Epinephelus areolatus	1	0.001	0.000	0.000	0.000
Epinephelus corallicola	1	0.001	0.000	0.000	0.000
Epinephelus fasciatus	38	0.016	0.004	0.004	0.010
Epinephelus malabaricus	1	0.000	0.000	0.000	0.001
Epinephelus merra	3	0.001	0.001	0.001	0.000
Plectropomus maculatus	42	0.021	0.004	0.006	0.006

Table 5. Percentage coral genus (%) based on 10 dominant coral genera in each station in Bidong Archipelago

Coral genus	Station (%)																	
	Bidong Island									Karah Island			Gelok Island			Tengkorak Island		
	St1	**St2**	**St3**	**St4**	**St5**	**St6**	**St7**	**St8**	**St9**	**St10**	**St11**	**St12**	**St13**	**St14**	**St15**	**St16**	**St17**	**St18**
Acropora	11.87	22.43	9.06	1.39	-	31.92	7.42	5.14	37.03	57.81	8.12	21.48	13.05	2.51	6.35	53.38	0.91	2.45
Diploastrea	-	-	0.23	18.23	9.42	0.53	-	-	-	-	0.48	-	-	0.05	2.83	-	-	1.79
Favites	0.03	-	0.53	1.58	1.29	3.48	0.13	0.01	-	0.17	0.16	0.24	0.27	3.25	3.01	0.03	0.38	3.40
Fungia	35.61	8.22	0.01	0.51	-	-	0.07	4.64	0.04	1.27	2.02	12.44	5.98	0.17	0.07	0.18	0.02	0.13
Galaxea	-	-	0.21	-	0.21	0.30	0.10	-	-	0.10	20.82	0.09	0.03	0.65	1.66	0.19	0.27	5.81
Goniastrea	-	-	0.46	0.02	0.28	-	0.02	-	-	-	0.67	-	0.02	1.71	4.62	0.06	-	1.97
Montipora	2.65	-	0.47	1.07	0.14	5.56	-	-	0.03	0.58	-	1.27	0.43	0.85	2.69	0.78	4.55	9.04
Pavona	0.79	0.03	0.05	-	0.03	-	-	-	-	1.07	0.45	0.34	4.95	0.03	0.44	0.04	-	4.09
Pocillopora	3.76	2.35	-	0.72	0.21	0.59	3.08	1.39	5.68	1.30	1.28	0.40	1.88	4.57	0.45	0.14	4.68	0.97
Porites	0.39	0.06	12.55	27.76	2.15	9.62	1.11	0.14	0.67	4.51	7.09	1.30	0.93	1.96	8.70	0.16	13.29	5.27

Table 6. Percentage benthic cover (%) in each station in Bidong Archipelago

Benthic cover	Station (%)																	
	Bidong Island									Karah Island			Gelok Island			Tengkorak Island		
	St1	**St2**	**St3**	**St4**	**St5**	**St6**	**St7**	**St8**	**St9**	**St10**	**St11**	**St12**	**St13**	**St14**	**St15**	**St16**	**St17**	**St18**
C	57.03	33.09	26.98	56.10	25.78	57.86	12.07	11.84	43.57	80.65	61.23	47.58	29.84	17.75	38.33	55.05	26.20	41.77
ALG	5.74	3.51	-	-	-	0.02	-	0.19	-	-	-	-	0.03	-	-	1.66	-	0.02
OT	0.20	0.09	0.25	0.78	0.04	0.48	27.64	0.52	0.01	3.02	6.92	8.76	1.70	7.57	3.19	0.72	0.23	0.34
DC	24.75	62.43	60.13	39.86	59.96	19.26	49.76	87.39	52.66	15.73	22.21	30.78	65.38	61.62	41.17	40.64	73.48	56.87
SR	12.30	0.87	5.22	3.09	14.13	22.35	10.51	-	3.76	0.60	9.63	12.88	3.05	13.05	17.31	1.93	0.09	1.00

Note: C: Coral, ALG: Algae, OT: Other Invertebrates, DC: Dead Coral, SR: Sand, Silt, and Rock

