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Ecological status of sea cucumber resources across depth strata in Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia

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[2]Sorong Coastal and Marine Resources Management Agency, Directorate General of Marine and Ocean Management, Ministry of Marine Affairs and Fisheries of the Republic of Indonesia. Jl. KPR PDAM Km. 10, Klawuyuk, East Sorong, Sorong City 98417, West Papua, Indonesia

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Abstract. *Kalidi NS, Saliyadi, Loupatty E, Arafat G, Aitem N. 2025. Ecological status of sea cucumber resources across depth strata in Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia. Biodiversitas 26: 6502-6512.* This study presents the first quantitative ecological assessment of sea cucumber (Holothuroidea) populations in the waters of Kapadiri Village, Raja Ampat, Indonesia, a coastal area subjected to long-term harvesting without formal management regulations. The study aimed to analyze species composition, community structure, and population density across two depth strata in order to characterize the current ecological condition of sea cucumber resources. Field surveys were conducted at five stations representing seagrass, coral reef, and sandy habitats at depths of <5 m and >5 m. Quadrat transects (60 m²) were applied in shallow areas, while belt transects (200 m²) were used in deeper zones. Nine sea cucumber species were recorded, with *Holothuria edulis, H. atra,* and *H. scabra* being the most abundant. Population densities ranged from 0.083-0.167 ind/m² in shallow waters and 0.105-0.230 ind/m² at depths >5 m. Community indices indicated moderate diversity, high evenness, and low dominance, reflecting a relatively balanced community at low overall abundance. A quasi-Poisson generalized linear model showed that depth and station significantly influenced density variation, whereas their interaction was not significant, indicating a consistent depth-related pattern across stations. Measured environmental parameters (temperature, salinity, pH, and dissolved oxygen) were within tolerance ranges reported for tropical sea cucumbers, suggesting that habitat conditions remain environmentally suitable. However, the consistently low population densities observed across all stations indicate that sea cucumber stocks are likely under pressure, inferred from density patterns and comparisons with regional studies. These findings underscore the need for strengthened community-based management, including adaptive harvesting regulations and targeted habitat protection, to support the recovery and long-term sustainability of sea cucumber populations in Kapadiri Waters.

Keywords: Benthic invertebrates, coastal exploitation, community structure, depth stratification, small-scale fisheries

INTRODUCTION

The degradation of fishery resources has become a major concern in Indonesia, particularly for high-value marine species increasingly threatened by overexploitation (Suman et al. 2018). Since 2012, the Indonesian Ministry of Marine Affairs and Fisheries (KKP), in collaboration with the Indonesian Institute of Sciences (LIPI), has established a national priority list for the management and protection of endangered marine biota, including sea cucumbers (Holothuroidea) (Arafat et al. 2022). Indonesia is one of the world's largest producers of sea cucumbers, supplying both domestic and international markets (Purcell et al. 2018; Setyastuti et al. 2019). Rising global demand has intensified pressure on national stocks, highlighting the urgency of implementing sustainable management strategies.

Sea cucumbers are benthic invertebrates inhabiting coral reefs, seagrass meadows, and sandy-muddy substrates (Wirawati et al. 2021). Ecologically, they function as benthic recyclers and ecosystem engineers by processing organic detritus, enhancing sediment oxygenation, and supporting biogeochemical cycles (Purcell et al. 2016; Sun et al. 2023). These processes facilitate remineralization, stabilize sediment pH, and increase nutrient availability, thereby sustaining benthic productivity and the integrity of shallow-water ecosystems (Uthicke 2001; Purcell et al. 2016). Consequently, declines in sea cucumber populations may disrupt benthic functioning and contribute to habitat degradation (Purcell et al. 2016).

In addition to their ecological role, sea cucumbers provide substantial economic and social benefits. Their dried products are highly valued in East Asian markets, particularly in China, Hong Kong, and Singapore, where they are consumed as luxury seafood and used in traditional medicine (Purcell et al. 2018; Al-Yaqout et al. 2021). Their economic importance is further supported by their nutritional value and the presence of bioactive compounds with pharmaceutical and biotechnological potential (Soltani and Baharara 2019; Sukmiwati et al. 2022; Hamel et al. 2024). However, increasing market demand has driven intensive exploitation and widespread depletion of stocks across Indonesia (Khatulistiani et al. 2022), consistent with the "boom-and-bust" dynamics observed in many tropical fisheries (Purcell et al. 2013; Mercier et al. 2025).

Recent studies indicate that sea cucumber population densities in many Indo-Pacific regions have declined below natural regeneration thresholds (<1 ind/m²), including Karimunjawa, South Konawe, Numfor, and Tual (Alwi et al. 2020; Kalidi et al. 2023). Such low densities may reduce ecological functionality and threaten the livelihoods of coastal communities that depend on sea cucumber harvesting (Uneputty et al. 2017; Siburian et al. 2023). Although most sea cucumber fisheries in the Asia-Pacific region are small-scale and community-based, weak governance, limited monitoring, and illegal trade have exacerbated stock declines and undermined long-term sustainability (Eriksson and Byrne 2015; Kinch 2024). These conditions emphasize the importance of strengthening community-based conservation systems, including traditional management institutions such as sasi laut, a customary marine tenure system that regulates harvest timing, access, and resource use in eastern Indonesia.

