

# Baseline assessment of coral and fish assemblage relationships in Tanjung Palas Timur Marine Protected Area, North Kalimantan, Indonesia

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**Abstract.** *Weliyadi E, Anggoro S, Haeruddin, Saputra SW, Najib M, Amaliah F, Kase AAB, Yusuf MY, Akhmadi MF. 2025. Baseline assessment of coral and fish assemblage relationships in Tanjung Palas Timur Marine Protected Area, North Kalimantan, Indonesia. Biodiversitas 26: 5303-5313.* Coral reefs are vital ecosystems supporting biodiversity, coastal defense, and local livelihoods, but remain vulnerable to human and environmental pressures. This study provides the first integrated ecological baseline for the core zone of the Tanjung Palas Timur Marine Protected Area (KKPTPT), North Kalimantan, Indonesia. Using Underwater Photo Transect (UPT) and Underwater Visual Census (UVC) methods alongside key water quality measurements, the study assessed coral cover, reef fish assemblages, and environmental parameters. Multivariate analyses: Jaccard similarity, Principal Coordinate Analysis (PCoA), Mantel test, and Procrustes analysis were employed to explore community patterns. The average live coral cover was moderate (46.19%), with higher values on fringing reefs. Coral species richness peaked at Station 1 (19 species), while fish richness was highest at Station 4 (8 species). Mantel ( $r: -0.452, p: 0.085$ ) and Procrustes ( $M^2: 0.624, p: 0.33$ ) analyses indicated weak congruence between coral and fish assemblages. Slight increases in TSS were associated with reduced biological richness, while stable hydrodynamic conditions supported reef health. These findings emphasize the importance of sediment management and habitat structure in sustaining reef resilience. These findings suggest that fish diversity is not solely dependent on coral assemblages but also influenced by environmental drivers such as substrate stability and hydrodynamics. The study offers critical insights for ecosystem-based management through sediment control, substrate rehabilitation, adaptive zoning, and participatory monitoring.

**Keywords:** Biodiversity, conservation, coral reef, ecosystem-based management, reef fish

## INTRODUCTION

Coral reefs are among the most productive and biologically diverse ecosystems on Earth. They provide essential services such as fisheries, tourism, and coastal protection, while also supporting food security and community resilience in tropical regions (Woodhead et al. 2019; González-Barríos et al. 2021; Wulandari et al. 2022). These ecosystems deliver ecological and economic benefits, including habitat provision, nutrient cycling, carbon sequestration, and shoreline stabilization. Despite their importance, coral reefs face escalating threats from global climate change and local human pressures, such as ocean warming, acidification, mass bleaching, sedimentation, eutrophication, destructive fishing, and unregulated tourism. Collectively, these factors accelerate coral degradation (Darling et al. 2017; Reguero et al. 2019).

Indonesia, located within the Coral Triangle, is home to some of the most diverse coral reef ecosystems worldwide. However, reef conditions vary widely, ranging from pristine

to severely degraded. Case studies from Taka Bonerate and Moramo Bay demonstrate how reef resilience depends on substrate stability, water quality, and governance effectiveness (Wulandari et al. 2022; Oetama et al. 2024). In poorly managed areas, increased coral mortality and declining fish diversity highlight the urgent need for rehabilitation and adaptive strategies. Recent innovations, such as Bored Pile Coral (BPC), have proven effective in boosting coral cover and associated fish populations, showing that active interventions can complement protection measures (Putri et al. 2024).

Research across the Indo-Pacific shows that environmental gradients strongly shape coral assemblages. For example, in Pulau Bidong (South China Sea), coral composition varies with depth, wave exposure, and substrate type (Qamarina et al. 2025). In contrast, degraded ecosystems such as Sempu Nature Reserve experience persistent sedimentation and unstable substrates, which restrict coral recruitment and weaken coral and fish associations (Bintoro et al. 2023; Isdianto et al. 2024). These

findings highlight the importance of integrated ecological assessments that link biological patterns with environmental drivers.

Although Indonesia has an extensive history of coral reef research, many newly designated Marine Protected Areas (MPAs) still lack comprehensive ecological baselines. One such example is the Tanjung Palas Timur Marine Protected Area (KKPTPT) in North Kalimantan, officially established in 2022 under Ministerial Decree No. 28. Currently, KKPTPT lacks integrated datasets that combine coral cover, reef fish assemblages, and water quality at the station level. Such data are essential for adaptive management, zoning refinement, and long-term monitoring. Previous studies have shown that coral and fish relationships are not strictly linear; fish communities are shaped by factors such as habitat complexity, prey availability, and localized environmental stressors (Darling et al. 2017; Komyakova et al. 2018). Without robust multivariate analysis, management decisions may rely on incomplete or misleading assumptions.

Multivariate statistical approaches are valuable tools for investigating complex community patterns. Methods such as the Jaccard similarity index (Castro-Insua et al. 2018), Principal Coordinate Analysis (PCoA) (Keith et al. 2018; Beukhof et al. 2019), Mantel tests (Mantel 1967; Legendre and Fortin 2010), and Procrustes analysis (Keith et al. 2018; McLean et al. 2019; Somers and Jackson 2022) enable researchers to quantify relationships among species and assess congruence or divergence between community structures. These techniques help reveal how coral and fish assemblages align or differ in response to environmental and anthropogenic influences.