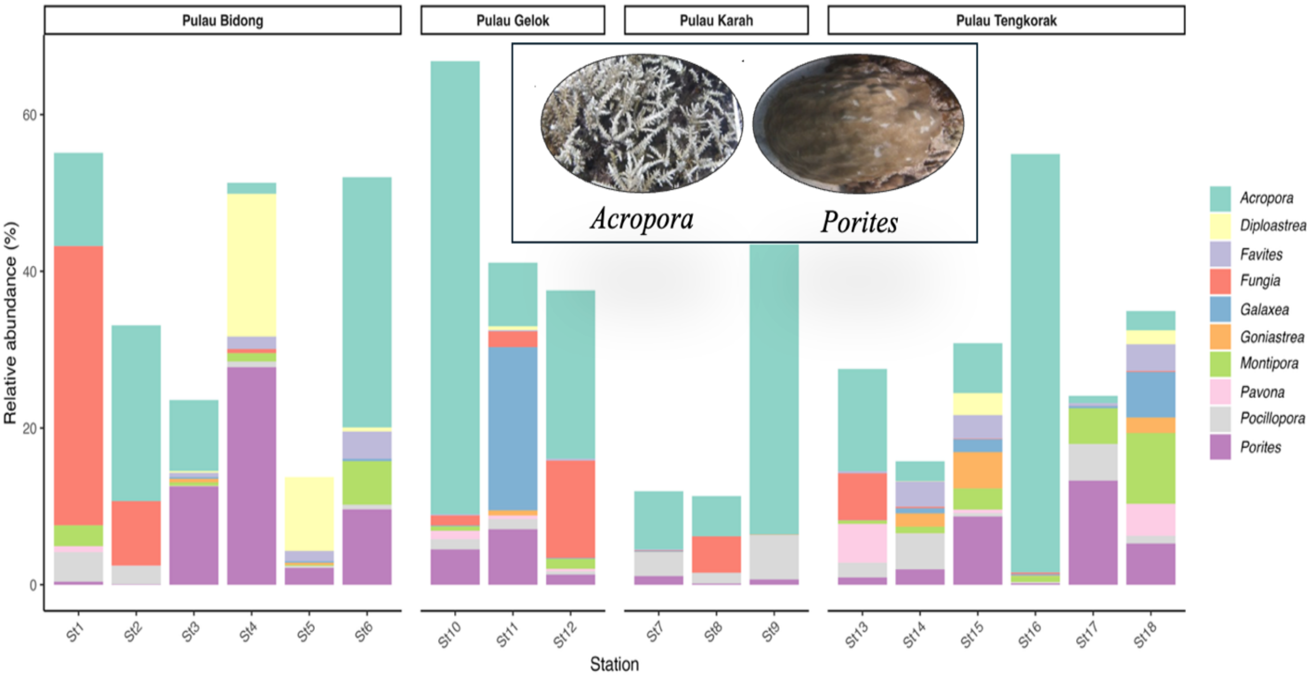


Figure 3. Relative abundance (%) of hard coral genera across survey stations in the Bidong Island archipelago, including Bidong Island, Gelok Island, Karah Island, and Tengkorak Island. Each bar represents the proportional composition of coral genera recorded at individual stations (St1-St18). The assemblages were predominantly dominated by *Acropora*, followed by *Porites*, *Montipora*, and *Favia*, although their contributions varied among locations and stations, reflecting spatial heterogeneity in benthic community structure. Representative colonies of dominant coral genera observed during the survey: *Acropora*, exhibiting characteristic branching morphology and high structural complexity, and *Porites*, displaying a massive growth form. Both genera contribute significantly to reef habitat formation and the support of fish assemblages