Raja Ampat, Indonesia, located within the Coral Triangle, is globally recognized for its exceptional marine biodiversity and extensive coastal ecosystems. Kapadiri Village, situated on North Waigeo Island, encompasses approximately 79 ha of seagrass habitat and 234 ha of coral reef ecosystems (Coral Atlas 2025). Local communities traditionally harvest sea cucumbers through bameti (low-tide gleaning) for sale to local collectors. Field observations indicate that harvesting activities commonly occur without size limits, gear restrictions, or seasonal closures, while access by external fishers further increases exploitation pressure. These conditions reflect weakening adherence to traditional stewardship practices and limitations in local management effectiveness.

Despite long-standing harvesting activities, no quantitative ecological assessment has previously evaluated the status of sea cucumber populations in the waters of Kapadiri Village. This lack of site-specific baseline data represents a critical knowledge gap, particularly given Raja Ampat's ecological significance and increasing local exploitation pressure (Purcell et al. 2014; Mercier et al. 2025). Local-scale ecological assessments are therefore essential to inform sustainable management, guide conservation planning, and support evidence-based policy development (Purcell et al. 2025).

In this context, the present study provides the first quantitative assessment of sea cucumber community structure and population density in Kapadiri Village across distinct depth strata. By integrating ecological indices and depth-based density analysis, this study offers novel baseline information to support community-based adaptive management and contributes to broader efforts to sustain exploited benthic resources in Raja Ampat and comparable tropical regions.

MATERIALS AND METHODS

Study area

This study was conducted in August 2025 in the waters of Kapadiri Village, Raja Ampat District, Southwest Papua Province, Indonesia (Figure 1). The study area covers approximately 1,595.05 ha and is not designated as a marine protected area, which potentially allows unrestricted access and harvesting activities that may increase local exploitation pressure (Coral Atlas 2025).

Five observation stations were established based on locations frequently utilized by local fishers for sea cucumber harvesting, as identified through preliminary consultations, while still representing the dominant habitat types present in the area. To reduce potential location selection bias, transects were deployed using a stratified random sampling approach across three dominant habitat types: seagrass beds, coral reefs, and sandy substrates. Each station represented one primary habitat type.

At each station, transect starting points were generated randomly using Global Positioning System (GPS)-based coordinates referenced to the WGS84 datum. Geographic coordinates and habitat characteristics for all stations are presented in Table 1 using Degrees-Minutes-Seconds (DMS) format to ensure spatial accuracy and reproducibility. Sampling was conducted at two depth strata, shallow (<5 m) and deep (>5 m), at each station.

Population data collection

Sea cucumber population data were collected across two depth strata, <5 m (shallow zone) and >5 m (deep zone), to account for variation in habitat conditions and species distribution between coastal and sublittoral environments. Differences in transect number and configuration between depth strata were applied to accommodate seabed conditions and underwater survey feasibility; however, this difference may limit direct comparability between depth strata and is therefore acknowledged as a methodological constraint.

Table 1. Sea cucumber sampling coordinate points

Depth	Station	Habitat characteristics	Coordinate point
< 5 meters	Yesbi (ST 1)	Seagrass, Coral, Sand	00°02'45.2" S, 130°44'12.29" E
	Kampung Tua (ST 2)	Seagrass, Coral	00°03'10.55" S, 130°44'5.47" E
	Yepnan (ST 3)	Seagrass, Coral, Sand	00°02'31.82" S, 130°43'29.8" E
	Tanjung Batu (ST 4)	Seagrass, Sand	00°02'56.24" S, 130°45'22.84" E
	Paput (ST 5)	Seagrass, Coral, Rubble	00°02'7.7" S, 130°44'31.53" E
> 5 meters	Yesbi (ST 1)	Coral, Sand	00°02'47.91" S, 130°44'15.45" E
	Kampung Tua (ST 2)	Coral, Rubble	00°03'5.51" S, 130°44'5.94" E
	Yepnan (ST 3)	Coral	00°02'33.53" S, 130°43'35.64" E
	Tanjung Batu (ST 4)	Coral, Sand	00°02'13.09" S, 130°44'39.24" E
	Paput (ST 5)	Coral, Sand	00°02'52.13" S, 130°45'26.77" E