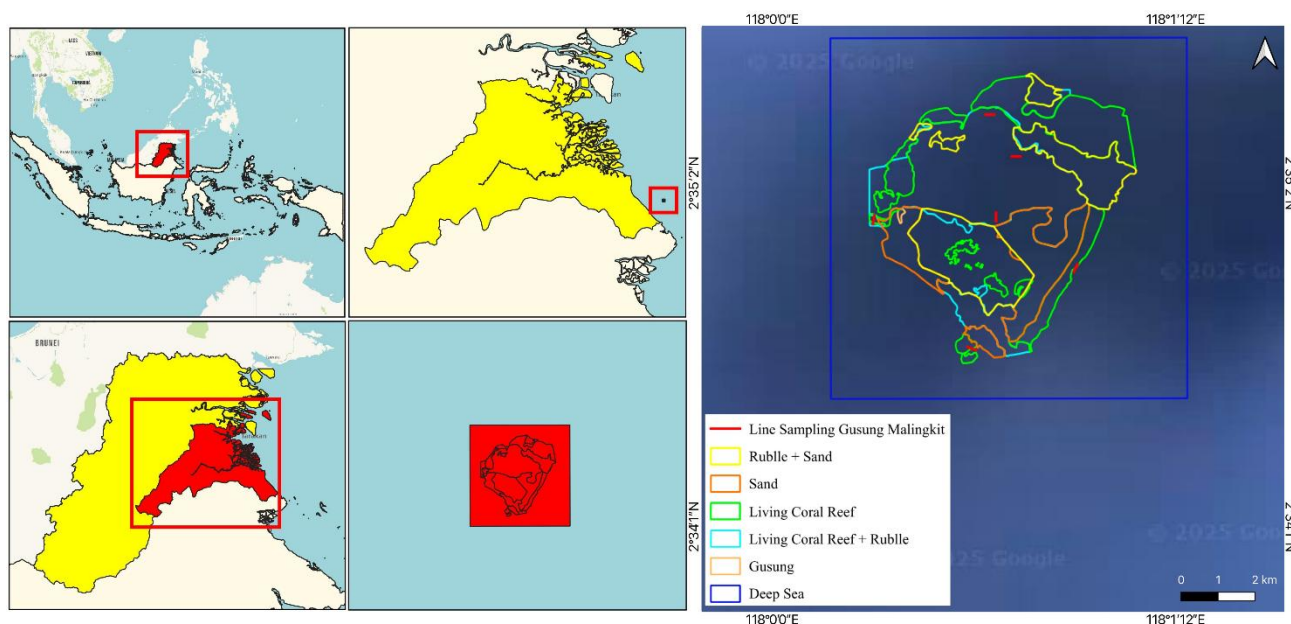
This study addresses the ecological knowledge gap in KKPTPT by employing a multivariate analytical framework. Its objectives are to: (i) quantify coral cover and assess reef condition; (ii) document the taxonomic richness of corals and reef fish; (iii) analyze spatial patterns of community similarity and dissimilarity across stations; and

4) evaluate the congruence between coral and fish assemblages using Mantel and Procrustes analyses. As the first integrated ecological baseline for KKPTPT, this research provides science-based insights to support ecosystem-based management, including substrate rehabilitation, sediment regulation, zoning refinement, and participatory monitoring. Scientifically, it advances understanding of coral and fish-environment interactions; in practice, it provides a foundation for more effective conservation planning in this newly designated marine protected area.

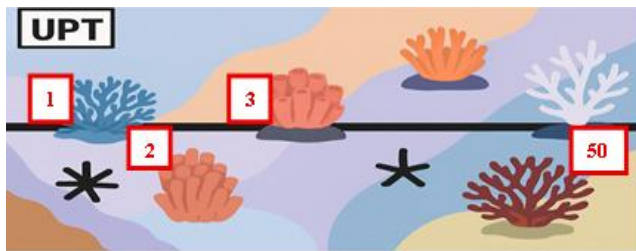
## MATERIALS AND METHODS

### Study area and sampling design

The study was carried out from 30 July to 3 August 2025 in the core zone of the Tanjung Palas Timur Marine Protected Area (KKPTPT), Bulungan District, North Kalimantan Province, Indonesia (Figure 1). Six observation stations were purposively selected to represent various habitat types within the core zone, including fringing reefs, reef flats, and sandy substrates. The geographical coordinates of the stations were precisely recorded: Station 1 (2°35'13.2"N, 118°0'32.4"E), Station 2 (2°35'06.0"N, 118°0'36.0"E), Station 3 (2°34'55.2"N, 118°0'10.8"E), Station 4 (2°34'55.2"N, 118°0'32.4"E), Station 5 (2°34'44.4"N, 118°0'46.8"E), and Station 6 (2°34'30.0"N, 118°0'28.8"E). Stations 1, 3, and 5 were located on coral-dominated reef slopes (6-8 m depth), Stations 2 and 4 on rubble-dominated reef flats (3-4 m depth), and Station 6 on a sandy flat (3 m depth). A single 50 m transect was laid parallel to the shoreline at each Station. Due to logistical limitations, replication was not feasible beyond one transect per site, and this limitation is explicitly addressed in the discussion.



**Figure 1.** Research location at Tanjung Palas Timur Marine Protected Area (KKPTPT), Bulungan, North Kalimantan, Indonesia



**Figure 2.** Illustration of the Underwater Photo Transect (UPT) sampling method in coral observation

### Research equipment

Standard SCUBA gear, underwater cameras, 50-meter fiberglass measuring tapes, and waterproof data sheets were used to support transect installation, underwater photographic documentation, and direct field data collection (Selmoni et al. 2023).

### Coral data collection

Coral cover was assessed using the Underwater Photo Transect (UPT) method (Urbina-Barreto et al. 2022) (Figure 2). Along each 50 m transect, 50 photographic quadrats (58×44 cm) were systematically captured, namely on the odd meters on the left side and the even meters on the right side. Image analysis was performed using Coral Point Count with Excel extensions (CPCe) software version 4.1 (Kohler and Gill 2006), applying a 50-point random grid per photo to classify benthic categories in accordance with Reef Check guidelines (Hodgson et al. 2016). These categories included: Hard Coral (HC), Soft Coral (SC), Sponge (SP), Recent Dead Coral (RDC), Dead Coral with Algae (DCA), Fleshy Seaweed (FS), Rubble (RB), Sand (S), Silt (Si), Rock (RK), and Other (OT). Coral cover classification thresholds were: poor (0-24.9%), moderate (25-49.9%), good (50-74.9%), and very good (>75%) (Zamani and Madduppa 2011).