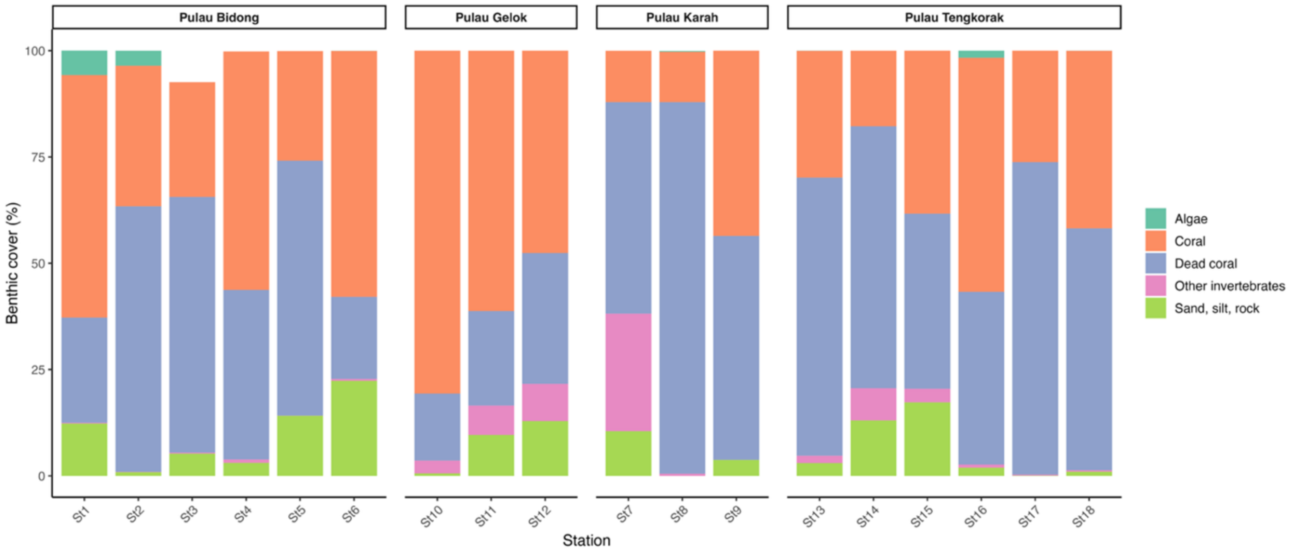


Figure 4. Benthic cover composition (%) across sampling stations in the Bidong archipelago, including Bidong Island, Gelok Island, Karah Island, and Tengkorak Island. Stacked bars show the percentage cover of major benthic categories: live coral, dead coral, algae, other invertebrates, and sand/silt/rock at each station (St1-St18). Dead coral and live coral dominate most sites, with variability in substrate composition reflecting differences in reef condition among islands

Benthic habitat structure

Most benthic cover at Bidong Archipelago consisted of abiotic components (Figure 4 and Table 6), particularly dead coral (DC), which accounted for approximately 48.2% of total benthic points. In contrast, live hard coral comprised about 40.3% of benthic and exhibited pronounced spatial variability among sampling stations. At Bidong Island, moderate live coral cover was recorded at stations St2, St3, St5, and St9, whereas stations St7 and St8 showed very low live coral cover and were dominated by dead coral substrate.

High live coral cover (>50%) was observed at St1, St4, and St6. Gelok Island exhibited moderate live coral cover at stations St13-St15, while Tengkorak Island showed moderate cover at St17 and St18. Although dead coral predominated across much of the study area, substantial site-specific variation in live coral cover was evident. Live coral exceeded ~50% at selected locations, notably at Bidong Island (St1, St4, St6), Karah Island (St10 and St11), and Tengkorak Island (St16).

Benthic habitat structure

Relationship between grouper assemblages, coral genera, and benthic cover

Non-metric multidimensional scaling (NMDS) analysis indicated that grouper assemblages were generally weakly structured across sampling sites, with substantial overlap observed in ordination space (Figure 5). In relation to coral genus composition, the distribution of samples showed high variability in species composition, with no clear clustering pattern evident (Figure 5.A). Similarly, the NMDS based on benthic cover variables showed only moderate structuring, with considerable overlap among sites despite a good ordination fit (stress: 0.115), suggesting weak differentiation of assemblages along benthic gradients (Figure 5.B).

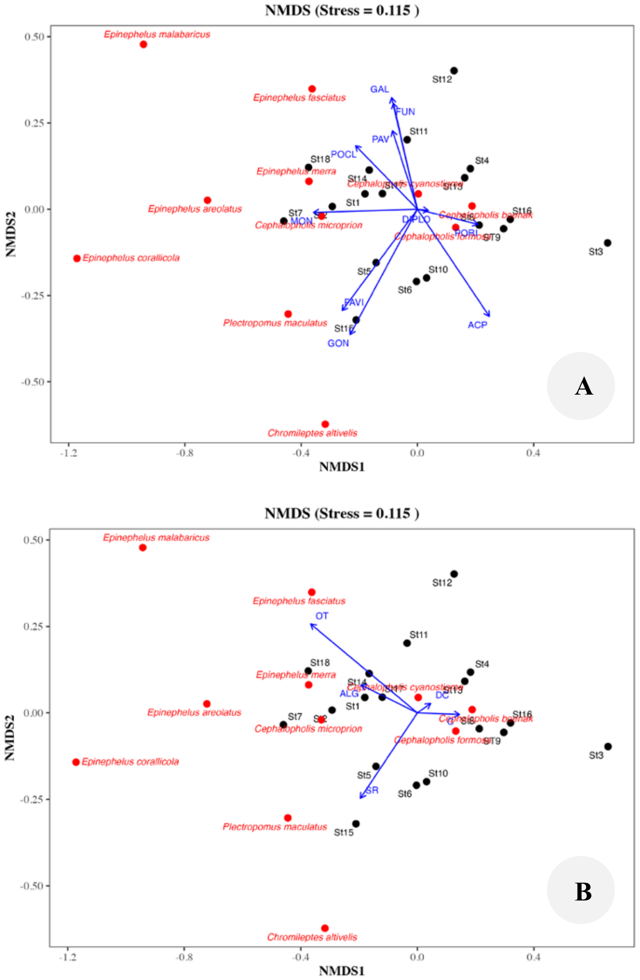


Figure 5. Non-metric multidimensional scaling (NMDS) ordination of grouper assemblages based on Bray-Curtis dissimilarity. A. Relationship between grouper assemblages and coral genus composition, showing substantial overlap among sites and weak structuring with no clear clustering. B. Relationship between grouper assemblages and benthic cover variables; points represent sampling sites, red symbols indicate grouper species, and blue vectors denote fitted benthic variables. Stress: 0.115