Note: ST: Station, <: Less than, >: More than

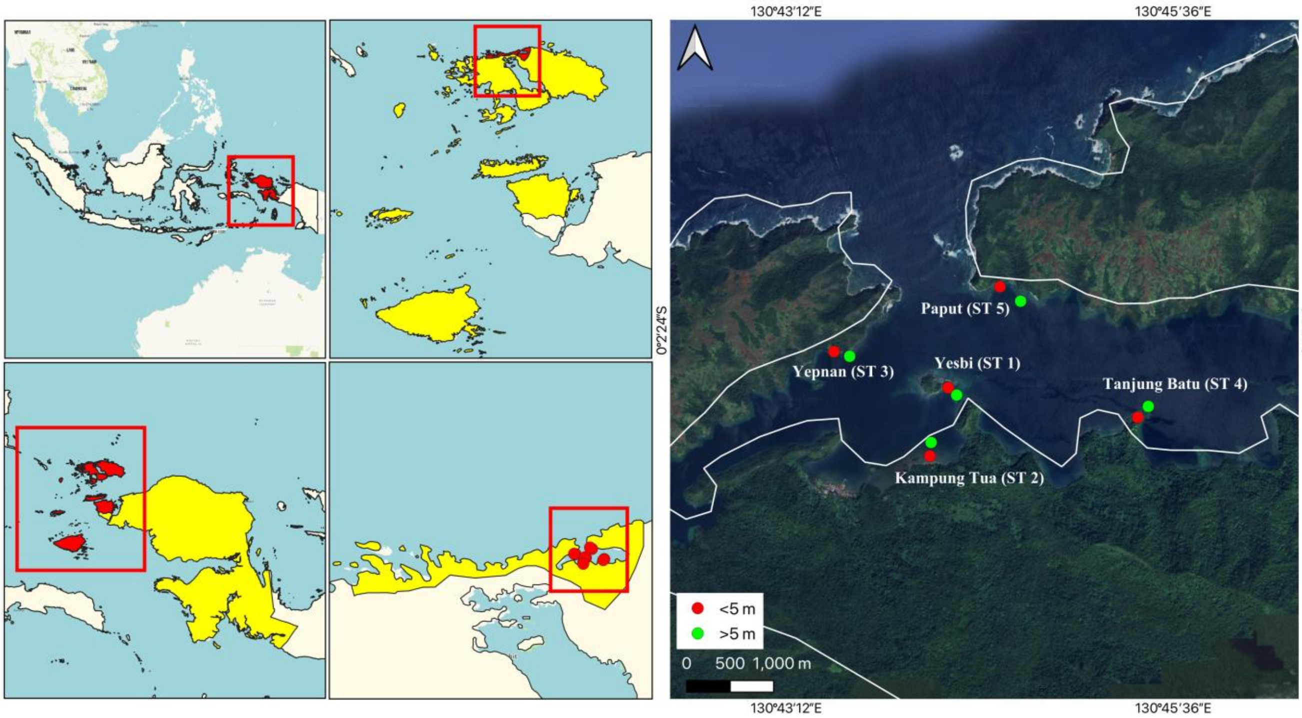

Figure 1. Sampling locations for sea cucumber resource ecology in Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia

In the shallow zone (<5 m), a modified quadrat transect method adapted from the Reef Check protocol was employed (English et al. 1997; Uneputty et al. 2017; Muzaki et al. 2019). At each station, three transects were established parallel to the coastline, each extending 50 m in length. Along each transect, 1×1 m quadrats were placed alternately on the right and left sides at 9 m intervals, resulting in 20 observation points per transect and a total surveyed area of 60 m² per station. Transects were aligned with depth contours (isobaths) to follow seabed topography and reflect the natural distribution patterns of sea cucumbers (Figure 2).

In the deep zone (>5 m), the Benthos Belt Transect (BBT) method was applied, incorporating elements of standard belt transects and the Reef Check Benthos approach (Munro 2013; LIPI 2017). At each station, one belt transects measuring 100 m in length and 2 m in width (1 m on each side) was deployed, yielding an observation area of 200 m² per station. Transects were positioned parallel to seabed contours to maintain habitat representativeness under deeper-water conditions (Figure 3).

Density estimates for both depth categories were standardized to individuals per square meter (ind/m²) using the formula Di = ni/A, where observation area (A): 60 m² for the shallow zone and A: 200 m² for the deep zone.

Species identification

Sea cucumber species were identified based on external morphological characteristics following the guidelines of Purcell et al. (2023), which serve as the primary reference for Holothuroidea identification in the Indo-Pacific region. In-situ observations were conducted along each transect by documenting key diagnostic features, including dorsal and ventral coloration, body shape, oral tentacle type, surface texture, and the arrangement of papillae and dermal nodules.

The majority of individuals (>90%) were identified directly in the field and documented using a high-resolution underwater camera (Olympus Tough TG-5). For individuals exhibiting ambiguous morphological traits (estimated to represent <10% of total observations), limited visual verification was conducted at the surface using morphological descriptions provided by Purcell et al. (2023). This verification was purely visual and performed without collecting, handling, or removing individuals from their natural habitat, and no microscopic ossicle analysis was undertaken.

Accordingly, species identification in this study combined direct in situ observations with limited visual verification, following internationally recognized guidelines for tropical sea cucumber biodiversity assessments. However, the absence of ossicle analysis may limit taxonomic resolution for morphologically similar species, and therefore potential misidentification cannot be entirely excluded.

Environmental parameters

Water quality parameters, including temperature, salinity, pH, and Dissolved Oxygen (DO), were measured concurrently with sea cucumber population surveys to represent in-situ habitat conditions. Water temperature (°C) was measured using a digital thermometer (Pharmacy and Healthy Tools Center, Indonesia; accuracy ±0.1°C). Salinity (ppt) was measured using a calibrated portable Brix refractometer, while pH was measured using a Ladycare digital pH meter with a resolution of 0.01 pH units.

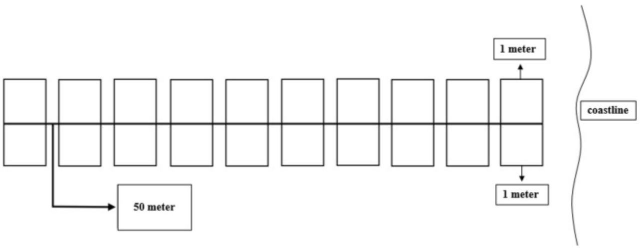

Figure 2. Transect design for sea cucumber sampling at depths <5 meters

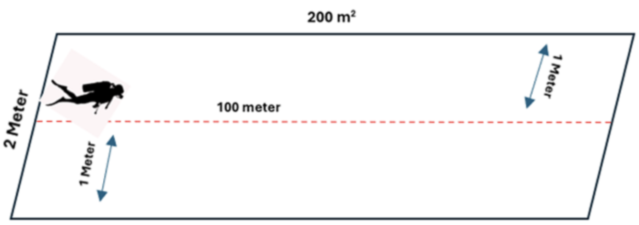

Figure 3. Transect design for sea cucumber sampling at depths >5 meters

Dissolved Oxygen (DO; mg L^{-1}) was measured using a PB-70A pen-type dissolved oxygen analyzer (Mandiri Damai Makmur, Indonesia). This galvanic electrode-based instrument has a measurement range of 0-20 mg L^{-1} and an accuracy of ±0.3 mg L^{-1}. Two-point calibration (zero and saturation) was performed prior to each sampling session using reagents A and B in accordance with the manufacturer's instructions.