### Reef fish data collection

Reef fish assemblages were surveyed using the Underwater Visual Census (UVC) method, following the same transect lines used for coral observation (Selmoni et al. 2023). Divers swam slowly above each transect within a belt measuring 50 m in length, 5 m in width, and 5 m in height (total volume: 250 m<sup>3</sup>). Fish were identified to the lowest possible taxonomic level, typically species, using standard regional identification guides. Observations were conducted between 09:00 and 14:00, with visibility exceeding 10 meters to minimize detection bias. Only one survey pass was conducted per transect to maintain consistency. Although fish abundance was initially recorded in situ, the data were converted to presence-absence format for subsequent multivariate analyses.

### Environmental parameters

Water quality was assessed at each Station in triplicate. Parameters including temperature (°C), salinity (ppt), pH, and dissolved oxygen (DO, mgL<sup>-1</sup>) were measured on-site using a calibrated YSI multiparameter probe. Total Suspended Solids (TSS, mgL<sup>-1</sup>) were calculated gravimetrically by filtering 1 L of water samples through

pre-weighed GF/C filters followed by oven-drying at 105°C. Current velocity (ms<sup>-1</sup>) was determined using a flow meter at three different points per station. These environmental variables were later used to interpret coral and fish assemblage patterns (Devlin et al. 2023; Ouédraogo et al. 2023).

### Statistical analyses

Coral and fish data were transformed into presence-absence matrices by Station. Community similarity was quantified using the Jaccard similarity index, calculated as the ratio of shared taxa to the total number of taxa (Castro-Insua et al. 2018). Jaccard dissimilarity matrices (1-similarity) were used as input for ordinations and matrix comparisons. Principal Coordinate Analysis (PCoA) was performed on Jaccard dissimilarity matrices to visualize community patterns among stations (Beukhof et al. 2019). To test coral fish associations, Mantel tests (999 permutations) were applied to assess the correlation between coral and fish dissimilarity matrices, reporting both the correlation coefficient (*r*) and *p*-value (Mantel 1967; Legendre and Fortin 2010). Procrustes analyses were used to compare PCoA ordinations of coral and fish communities. The Procrustes statistic (*M*<sup>2</sup>) indicates the degree of congruence, with significance assessed via 999 permutations (Keith et al. 2018; McLean et al. 2019). Additionally, a Spearman rank correlation was conducted between coral species richness and fish species richness across stations to complement multivariate analyses (Graham and Nash 2013). Environmental data were compared with biological patterns descriptively, with emphasis on TSS and substrate stability. All statistical analyses were performed in R (version 4.3.1) using the *vegan* package, a standard tool in community ecology. Additional validation was carried out using AI Julius Statistics, a specialized artificial intelligence platform for data analysis. Julius AI was employed to assess the stability of ordinations, detect potential overfitting, and perform sensitivity analysis across similarity thresholds. Its automated pattern recognition and uncertainty estimation capabilities allowed for robust verification of conventional statistical outputs, enhancing both methodological rigor and interpretative reliability. This hybrid approach ensured that the study's conclusions were well supported and applicable to conservation management.

## RESULTS AND DISCUSSION

### Coral reef conditions

Coral reef conditions in the core zone of the Tanjung Palas Timur Marine Protected Area (KKPTPT) showed notable spatial variation across observation stations. Fringing reef slopes Stations 1, 3, and 5 exhibited relatively high live coral cover, recorded at 68.94%, 62.99%, and 65.55%, respectively (Figure 3.A). Based on the classification by Zamani and Madduppa (2011), these values indicate 'good' coral condition. These habitats were dominated by structurally complex hard coral genera such as *Acropora* and *Porites*, which are known to support high levels of reef-associated biodiversity.

Conversely, Stations 2, 4, and 6, located on reef flats or sandy habitats, had significantly lower live coral cover, measured at 17.80%, 36.46%, and 25.40%, respectively. According to Zamani and Madduppa (2011), Station 2 is categorized as 'poor,' while Stations 4 and 6 fall under the 'moderate' category. These stations were predominantly characterized by sandy and rubble substrates, which diminish structural stability, impair coral larval settlement, and constrain natural reef regeneration.

The mean live coral cover across the KKPTPT core zone was 46.19%, which places it in the 'moderate' category (Gomez and Yap 1988). Non-living substrates, including sand, rubble, and dead coral with algae, comprised 53.81% of the total coverage (Figure 3.B), reflecting a considerable proportion of degraded habitat. This variability illustrates a clear contrast: fringing reef slopes tend to support healthier coral assemblages, whereas reef flats and sandy areas are more susceptible to ecological disturbance.

These findings are consistent with broader assessments across Indonesia, which indicate that stable substrates and favorable hydrodynamic conditions promote higher coral cover, whereas sedimentation and substrate instability accelerate reef degradation (Connolly et al. 2017; Hughes et al. 2019; Oetama et al. 2024). The present results offer a solid quantitative baseline to guide spatial prioritization for reef management and rehabilitation in KKPTPT.

### Coral species richness

Coral species richness varied notably among the 6 observation stations; Station 1 recorded the highest diversity, comprising 19 species across 11 genera (Figure 4). This high richness reflects a stable environment that accommodates both fast-growing branching species, such as *Acropora*, and more resilient massive forms, including *Porites* and *Montipora*. The coexistence of multiple coral morphologies indicates elevated structural complexity and ecological integrity.