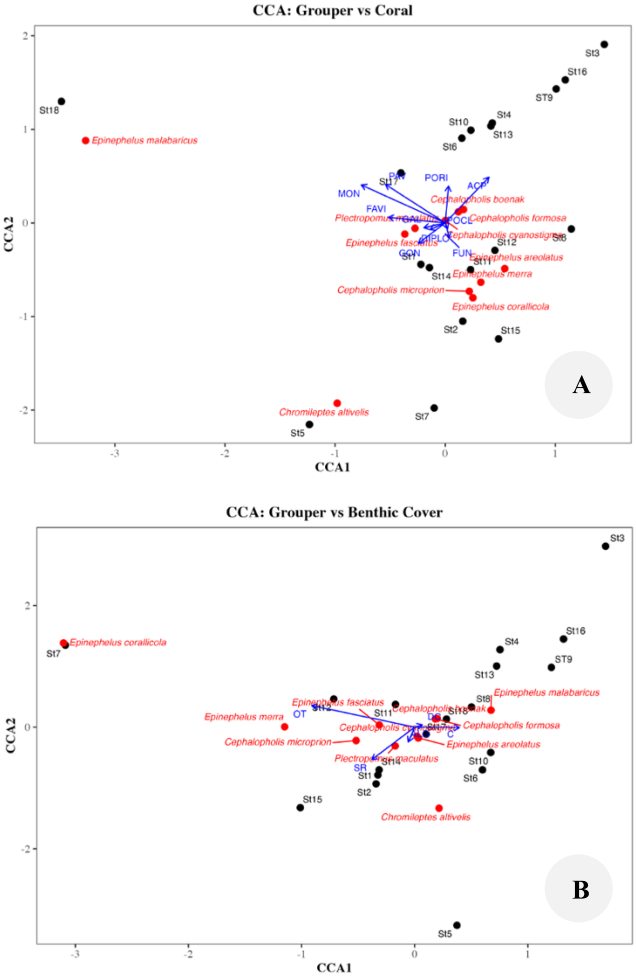


Figure 6. Canonical Correspondence Analysis (CCA) biplots showing the relationships between grouper assemblages and environmental variables. A. grouper species in relation to coral genera, B. grouper species in relation to benthic cover categories. Arrows represent environmental variables (coral genera or benthic cover components), while points represent grouper species (red) and sampling sites (black). The direction and length of arrows indicate the gradient and relative influence of each variable on species distribution

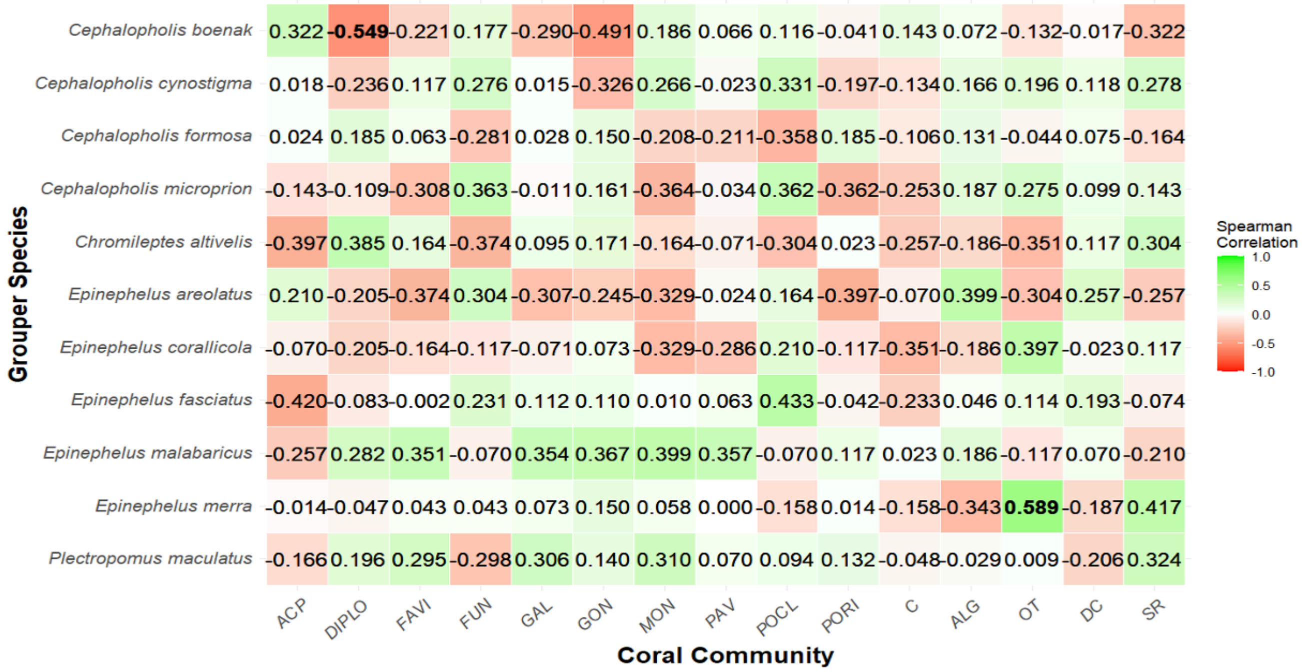
Canonical Correspondence Analysis (CCA) further examined the relationships between grouper assemblages and environmental variables (Figure 6). For coral genera, the model explained 48.9% of the variation (total inertia: 0.640), but the overall relationship was not statistically significant (F: 0.669, p: 0.942), indicating weak species-environment associations (Figure 6.A). For benthic cover, the model explained 36.0% of the variation but remained non-significant overall (F: 1.353, p: 0.200). The first canonical axis showed a marginal trend towards significance (F: 3.311, p: 0.067), suggesting a potential ecological gradient influencing species distribution, although this did not reach statistical significance (Figure 4.B). In both analyses, the ordination biplots showed no clear directional alignment between grouper species and environmental variables, reinforcing the weak structuring effect.