Each water quality parameter was measured three times at each station, and mean values were used as representative measurements. All measurements were conducted during low tide between 08:00 and 11:00 WIT. Consequently, the recorded environmental parameters represent a short-term temporal snapshot of conditions during the sampling period and do not capture seasonal variability.

Habitat characteristics were documented through direct field observations, including substrate type (coral, sand, coral rubble, and seagrass) and general benthic condition. All survey locations were photographed using an Olympus Tough TG-5 underwater camera to support interpretation of sea cucumber habitat conditions.

Data analysis

Data analysis was performed to assess the community structure and ecological conditions of sea cucumber populations based on diversity, evenness, dominance, and density across stations and depth strata.

Diversity index (H')

Species diversity was calculated using the Shannon-Wiener Index (H') following Magurran (2013), with the formula:

$$H' = -\Sigma\, pi \ln(pi)$$

Where, pi is the proportion of individuals of species i to the total number of individuals ($pi = ni/N$), ni is the number of individuals of species i, and N is the total number of individuals recorded at a station. The H' value reflects community complexity and is categorized as follows: H'<1: low diversity, 1≤H'≤3: moderate diversity, and H'>3: high diversity (Magurran 2013).

Pielou's Evenness Index (J)

Evenness was assessed using Pielou's Evenness Index (J) (Pielou 1975):

$$J = H'/\ln S$$

Where, S is the total number of species observed. A J value approaching 1 indicates a balanced distribution of individuals among species, whereas values near 0 indicate strong dominance by one or a few species. Evenness levels were classified according to Ulfah et al. (2019): J′<0.4: low, 0.4≤J′≤0.6: moderate, and J′>0.6: high.

Simpson's Dominance Index (D)

Community dominance was analyzed using the Simpson Dominance Index (D) (Simpson 1949):

$$D = \Sigma\, pi^2$$

Where pi is the proportion of individuals of species i. Values of D close to 0 indicate minimal dominance, whereas values approaching 1 indicate strong dominance by one or several species. Dominance categories followed Aulia et al. (2021) and Nurcahyo et al. (2024): D≤0.5 (low dominance), 0.5<D≤0.7 (moderate dominance), and D>0.7 (high dominance).

Density (Di)

Density was calculated according to Mueller-Dombois and Ellenberg (1974):

$$Di = ni/A$$

Where, Di is the density of species i (ind/m²), ni is the number of individuals of species i, and A is the observation area (60 m² for shallow transects and 200 m² for deep transects). Mean density values were then calculated for each station and depth to enable comparison across habitats.

Statistical analysis

Differences in sea cucumber density among stations and depth strata were analyzed using a Generalized Linear Model (GLM) with a quasi-Poisson distribution. This distribution was selected because the response data consisted of count values exhibiting overdispersion and were derived from an unbalanced sampling design (three transects in the shallow zone and one transect in the deep zone). This approach was therefore considered more appropriate than ANOVA, which did not meet assumptions of normality and homogeneity of variance. The number of individuals per transect (ni) was used as the response variable, with Station, Depth, and the Station×Depth interaction specified as fixed factors. To account for differences in transect area between depth strata, an offset term of log(*A*) was included, where *A*: 60 m² for shallow transects and *A*: 200 m² for deep transects. This ensured that model outputs represented standardized densities (ind/m²). Statistical significance was evaluated at α: 0.05 using Type III sums of squares, which are appropriate for unbalanced designs. All analyses were performed using R statistical software (version 4.3.2).

RESULTS AND DISCUSSION

Sea cucumber species in Kapadiri Waters

Based on field observations conducted at depths of <5 m and >5 m, nine sea cucumber species were identified in the waters of Kapadiri Village, Raja Ampat District. The recorded species comprised *Holothuria edulis*, *Holothuria atra*, *Holothuria scabra*, *Actinopyga miliaris*, *Pearsonothuria graeffei*, *Stichopus horrens*, *Stichopus naso*, *Bohadschia argus* and *Thelenota anax*. Species names, local names, and depth occurrence are summarized in Table 2, while photographic documentation of each species is provided in Figure S1.

These species are widely distributed across the Indo-Pacific region, including the South China Sea, Sulu Sea, Sulawesi Sea, and eastern Indonesian waters such as Tual (Woo et al. 2013; Kalidi et al. 2023). Sea cucumber diversity in Kapadiri Waters (9 species) was higher than that reported from Fafanlap and Gamta Waters, Raja Ampat District, where only two species (*H. scabra* and *H. vacabunda*) were previously recorded (Rumlus et al. 2015).

The dominance of *H. edulis, H. atra*, and *H. scabra* in Kapadiri Waters reflects both functional and commercial structuring of the sea cucumber community. *Holothuria scabra* is a high-value commercial species that is widely recognized as highly vulnerable to overexploitation, whereas *H. atra* and *H. edulis* are more tolerant, low to medium-value species that often persist in exploited systems. Similar shifts toward assemblages dominated by resilient, lower-value taxa following the depletion of commercially valuable species have been documented across Indo-Pacific Sea cucumber fisheries, suggesting selective harvesting pressure as a key driver shaping current species composition in Kapadiri Waters.