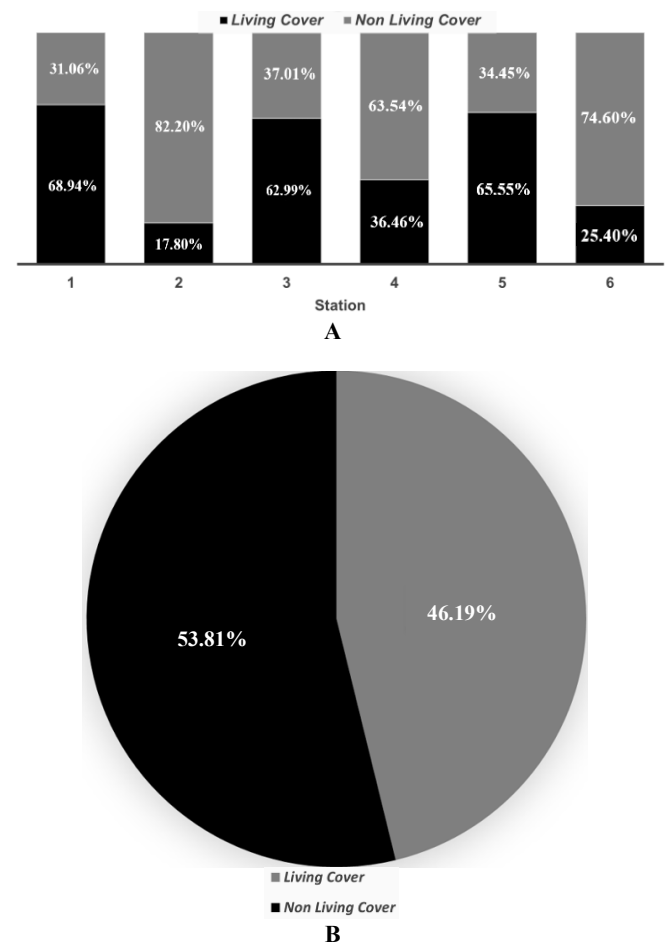
Stations 3 and 4 exhibited intermediate diversity, recording 13 species (8 genera) and 12 species (6 genera), respectively. These locations had moderate structural complexity but were affected by substrate limitations that reduced opportunities for further coral recruitment. Meanwhile, Stations 2, 5, and 6 each harbored only 7 species within 5-6 genera, and were characterized by sand and rubble substrates, which hinder larval settlement and the development of diverse coral communities.

In general, the results underscore a positive association between substrate stability and coral species richness. Stations with firm, complex substrates supported higher coral diversity, whereas habitats dominated by sand or rubble showed reduced richness. These findings are in line with studies from the broader Indo-Pacific, where stable and structurally complex habitats are recognized as key drivers of coral assemblage diversity (Darling et al. 2017; Baird et al. 2018; Browne et al. 2019; González-Barrios et al. 2021; Lee et al. 2021). Figure 5 clearly visualizes these relationships, emphasizing the role of substrate type in shaping coral community patterns.