Permutational multivariate analysis of variance (PERMANOVA) supported these findings (Table 7). Coral genera explained 49.17% of the variation in grouper assemblages (R^2: 0.492), but the effect was not statistically significant (F: 0.677, p: 0.811). Similarly, benthic cover explained 43.43% of the variation (R^2: 0.434) and showed a marginally non-significant effect (F: 1.842, p: 0.078), indicating a weak but potentially meaningful ecological relationship.

Overall, the combined results from NMDS, CCA, and PERMANOVA consistently demonstrate that grouper assemblages exhibit high spatial variability but are not strongly structured by coral genus composition or benthic cover. While benthic variables, particularly the “other invertebrates” category, show some influence, these relationships remain weak or marginal. This suggests that other environmental or ecological factors may play a more important role in determining grouper distribution and community structure.

Diversity of grouper correlation with coral community and benthic habitat structure

Spearman rank correlation coefficient (Figure 7) between grouper species abundance and coral community structure. Correlation coefficients range from -1 to 1 and are visualized using color gradients, with green indicating positive correlations and red indicating negative correlations. Color intensity reflects the magnitude of the correlation. All correlations were non-significant (p>0.05) and are therefore interpreted as ecological tendencies rather than statistically confirmed relationships. *C. boenak* exhibited a moderate negative correlation with *Diploastrea*, dominated coral assemblages (“*DIPLO*”; r_s: -0.549), indicating a tendency for reduced abundance in reefs dominated by massive *Diploastrea* colonies. The species also showed a moderate negative correlation with *Montipora* (“*MON*”; r_s: −0.491) and a very weak negative correlation with *Porites* (“*PORI*”; r_s: −0.041), suggesting little to no association with *Porites*-dominated habitats. *E. merra* showed a moderate positive correlation with “SR” (r_s: 0.417) and a stronger positive correlation with “OT” (r_s: 0.589). These associations indicate a tendency for this species to occur in reef areas characterized by these habitat categories, without implying broader habitat heterogeneity beyond the definitions of the codes used. *C. altivelis* displayed a moderate negative correlation with *Acropora* (“*ACP*”; r_s: −0.397), suggesting reduced occurrence in branching coral-dominated habitats.