Water quality parameters

Water quality is a critical factor influencing the survival and distribution of sea cucumbers as well as others marine biota (Tanjung et al. 2019). In this study, physicochemical parameters measured included temperature, salinity, pH, and Dissolved Oxygen (DO), with results summarized in Table 3.

The recorded temperature range reflects typical tropical coastal conditions and falls within values reported to support metabolic and physiological processes of sea cucumbers. Several species recorded in Kapadiri Waters, including *H. scabra*, *H. edulis*, and *A. miliaris*, are known to tolerate and perform well within similar temperature ranges (Purcell et al. 2012; Hamel and Mercier 2013; Padang et al. 2015; Helmiyani et al. 2024). This suggests that thermal conditions in the study area are within the ecological tolerance limits of the observed taxa.

Salinity values recorded during the survey were consistent with ranges commonly reported for Holothuroidea inhabiting shallow tropical waters. Previous studies indicate that most sea cucumber species tolerate salinities between 30 and 35‰ (Al-Rashdi et al. 2013; Cleary et al. 2016), a range that encompasses conditions observed at all stations. Similarly, measured pH values correspond to conditions considered suitable for echinoderms and support key physiological functions in sea cucumbers (Rumlus et al. 2015; Komala et al. 2018).

Dissolved oxygen concentrations indicated well-oxygenated waters that are adequate to meet the respiratory requirements of sea cucumbers. Species recorded in Kapadiri Waters, such as *S. horrens*, have been reported to tolerate DO levels above 4 mg L^{-1} (Hamel and Mercier 2013), suggesting that oxygen availability during the survey period did not pose a limiting factor.

Although measured temperature, salinity, pH, and dissolved oxygen values fell within tolerance ranges reported for tropical sea cucumbers, these environmentally suitable conditions did not correspond with high population densities. This indicates that water quality was not the primary limiting factor controlling sea cucumber abundance during the survey period. Instead, the persistence of low densities under favorable physicochemical conditions suggests that non-environmental drivers, particularly harvesting pressure, play a more critical role in shaping current population status in Kapadiri Waters.

Diversity (H'), Evenness (J), and Dominance (D)

The results of ecological index analyses for sea cucumber communities in Kapadiri Village are summarized in Table 4. Sea cucumber diversity (H') values indicate moderate diversity across stations and depth strata (Magurran 2013; Helmiyani et al. 2024). This pattern suggests that the ecosystem is still capable of supporting multiple species. Comparable diversity levels have been reported from Kemujan and Sintok Islands, Karimunjawa (Yusup et al. 2025), whereas higher H' values are generally observed in well-protected areas such as East Penjaliran Island (Yuniarga et al. 2021).

Evenness values (J) indicate a relatively uniform distribution of individuals among species. However, this high evenness should be interpreted cautiously, as it is associated with low total abundance (N) rather than high population size. Similar patterns have been documented in other Indonesian reef systems, where communities appear evenly structured but persist at low densities (Yuniarga et al. 2021). Such conditions may reflect reduced population size while maintaining proportional representation among species. In this context, high evenness should not be interpreted as an indicator of a healthy community, but rather as a consequence of uniformly low population sizes across species following sustained exploitation, a pattern commonly observed in depleted sea cucumber fisheries.

Dominance Index (D) values indicate the absence of a single strongly dominant species. Nevertheless, low dominance in combination with moderate diversity and low abundance may also reflect shifts away from high-value commercial species under sustained fishing pressure, as reported in other tropical sea cucumber fisheries (Friedman et al. 2011; Arriesgado et al. 2022).

Taken together, the combination of moderate diversity, high evenness, and low dominance suggests a community that remains structurally organized but ecologically vulnerable. Similar index patterns have been interpreted as indicative of early stages of population depletion in exploited sea cucumber assemblages (Friedman et al. 2011; Arriesgado et al. 2022), highlighting the need for conservation-oriented management to prevent further declines in ecosystem function and the loss of economically important species.

Density (Di)

It should be emphasized that the density values reported here represent a snapshot of population status during the August 2025 survey and do not reflect long-term population trends or interannual variability. Sea cucumber density was calculated as the number of individuals per unit area within each transect. Standard Deviation (SD) is reported only for the <5 m depth stratum because density estimates at this depth were based on three transect replicates per station. Density values for each station and depth are summarized in Table 5, and species-specific density variation across stations is illustrated in Figure 4.

Sea cucumber densities in the waters of Kapadiri Village exhibit a consistent spatial pattern across stations and depth strata (Table 5; Figure 4), with all recorded values remaining below 1 ind/m². Density levels below this threshold are widely recognized as indicative of depleted or heavily exploited sea cucumber populations in tropical fisheries (Friedman et al. 2011; Purcell et al. 2013). Such low densities suggest reduced population resilience and a limited capacity for recovery under continued harvesting pressure.

In the shallow zone (<5 m), density patterns varied among stations, reflecting heterogeneous habitat conditions dominated by mixed seagrass, sand, and coral rubble. Differences among stations are likely associated with localized harvesting intensity and habitat openness, particularly in areas subjected to bameti (low-tide gleaning) practices (Hasan 2019). These findings indicate that shallow-water habitats experience stronger direct fishing pressure compared to deeper areas.