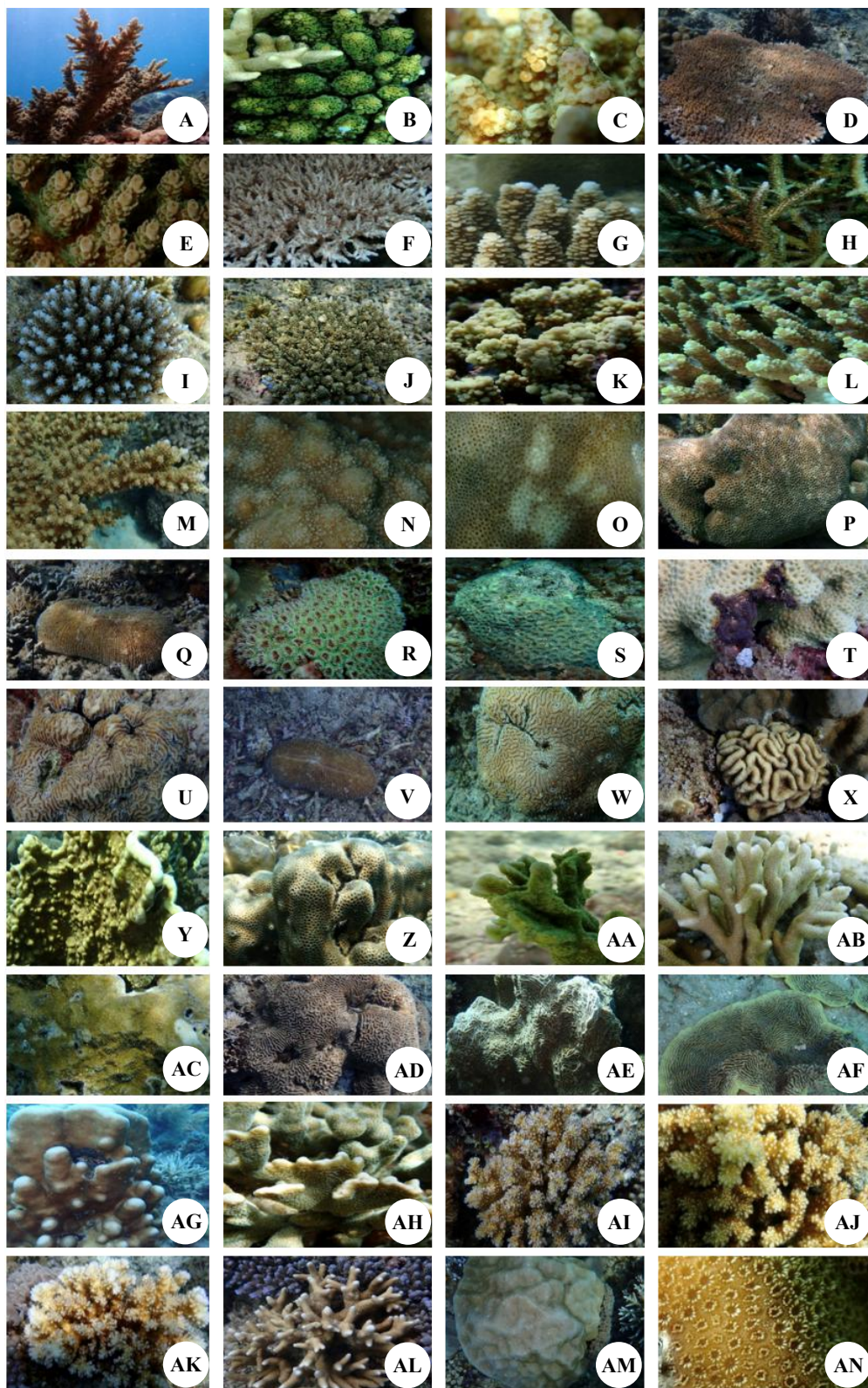
### Reef fish community

Reef fish assemblages varied notably across the 6 observation stations. A total of 22 species were recorded, with richness and composition reflecting differences in habitat quality and coral condition (Table 1). Station 4 supported the highest richness with 8 species, including herbivores (*Ctenochaetus hawaiiensis*), planktivores (*Pterocaesio tile*), and carnivores (*Lutjanus decussatus*). The coexistence of these functional groups indicates relatively high habitat complexity and resource availability (Maire et al. 2018; Dai et al. 2022; Hemingson et al. 2022; Mihalitsis et al. 2022; Brandl 2023).

Station 3 supported 4 species, including *Cephalopholis urodeta* and *Pomacentrus moluccensis*, while Station 1 recorded 3 species, such as *Dascyllus reticulatus* and *Paracirrhites arcatus*. Stations 5 and 6 each hosted 5 species, including *Cirrhitichthys falco* and *Amphiprion ocellaris*. In contrast, Station 2 exhibited the lowest richness with only 2 species (*Halichoeres hortulanus* and *Pomacentrus auriventris*), consistent with the poor coral condition observed at this site.



**Figure 3.** Coral cover variation across stations. A. Percentage of live and non-living cover at each station, B. The overall average cover across all stations

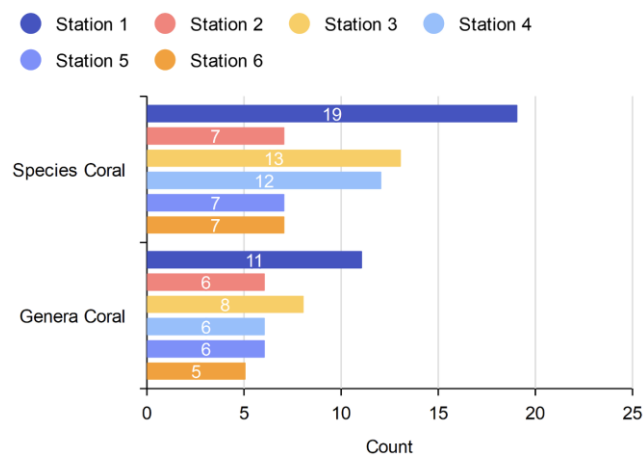


**Figure 4.** Results of coral reef identification in the core zone of the conservation area. A. *Acropora cytherea*, B. *Acropora digitifera*, C. *Acropora gemmifera*, D. *Acropora hyacinthus*, E. *Acropora kimbeensis*, F. *Acropora microphthalma*, G. *Acropora millepora*, H. *Acropora parilis*, I. *Acropora nasuta*, J. *Acropora spathulata*, K. *Acropora secale*, L. *Acropora subulata*, M. *Acropora vermiculata*, N. *Echinopora lamellosa*, O. *Favia helianthoides*, P. *Favites flexuosa*, Q. *Fungia fungites*, R. *Galaxea fascicularis*, S. *Goniastrea aspera*, T. *Goniastrea pectinata*, U. *Goniastrea favulus*, V. *Herpolitha limax*, W. *Leptoria phrygia*, X. *Lobophyllia robusta*, Y. *Montipora capitata*, Z. *Platygyra verweyi*, AA. *Montipora porites*, AB. *Montipora samarensis*, AC. *Montipora stilosa*, AD. *Oulophyllia levis*, AE. *Pachyseris rugosa*, AF. *Pachyseris speciosa*, AG. *Pavona maldivensis*, AH. *Montipora digitata*, AI. *Pocillopora damicornis*, AJ. *Pocillopora meandrina*, AK. *Pocillopora verrucosa*, AL. *Porites cylindrica*, AM. *Porites lobata*, AN. *Porites lutea*

**Table 1.** Fish species found at the research station

Fish species	Sites					
	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
<i>Amphiprion ocellaris</i>	-	-	-	-	-	+
<i>Cephalopholis urodeta</i>	-	-	+	-	-	-
<i>Chromis viridis</i>	-	-	-	-	-	+
<i>Cirrhitichthys falco</i>	-	-	-	-	+	-
<i>Ctenochaetus hawaiiensis</i>	-	-	-	+	+	-
<i>Dascyllus aruanus</i>	-	-	-	+	-	-
<i>Dascyllus reticulatus</i>	+	-	-	-	-	-
<i>Ecsenius bimaculatus</i>	+	-	-	-	-	-
<i>Halichoeres hortulanus</i>	-	+	-	+	-	-
<i>Halichoeres ornatissimus</i>	-	-	-	-	+	-
<i>Lutjanus decussatus</i>	-	-	-	+	-	-
<i>Paracirrhites forsteri</i>	-	-	+	-	-	-
<i>Parupeneus barberinus</i>	-	-	-	+	-	-
<i>Pomacentrus auriventris</i>	-	+	-	+	-	-
<i>Pomacentrus moluccensis</i>	-	-	+	-	-	-
<i>Pseudanthias squamipinnis</i> (Male)	-	-	-	-	-	+
<i>Pseudanthias squamipinnis</i> (Female)	-	-	-	-	-	+
<i>Pterocaesio tile</i>	-	-	-	-	+	+
<i>Trimma rubromaculatum</i>	-	-	+	-	-	-
<i>Thalassoma hardwicke</i>	-	-	-	+	-	-
<i>Thalassoma lunare</i>	-	-	-	+	+	-
<i>Paracirrhites arcatus</i>	+	-	-	-	-	-

Note: +: Indicates presence; -: Indicates absence

**Figure 5.** Number of coral species and genera at each station

Distribution patterns reveal that stations with greater structural complexity and higher coral cover generally supported more diverse fish communities. In contrast, stations dominated by sand or rubble, such as Station 2, had limited capacity to sustain fish diversity. These findings underscore the dependence of reef fish assemblages on coral habitat quality and complexity, consistent with previous studies highlighting the role of coral structure in supporting reef fish diversity and ecological functions (Jones et al. 2004; Graham and Nash 2013; Dai et al. 2022; Hemingson et al. 2022; Cumming and Bellwood 2023).