	ACP	DIPLO	FAVI	FUN	GAL	GON	MON	PAV	POCL	PORI	C	ALG	OT	DC	SR
Cephalopholis boenak	0.322	**-0.549**	-0.221	0.177	-0.290	-0.491	0.186	0.066	0.116	-0.041	0.143	0.072	-0.132	-0.017	-0.322
Cephalopholis cynostigma	0.018	-0.236	0.117	0.276	0.015	-0.326	0.266	-0.023	0.331	-0.197	-0.134	0.166	0.196	0.118	0.278
Cephalopholis formosa	0.024	0.185	0.063	-0.281	0.028	0.150	-0.208	-0.211	-0.358	0.185	-0.106	0.131	-0.044	0.075	-0.164
Cephalopholis microprion	-0.143	-0.109	-0.308	0.363	-0.011	0.161	-0.364	-0.034	0.362	-0.362	-0.253	0.187	0.275	0.099	0.143
Chromileptes altivelis	-0.397	0.385	0.164	-0.374	0.095	0.171	-0.164	-0.071	-0.304	0.023	-0.257	-0.186	-0.351	0.117	0.304
Epinephelus areolatus	0.210	-0.205	-0.374	0.304	-0.307	-0.245	-0.329	-0.024	0.164	-0.397	-0.070	0.399	-0.304	0.257	-0.257
Epinephelus corallicola	-0.070	-0.205	-0.164	-0.117	-0.071	0.073	-0.329	-0.286	0.210	-0.117	-0.351	-0.186	0.397	-0.023	0.117
Epinephelus fasciatus	-0.420	-0.083	-0.002	0.231	0.112	0.110	0.010	0.063	0.433	-0.042	-0.233	0.046	0.114	0.193	-0.074
Epinephelus malabaricus	-0.257	0.282	0.351	-0.070	0.354	0.367	0.399	0.357	-0.070	0.117	0.023	0.186	-0.117	0.070	-0.210
Epinephelus merra	-0.014	-0.047	0.043	0.043	0.073	0.150	0.058	0.000	-0.158	0.014	-0.158	-0.343	**0.589**	-0.187	0.417
Plectropomus maculatus	-0.166	0.196	0.295	-0.298	0.306	0.140	0.310	0.070	0.094	0.132	-0.048	-0.029	0.009	-0.206	0.324

Figure 7. Spearman correlation heatmap illustrating the relationship between grouper species abundance and various coral community components across surveyed stations. Positive correlations (green) indicate higher species abundance associated with specific coral categories, while negative correlations (red) indicate avoidance or low association

Table 7. Results of permutational multivariate analysis of variance (PERMANOVA) testing the effects of environmental variables on grouper assemblages based on Bray-Curtis dissimilarity. Coral genus: explaining 50.5% of the variation with a non-significant effect (p: 0.811). Benthic cover variables: explaining 43.43% of the variation with a marginally non-significant effect (p: 0.078)

Factor	Df	Sum of squares	R^2	F	p-value
Coral genus	10	0.31321	0.4917	0.6771	0.811
	7	0.32378	0.5083		
	17	0.63699	1.0000		
Benthic cover	5	0.27661	0.4343	1.8422	0.078
	12	0.36038	0.5658		
	17	0.63699	1.0000		

Discussion

Distribution of Epinephelidae assemblages

The dominance of the genus *Cephalopholis* within the Epinephelidae assemblages of the Bidong Archipelago is consistent with its ecological role as a primary mesopredator in Indo-Pacific coral reefs (Stewart and Jones 2001; Donaldson 2002). The dominance of the genus *Cephalopholis* within the Bidong Archipelago is consistent with its established role as a primary mesopredator in shallow-water coral reef assemblages across the Indo-Pacific (Stewart 1998; Pears 2005). At Lizard Island on the Great Barrier Reef, for instance, species such as *C. boenak* and *C. cyanostigma* are among the most abundant piscivorous serranids, reaching high densities that are over 90% piscivorous and significantly impact prey mortality (Stewart 1998).

Similar patterns of dominance are observed in the Gulf of Aqaba, where *Cephalopholis* species exhibit clear habitat partitioning across the reef profile, with *C. argus* dominating shallow reef tables and *C. miniata* occupying deeper coral knolls, supported by a distinct interspecific dominance hierarchy (Shpigel and Fishelson 1989, 1991). This ecological persistence is further evidenced by biogeographic comparisons between the Seychelles and the Great Barrier Reef, where these "cryptic" serranids remain a stable and abundant fixture of the predator guild despite regional variations in recruitment and lifespan (Pears 2005). Furthermore, the capacity of the genus to dominate is highlighted by the case of *C. argus* in Hawaii; after being introduced into a reef system with fewer native competitors than its original habitat in Moorea, it underwent "competitive release" to become the dominant apex predator on many reefs (Meyer and Dierking 2011).

Recent surveys at Bidong Island have documented a high diversity of reef fishes, recording 101 species across 30 families, confirming the archipelago's status as a critical local-scale diversity hotspot (Afiq-Firdaus et al. 2021, 2023). The widespread distribution and high densities of *C. cyanostigma*, *C. boenak*, and *C. formosa*, species known for strong site fidelity, suggest that they are the principal serranids utilizing available resources in these South China Sea habitats (Afiq-Firdaus et al. 2021, 2023). The grouper assemblage in the Bidong Island archipelago is primarily composed of species categorized as Least Concern by the IUCN, including *C. cyanostigma*, *C. boenak*, and *C. formosa* (Barik et al. 2018; Fricke et al. 2018; Prihatiningsih et al. 2019; Pranata et al. 2022). While this suggests stable global population trends, these species remain highly susceptible to localized fishing pressure from artisanal and small-scale fisheries (Yulianto et al. 2013; Astuti et al. 2016). The inherent life-history traits of serranids, such as longevity, late sexual maturation, and high site fidelity, often lead to a disconnect between global conservation status and local population health (Mitcheson et al. 2013; Tuohy et al. 2023). Research indicates that approximately 25% of all grouper species are currently threatened or near-threatened, emphasizing that even LC-listed taxa require careful local monitoring to prevent overexploitation (Mitcheson et al. 2013; Hackradt et al. 2014). Particular concern is the presence of the humpback grouper *C. altivelis*. This species is a primary target of the high-value live reef fish trade in Southeast Asia, where it commands premium prices in markets such as Hong Kong and Southern China (Scales et al. 2007; Sugama et al. 2017). Due to its extreme commercial value and susceptibility to overfishing, *C. altivelis* has become rare in many parts of its range (Sugama et al. 2017).