Table 2. Sea cucumber species recorded in Kapadiri Waters, Raja Ampat, and their depth occurrence

Scientific name	Local name	<5 m	>5 m
Holothuria atra	Teripang hitam/Keling	+	+
Holothuria edulis	Cera dada/Lakling merah	+	+
Holothuria scabra	Teripang gosok/Teripang pasir	+	+
Actinopyga miliaris	Lotong/Kapuk/Sepatu	-	+
Pearsonothuria graeffei	Bintik merah/Gomboyok	+	+
Stichopus horrens	Kacang goreng	+	+
Stichopus naso	Gamet emas/Gamet kacang	+	+
Bohadschia argus	Bintik/Patola/Cempedak	+	+
Thelenota anax	Donga/Duyung	-	+

Note: (+): Found, (-): Not found

Table 3. Water quality parameters in Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia

Station	Temperature (℃)	Salinity (‰)	pH	DO (mg/L)
Yesbi (ST1)	30.31	34.45	7.6	5.11
Kampung Tua (ST2)	29.40	34.41	7.5	5.02
Yepnan (ST3)	30.29	33.66	7.5	5.14
Tanjung Batu (ST4)	30.31	34.83	7.6	5.21
Paput (ST5)	29.40	34.28	7.5	5.33

Source: Primary data (2025)

Table 4. Diversity (H'), evenness (J), and dominance (D) indices of sea cucumbers in Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia

Depth	Station	N	S	H'	J	D
< 5 meters	Yesbi (ST1)	7	4	1.277	0.921	0.306
	Kampung Tua (ST2)	5	4	1.332	0.961	0.280
	Yepnan (ST3)	7	5	1.550	0.963	0.224
	Tanjung Batu (ST4)	9	6	1.735	0.968	0.185
	Paput (ST5)	10	5	1.557	0.967	0.220
> 5 meters	Yesbi (ST1)	34	7	1.868	0.960	0.166
	Kampung Tua (ST2)	21	6	1.686	0.941	0.206
	Yepnan (ST3)	37	7	1.880	0.966	0.160
	Tanjung Batu (ST4)	42	8	1.947	0.936	0.155
	Paput (ST5)	46	8	2.043	0.983	0.134

Note: N: Total number of individuals recorded per station, S: Number of species

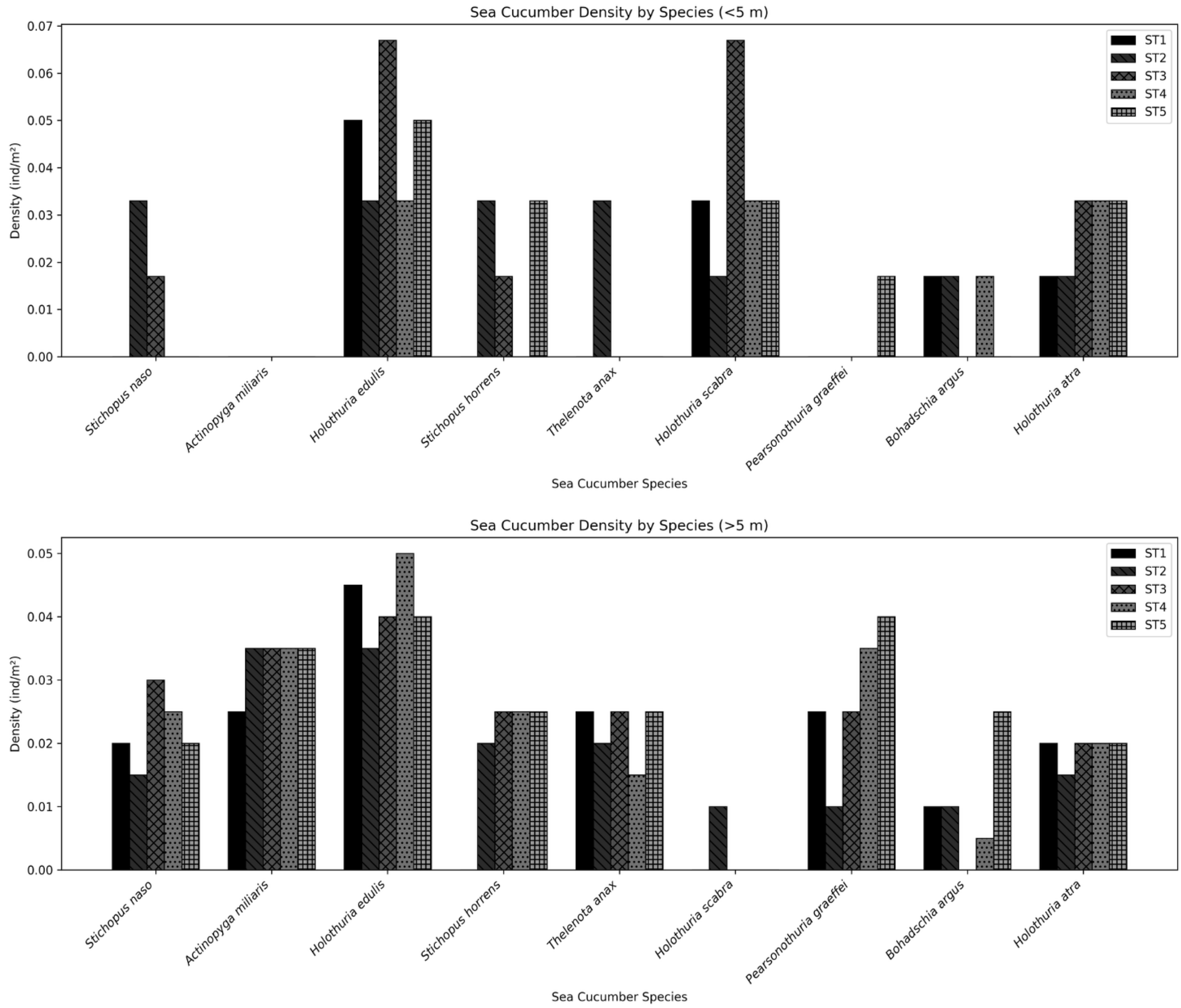

Figure 4. Sea cucumber density based on species in Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia

In contrast, densities in the deeper zone (>5 m) were generally higher across stations (Table 5). This pattern is likely associated with reduced accessibility to fishers, lower harvesting intensity, and more stable environmental conditions at depth. Similar depth-related contrasts have been documented in other regions, including the San Juan Islands, where fishing pressure in shallow waters substantially contributes to declines in sea cucumber density (Carson et al. 2016).