Figure 6 illustrates that coral species richness peaked at Station 1 (19 species, 11 genera), while fish richness was highest at Station 4 (8 species). Stations 2, 5, and 6 recorded lower values for both coral and fish diversity, reflecting habitat degradation and substrate instability. This

visualization highlights the influence of coral diversity and habitat complexity on reef fish assemblage patterns across KKPTPT.

### Relationship between coral and fish

The relationship between coral and fish assemblages in the KKPTPT core zone was evaluated using several statistical approaches. Analyses were conducted on presence-absence data transformed into Jaccard dissimilarity matrices for each taxon, a standard procedure for community comparisons (Legendre and Fortin 2010; Lamy et al. 2015). The Mantel test revealed a moderate negative correlation ( $r: -0.452$ ,  $p: 0.085$ , 999 permutations,  $n: 6$  stations) between coral and fish community dissimilarities (Figure 7). Although the coefficient suggests a potential trend, the result was not statistically significant at  $\alpha: 0.05$ . This finding indicates that stations with similar coral communities were not consistently similar in fish assemblages. Given the limited number of stations, the statistical power is low, and results should be interpreted as suggestive rather than conclusive.

Procrustes analysis comparing PCoA ordinations (Jaccard) of coral and fish communities yielded a disparity ( $M^2$ ) of 0.624 with a non-significant permutation test ( $p: 0.33$ , 999 permutations) (Figure 8). This outcome demonstrates limited congruence between coral and fish community structures across stations. In the Procrustes plot, gray linking lines highlight mismatches, particularly at stations where coral composition and fish assemblages diverged markedly. A supplementary Spearman rank correlation was conducted between coral and fish species richness as part of the main statistical analyses. The test showed a weak, non-significant negative relationship ( $\rho: -0.154$ ,  $p: 0.771$ ), confirming that richness alone does not

adequately explain fish assemblage variation relative to coral diversity. That reinforces the importance of multivariate approaches when examining cross-taxon patterns.

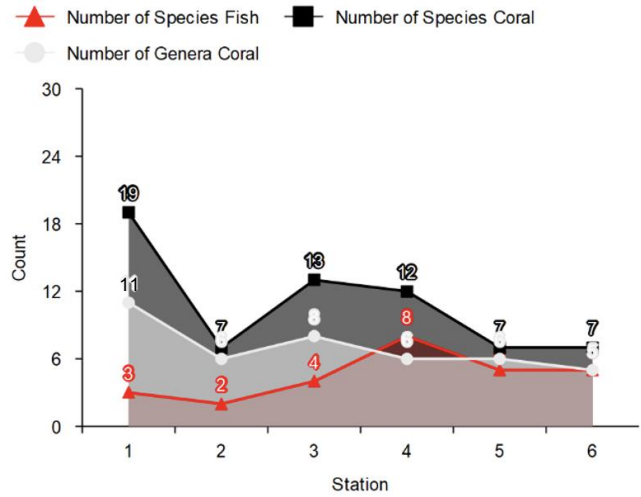
Overall, these analyses suggest that coral assemblage composition does not strongly predict fish assemblage composition in KKPTPT. While structurally complex coral habitats can support higher fish richness at specific sites, congruence in community-level patterns across stations was weak. This finding is consistent with ecological literature indicating that reef fish distributions are influenced not only by coral community structure but also by environmental conditions, habitat complexity, and anthropogenic pressures (Wilson et al. 2010; Graham and Nash 2013).

**Environmental parameters**

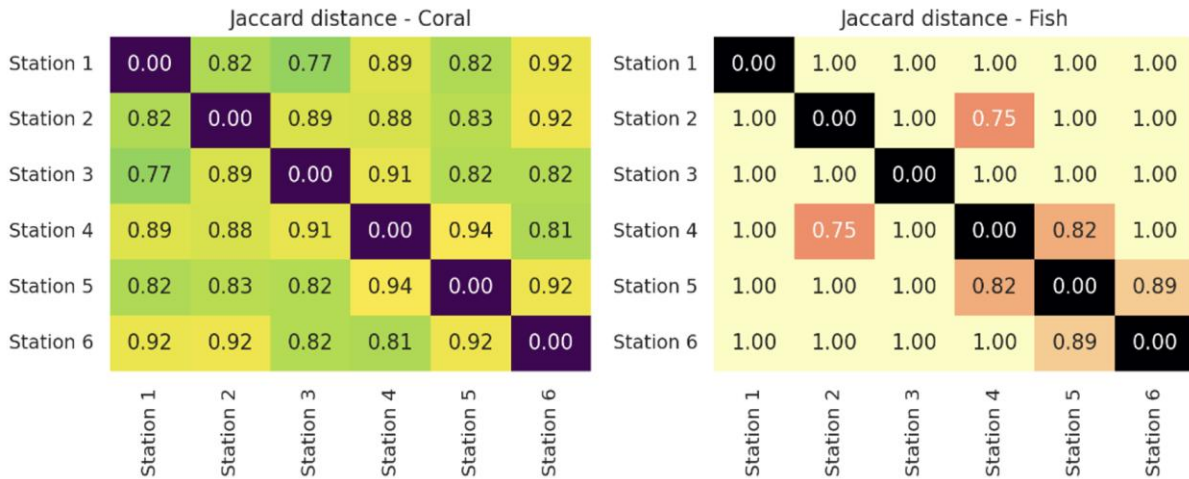
Water quality and hydrodynamic conditions across the six stations of the KKPTPT core zone were generally within Indonesian marine water quality standards, though some spatial variability was evident. The measured parameters included temperature (°C), salinity (ppt), pH, dissolved oxygen (DO, mgL<sup>-1</sup>), Total Suspended Solids (TSS, mgL<sup>-1</sup>), and current velocity (ms<sup>-1</sup>). Results are summarized in Table 2.