These ecological patterns are consistent with the multivariate results. The NMDS ordination revealed substantial overlap among sampling stations and no clear clustering of assemblages in relation to coral genus composition, indicating weak spatial structuring. Similarly, PERMANOVA results showed that coral genus composition explained 49.17% of the variation in grouper assemblages but was not statistically significant, reinforcing the absence of strong habitat-driven separation. Together, these findings suggest that while habitat variables contribute to assemblage variability, they do not exert a dominant or deterministic influence at the scale examined.

The central positioning of species such as *C. cyanostigma* and *C. formosa* in the NMDS ordination supports their classification as generalists, characterized by weak specialization toward specific coral genera (Donaldson 2002). Such ecological flexibility likely enables these species to maintain stable populations across varying reef conditions, a key advantage in dynamic or disturbed environments (Komyakova et al. 2013; Montgomery et al. 2021).

In contrast, *C. boenak* exhibited a clearer association with structurally complex habitats, particularly branching coral assemblages such as *Acropora*, as indicated by its directional pattern in the ordination space and its relationship with habitat variables in the Canonical Correspondence Analysis. Branching corals provide high structural complexity and smaller inter-branch spaces that are critical for predator avoidance, recruitment success, and ambush foraging efficiency in many grouper species (Nanami et al. 2013; Hempson et al. 2017).

Despite the weak overall structuring detected by NMDS and PERMANOVA, habitat quality, particularly live coral cover, remains an important ecological driver at finer scales. Higher grouper densities were consistently recorded at stations with elevated live coral cover, particularly at Bidong Island, compared to nearby islands such as Karah Island and Tengkorak Island, suggesting superior habitat conditions. In contrast, degraded sites dominated by dead coral or unconsolidated substrates supported fewer individuals. These findings reinforce the well-established paradigm that structurally complex reef habitats enhance fish diversity and biomass by providing essential refuge and optimized ambush sites for predatory species (Eggleston et al. 1997; Zeller 1997; Richardson et al. 2017).

The combined evidence from NMDS, PERMANOVA, and CCA indicates that grouper assemblages in the Bidong Island archipelago are shaped by a combination of generalist species resilience and localized habitat associations rather than strong, genus-specific coral dependence. While generalist *Cephalopholis* species can persist across a range of habitat conditions, the apparent specialization of *C. boenak* toward *Acropora*-dominated reefs highlights the ecological importance of maintaining coral structural complexity. Given the vulnerability of branching corals to environmental disturbances, the preservation of these habitats is critical for sustaining the biomass and diversity of Epinephelidae assemblages in the Bidong Island archipelago (Nanami et al. 2013; Afiq-Firdaus et al. 2023).

Habitat structure and spatial distribution

Reef fish assemblages are intrinsically linked to coral reef habitats, which serve as essential shelter, feeding grounds, and reproductive sites (Liu and Sadovy 2005). In this study, grouper assemblages were recorded within shallow reef environments (5-16 m depth), where environmental conditions typically support coral growth and high structural complexity. Within this depth range, variations in grouper density and species composition among stations were more closely aligned with differences in benthic composition and coral community structure than with depth alone. This aligns with broader ecological patterns where depth often drives shifts in benthic assemblages, which subsequently exert a primary influence on the associated reef fish community. For example, in the Great Barrier Reefs, habitat complexity and the presence of specific coral forms (like branching corals) explained a significant portion of the variation in fish community structure (Komyakova et al. 2013). While depth was a factor, the "niche breadth" and specialization of reef fish often related more to the type of benthic cover available (Jankowski 2022).

Groupers were consistently associated with coral-dominated habitats, reflecting their ecological role as predatory species that rely on the structural complexity of reefs for refuge and hunting (Pothin et al. 2004). High structural complexity characterized by features such as coral bommies, overhangs, and crevices is a key driver of fish species richness and abundance. Canonical Correspondence Analysis indicated spatial structuring along habitat gradients, distinguishing coral-dominated substrates from sites characterized by dead coral or other invertebrates.