Species-specific density patterns further highlight the combined influence of depth and substrate type on sea cucumber distribution (Figure 4). In the shallow zone, fewer species were recorded, with *T. anax* and *A. miliaris* absent, and densities dominated by *H. edulis* and *H. scabra*, species commonly associated with mixed seagrass-coral habitats rich in organic detritus (Dissanayake and Stefansson 2012; Arriesgado et al. 2022). Conversely, *P. graeffei* occurred at very low densities in shallow waters, consistent with its preference for structurally complex coral substrates.

At depths >5 m, all recorded species were present and generally occurred at higher densities. Several taxa reached higher densities at stations characterized by complex coral habitats, whereas *H. scabra* exhibited relatively lower densities at sites with limited seagrass cover and higher fishing pressure (Purcell 2014). Overall, these patterns reinforce previous findings that depth, substrate complexity, and fishing pressure jointly influence sea cucumber density and spatial distribution (De Guzman and Quinones 2021).

Statistical analysis results (GLM)

The Generalized Linear Model (GLM) analysis showed that depth and station had significant effects on sea cucumber density, whereas the interaction between station and depth was not significant. The Type III sums of squares, F-values, and p-values are presented in Table 6.

Table 5. Sea cucumber density in Kapadiri Waters, Raja Ampat, Southwest Papua, Indonesia, at depths <5 meters and >5 meters

Depth	Station	Di (ind/m²)	Standard Deviation (SD)
<5 meters	Yesbi (ST1)	0.117	0.075
	Kampung Tua (ST2)	0.083	0.047
	Yepnan (ST3)	0.117	0.015
	Tanjung Batu (ST4)	0.150	0.015
	Paput (ST5)	0.167	0.047
>5 meters	Yesbi (ST1)	0.170	-
	Kampung Tua (ST2)	0.105	-
	Yepnan (ST3)	0.185	-
	Tanjung Batu (ST4)	0.210	-
	Paput (ST5)	0.230	-

Source: Primary data, 2025

Table 6. Quasi-poisson GLM results for sea cucumber density

Source of variation	df	SS (Type III)	F	p-value
Station	4	0.0123	4.91	0.012*
Depth	1	0.0158	13.27	<0.001*
Station x Depth	4	0.0041	1.54	0.221 ns

Note: SS: Deviance (Type III); ns: not significant

The quasi-Poisson GLM results indicate that sea cucumber density differed significantly among stations and between depth strata in the waters of Kapadiri Village. The station factor had a significant effect on density, suggesting that local spatial differences contribute to variation in sea cucumber abundance. However, depth exhibited a stronger and more consistent effect, indicating that vertical habitat differences play a dominant role in structuring sea cucumber density within the study area.

In contrast, the interaction between station and depth was not significant, indicating that the relative differences among stations were broadly similar across both depth strata. This suggests that, although habitat characteristics vary among stations, the effect of depth on density does not differ markedly between locations.

It should be noted that the absence of a significant interaction effect may also reflect unequal replication between depth strata, as density estimates in the shallow zone were based on three transect replicates per station, whereas the deep zone was represented by a single belt transect per station. Such imbalance may reduce statistical power to detect interaction effects.

Ecologically, the strong effect of depth on sea cucumber density likely reflects depth-related gradients in accessibility to fishing activities, substrate stability, and habitat complexity. Shallow habitats are more exposed to direct harvesting, particularly through bameti practices, whereas deeper habitats may function as partial refugia. However, as this study is based on observational data from a single survey period, these ecological mechanisms should be interpreted cautiously and cannot be inferred as causal relationships.

Integrated interpretation and management implications

Ecologically, the sea cucumber densities recorded in Kapadiri Village consistently remained below 1 ind/m², indicate populations occurring at low abundance levels typical of exploited sea cucumber fisheries (Purcell et al. 2010). Although a universal density threshold for reproductive success cannot be strictly defined, densities as low as 10-50 individuals per hectare (0.001-0.005 ind/m²) may still permit fertilization in tropical systems (Bell et al. 2008). The observed densities therefore suggest that complete reproductive failure is unlikely; however, densities below approximately 0.5 ind/m² at most shallow stations may increase the risk of reduced reproductive efficiency due to greater inter-individual distances, particularly under continued harvesting pressure and weakening traditional sasi practices.

These density patterns should be interpreted as reflecting the current population status during a single survey period rather than long-term trends. Nevertheless, the consistently low densities observed in Kapadiri align with patterns reported from other exploited regions in Indonesia and contrast with higher densities documented in protected areas, reflecting the characteristic "boom-and-bust" dynamics of tropical sea cucumber fisheries (Anderson et al. 2011; Purcell et al. 2025). Such dynamics may compromise key ecological functions of sea cucumbers, including sediment bioturbation and nutrient cycling (Purcell et al. 2016; Mercier et al. 2025).