Temperature remained stable across stations (30.6-30.8°C), consistent with typical tropical reef conditions (Hughes et al. 2019). Salinity values were constant at 36 ppt, indicating minimal freshwater input. Dissolved oxygen ranged from 6.55-7.05 mgL<sup>-1</sup>, levels sufficient to support reef metabolism and aerobic organisms. pH values varied

between 7.82-8.25, characteristic of healthy reef waters (Devlin et al. 2023). Current velocity was uniform across all stations at 0.2 ms<sup>-1</sup>, suggesting consistent hydrodynamic conditions that help prevent stagnation (Ouédraogo et al. 2023). The most noticeable variation occurred in Total Suspended Solids (TSS), ranging from 1.93 mgL<sup>-1</sup> at Station 1 to 2.27 mgL<sup>-1</sup> at Station 3.



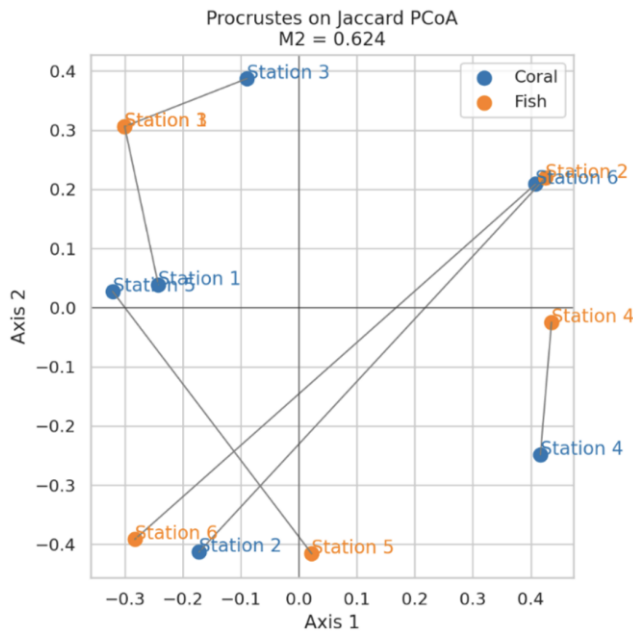
**Figure 6.** Relationship between fish species, coral species, and coral genera



**Figure 7.** Mantel analysis (Jaccard coral vs. Jaccard fish)

**Table 2.** Water quality at the research site

Water quality parameters	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
Temperature (°C)	30.7	30.7	30.6	30.6	30.8	30.8
Salinity (ppt)	36.0	36.0	36.0	36.0	36.0	36.0
DO (mg/L)	7.05	6.75	6.70	6.80	7.05	6.55
pH	8.25	7.88	7.96	7.92	8.17	7.82
TSS (mg/L)	1.93	2.05	2.27	1.97	2.26	2.19
Current velocity (m/s)	0.2	0.2	0.2	0.2	0.2	0.2



**Figure 8.** Procrustes analysis (PCoA coral vs. fish)

Elevated TSS levels at Stations 2, 5, and 6 corresponded with reduced coral cover and lower fish diversity, suggesting that sediment accumulation may inhibit coral recruitment and degrade habitat quality (Fabricius et al. 2012; Bhuyan et al. 2025). Conversely, lower TSS values at Stations 1 and 4 were associated with higher coral cover and more stable fish assemblages. According to Government Regulation (PP) No. 22 of 2021 on Environmental Protection and Management, the marine water quality standards for coral biota include temperature 28-30°C, salinity 33-34 ppt, pH 7-8.5,  $DO > 5 \text{ mgL}^{-1}$ , and  $TSS \leq 20 \text{ mgL}^{-1}$ . The measured parameters in this study meet these national standards, indicating that the water quality remains within the acceptable range to support coral reef ecosystems. Overall, environmental parameters were within acceptable thresholds; however, localized increases in TSS appear to contribute to habitat degradation and weaker coral-fish congruence at certain stations, emphasizing the importance of sediment control and stable hydrodynamic conditions in maintaining reef health and biodiversity.

#### Ecological discussion and conservation implications

This study reveals significant ecological variability among coral reef habitats in the KKPTPT core zone and their impact on associated reef fish assemblages. Fringing reef slopes (Stations 1, 3, 5) demonstrated relatively high coral cover and diversity, while reef flat and sandy areas (Stations 2, 4, 6) exhibited degraded conditions, with reduced coral cover and species richness. These findings underscore the importance of substrate stability and hydrodynamic conditions in maintaining coral health. Reef slopes offer favorable light exposure and water flow, which enhance coral growth (Solihuddin et al. 2020; Lesser et al. 2021), whereas reef flats face stronger sediment transport and wave exposure that can hinder coral regeneration (Lan 2021). In

addition, stable sloping habitats facilitate faster rubble consolidation and increased calcification rates, which are essential for long-term reef recovery (Clark et al. 2022; Vercelloni et al. 2023; Kenyon et al. 2025).

Coral species richness followed the same spatial trends, with greater diversity observed in stations dominated by *Acropora* and *Porites* species. These corals contribute significantly to three-dimensional habitat complexity and offer a wide array of microhabitats, thereby promoting ecosystem resilience (Torres-Pulliza et al. 2020; Hall et al. 2021; Hall and Kingsford 2021). Structural features like coral bommies and the remnants of coral skeletons serve as refuges for marine life and enhance system stability (Castaño et al. 2021; Engleman et al. 2023). *Porites*, in particular, function as essential framework builders that reinforce reef structural integrity (Solihuddin et al. 2020). Consequently, maintaining structural complexity is key to ensuring long-term ecological resilience.