The CCA further examined these relationships (Figure 6). For coral genera, the model explained 48.9% of the variation (total inertia: 0.640), though the overall relationship was not statistically significant (F: 0.669, p: 0.942), indicating relatively weak species-environment associations at this scale (Figure 6.A). For benthic cover, the model explained 36.0% of the variation but also remained non-significant (F: 1.353, p: 0.200) (Figure 6.B). However, the first canonical axis showed a marginal trend (F: 3.311, p: 0.067), suggesting a potential ecological gradient influencing distribution. In many reef systems, the three-dimensional complexity provided by foundation species like corals increases the availability of predation refuges, resulting in more heterogeneous fish assemblages (Smallhorn-West et al. 2017).

Species-level ordination suggested that *E. malabaricus* was primarily associated with coral-dominated habitats. While adults of this species are known generalists capable of inhabiting rocky reefs, estuaries, and even sandy/muddy bottoms up to 150 m deep, their presence in coral-rich areas highlights a reliance on these productive environments during specific life stages (Mwijage et al. 2018; Manojkumar et al. 2019). In contrast, *E. corallicola* and *E. merra* aligned more closely with other invertebrate and unconsolidated substrates. This is consistent with the known ecology of *E. corallicola*, which frequently occurs in shallow silty reef habitats (Rhodes et al. 2018), and *E. merra*, which is often associated with reef flats, lagoon habitats, and rubble zones (Pothin et al. 2004; Crochelet 2015).

Spearman rank correlation coefficient (Figure 7) further illustrated these ecological tendencies. *C. boenak*, a species known to be diurnally active and closely associated with coral crevices (Liu and Sadovy 2005) exhibited moderate negative correlations with Diploastrea-dominated (r_s: -0.549) and *Montipora* (r_s: -0.491) assemblages. *E. merra* showed positive correlations with "SR" (r_s: 0.417) and "OT" (r_s: 0.589), reinforcing its tendency to occupy varied reef categories. *C. altivelis* displayed a moderate negative correlation with *Acropora* (r_s: -0.397), suggesting a reduced occurrence in branching coral-dominated habitats, possibly due to its preference for larger crevices or specific refuge types not provided by dense branching structures. All correlations were non-significant ($p>0.05$) and are therefore interpreted as ecological tendencies rather than statistically confirmed relationships.

Several limitations should be considered. The study was based on a single survey per station, which may not capture temporal variability in assemblage structure. Detection probability may have varied among species and habitat types, potentially influencing density estimates. In addition, structural complexity was not directly quantified, limiting the ability to explicitly test its influence on assemblage patterns. However, this study establishes a robust baseline for grouper assemblages in the Bidong Island archipelago and demonstrates that assemblage structure is weakly associated with coral and benthic habitat variables at the spatial scale examined. The findings suggest that additional factors such as microhabitat complexity, prey availability, or anthropogenic pressures may play a more important role in shaping grouper distribution. Future studies incorporating repeated temporal sampling and direct quantification of habitat complexity are recommended to better resolve the ecological drivers of grouper assemblages in coral reef ecosystems.

In conclusion, this study recorded 11 grouper species across Bidong Archipelago, providing a baseline inventory of species composition, relative abundance, and spatial distribution. Based on transect-based density estimates (individuals m^{-3}), *C. boenak*, *C. formosa*, and *C. cyanostigma* were the most abundant species across sampling stations, with the highest overall densities observed at Bidong Island. Multivariate analyses consistently indicated weak spatial structuring of grouper assemblages. NMDS ordination showed substantial overlap among sampling stations, with no clear clustering patterns in relation to coral genus composition or benthic habitat variables. PERMANOVA results further supported this, with coral genera explaining a moderate proportion of variation (R^2: 0.492) but not statistically significant (p: 0.811), while benthic cover showed a marginal but non-significant effect (R^2: 0.434, p: 0.078). Canonical Correspondence Analysis (CCA) similarly indicated weak species-environment relationships. Although the models explained a portion of the total variation (48.9% for coral genera and 36.0% for benthic cover), neither was statistically significant, and species distributions showed no strong directional alignment with environmental gradients. A marginal trend along the first canonical axis suggests a potential ecological gradient; however, this did not reach statistical significance and should be interpreted cautiously. At the species level, patterns observed in ordination and correlation analyses suggest generalist ecological strategies for dominant species such as *C. cyanostigma* and *C. formosa*, which were broadly distributed across habitats. *C. boenak* showed a tendency toward structurally complex, coral-rich environments, but this pattern was not statistically supported and likely reflects a weak ecological preference rather than strict habitat specialization. Overall, associations between grouper assemblages and coral or benthic variables should be interpreted as ecological tendencies rather than confirmed drivers.

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