Interestingly, reef fish communities did not always correspond with coral richness patterns. For instance, Station 4 exhibited only moderate coral diversity but the highest fish species richness. This suggests that variables such as water flow, larval availability, and food resources also play critical roles in structuring reef fish assemblages (Suca et al. 2020; Moynihan et al. 2022; Pangestu et al. 2023). Habitat morphology and rugosity are also important determinants of fish abundance (Nugraha et al. 2020), and behavioral cues or ecological roles (functional guilds) may further explain the disconnect between coral and fish communities (Carlson et al. 2024). Thus, coral cover or richness alone may not serve as adequate proxies for predicting reef fish diversity, echoing conclusions from broader studies on cross-taxon incongruence (Ditzel et al. 2022; Isdianto et al. 2024).

The weak alignment between coral and fish communities was statistically supported. The Mantel test showed a moderate negative correlation ( $r: -0.452$ ,  $p: 0.085$ ), while Procrustes analysis ( $M^2: 0.624$ ,  $p: 0.33$ ) revealed low congruence between ordination results. Furthermore, the Spearman correlation of species richness ( $\rho: -0.154$ ,  $p: 0.771$ ) confirmed that coral richness is not a reliable predictor of fish richness. Although not statistically significant, these results, interpreted with caution due to small sample size and methodological constraints, suggest that reef fish communities are shaped by more complex environmental and biological drivers than coral composition alone (Sommerfield et al. 2021; Somers and Jackson 2022; Quilodrán et al. 2023). Large Procrustes distances demonstrate that fish composition cannot be directly inferred from coral composition (Andreella et al. 2023).

Environmental variables, particularly Total Suspended Solids (TSS) and current velocity, provided important insights into the structure of reef communities. TSS values ranged from  $1.93 \text{ mgL}^{-1}$  at Station 1 to  $2.27 \text{ mgL}^{-1}$  at Station 3, with slightly elevated levels also observed at Stations 2, 5, and 6 ( $> 2.0 \text{ mgL}^{-1}$ ). Despite these minor variations, coral cover remained high at Stations 1, 3, and 5 (68.94%, 62.99%, and 65.55%, respectively), indicating that TSS concentrations within this range were too low to negatively affect coral health. Conversely, Stations 2, 4, and 6 exhibited

lower coral cover (17.80-36.46%), largely due to sandy and unstable substrates rather than suspended sediment concentration. This suggests that substrate composition plays a more dominant role in shaping coral distribution and habitat quality in the study area (Asmawi et al. 2020; McClure et al. 2021; Bhuyan et al. 2025). The current velocity across all stations was stable at approximately 0.2 ms<sup>-1</sup>, providing sufficient water movement to prevent stagnation while supporting nutrient exchange and larval dispersal (Galbraith et al. 2022, 2023). These observations emphasize the importance of sediment control and maintaining stable hydrodynamic conditions in strategies aimed at enhancing reef resilience (Bozec et al. 2021; Li et al. 2024). This study also has several limitations that should be considered. The small sample size (n: 6 stations) limited the statistical robustness of the analyses, and reliance on a single transect per site reduced within-site replication (Hayek et al. 2021). The use of presence-absence data precluded the analysis of species abundance or biomass, potentially obscuring ecological trends (Brian and Aldridge 2021). Furthermore, the lack of additional ecological variables, such as depth variation, structural complexity (rugosity), and levels of anthropogenic pressure, restricted the scope of interpretation (Çelekli et al. 2022; Evcen and Çınar 2025). It should also be noted that co-occurrence patterns cannot be used as direct evidence of ecological interactions, suggesting a need for future studies to incorporate more advanced modeling techniques (Blanchet et al. 2020).

From a conservation standpoint, these findings provide a crucial baseline for KKPTPT. Coral assemblages cannot serve as full surrogates for fish communities, as environmental and anthropogenic drivers influence fish dynamics (Ulumuddin et al. 2021; Isdianto et al. 2024). Management should prioritize sediment control, substrate rehabilitation, and the integration of structural indicators such as rugosity and carbonate budgets (Lendo et al. 2024). Artificial reefs and reef modules have been shown to enhance fish diversity and abundance (Boakes et al. 2022; Liu et al. 2023). Community engagement and adaptive policies are equally vital, with evidence showing that restrictions on human activity can substantially increase fish biomass (Boakes et al. 2023; Johnson et al. 2023). Future monitoring should combine biological and environmental metrics, supported by participatory approaches, to secure long-term resilience.

In conclusion, the weak congruence between coral and fish assemblages in KKPTPT reflects the complexity of reef ecosystems. Coral communities provide essential habitat, but fish assemblages respond to additional environmental and anthropogenic drivers. Effective conservation, therefore, requires integrated management that addresses biological, environmental, and social dimensions, ensuring the resilience of this marine protected area. This study provides the first integrated ecological baseline for the Tanjung Palas Timur Marine Protected Area (KKPTPT), North Kalimantan, using a multivariate approach that combines coral, reef fish, and environmental data. Fringing reef slopes exhibited higher coral cover and diversity, largely due to the presence of structurally complex genera

such as *Acropora* and *Porites*. In contrast, reef flats and sandy areas were more degraded, with lower coral richness and structural integrity. While coral communities played a role in shaping fish assemblages, the weak and non-significant correlations observed through Mantel, Procrustes, and Spearman analyses indicate that hydrodynamic conditions, habitat morphology, and sediment-related stressors also drive reef fish diversity. Slight increases in TSS were associated with reduced biological richness, while stable hydrodynamic conditions supported reef health. These findings emphasize the importance of sediment management and habitat structure in sustaining reef resilience. For effective conservation, management strategies should integrate biological monitoring of both corals and fish, address sediment and substrate conditions, and involve local stakeholders through participatory governance. A holistic, ecosystem-based approach that includes biological, environmental, and social considerations is essential to safeguard the ecological function and long-term sustainability of KKPTPT. The study's spatial coverage and sampling replication were limited, and abundance-based analyses were not included. Future research should integrate temporal monitoring, benthic complexity metrics, and trophic modeling to understand long-term coral-fish interactions better.

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