Given these site-specific conditions, ecosystem-based and adaptive management approaches are required to address the primary drivers of depletion in Kapadiri Village. Priority actions include spatial protection of productive shallow habitats, locally agreed harvest controls such as size limits and catch restrictions, and the revitalization of community-based management through the integration of traditional sasi practices with contemporary monitoring and enforcement mechanisms.

Limitations

This study has several limitations that should be considered when interpreting the results. First, data were collected during a single survey period, providing only a temporal snapshot of sea cucumber populations and precluding assessment of seasonal variability or long-term trends. Second, differences in sampling design and unequal transect replication between shallow (<5 m) and deep (>5 m) strata may limit direct comparability across depth categories and reduce statistical power for detecting interaction effects. Third, species identification relied primarily on external morphological characteristics without ossicle analysis, which may limit taxonomic resolution for morphologically similar species. Despite these limitations, the study provides a robust ecological baseline.

In conclusion, this study provides the first quantitative ecological assessment of sea cucumber resources in the waters of Kapadiri Village, Raja Ampat, documenting species composition, community structure, and population density across two depth strata. The results indicate moderate species diversity and high evenness but consistently low population densities (<1 ind/m²) across all stations, suggesting that sea cucumber populations are currently occurring at low abundance levels.

These findings represent the ecological condition during the survey period and should not be interpreted as long-term population trends. Nevertheless, the observed density patterns highlight potential constraints on population recovery under continued harvesting pressure, particularly in shallow and easily accessible habitats. Overall, this study establishes an essential site-specific ecological baseline for Kapadiri Village that can support future monitoring, hypothesis testing, and evaluation of adaptive community-based management strategies.

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All interviews were conducted in accordance with established social research ethics and with informed consent from participants. The biota surveys were carried out without collecting or removing specimens, and no protected species were disturbed during the study. Research access was formally granted by the Kapadiri Village Government. All datasets generated during this study, including biodiversity records, density measurements, water quality parameters, and statistical outputs, are available from the corresponding author upon reasonable request.

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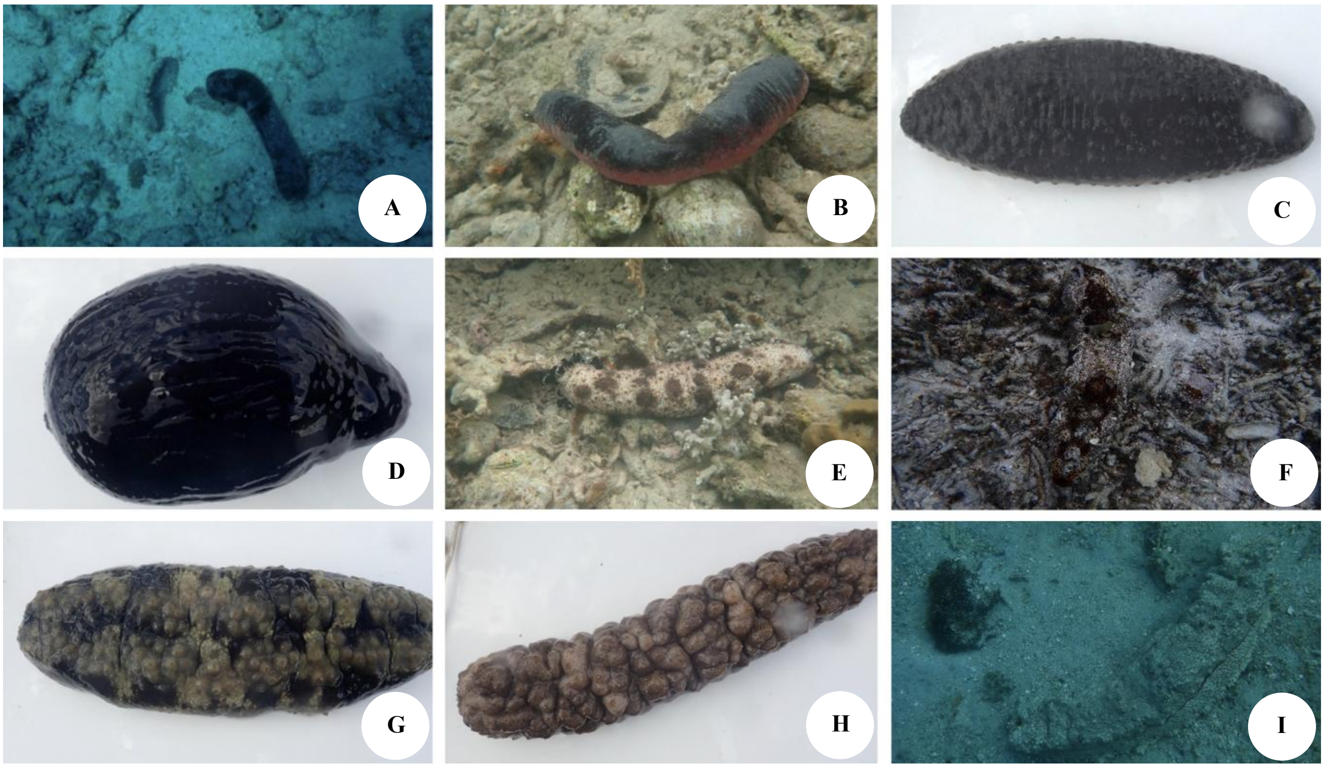

Figure S1. Sea cucumber species identified in the waters of Kapadiri Village, Raja Ampat, Southwest Papua, Indonesia. A. *Holothuria* (*Halodeima*) *atra* (FAO: Lollyfish; Local name: Teripang hitam, Keling), B. *Holothuria* (*Halodeima*) *edulis*, (FAO: Pinkfish/Trepang rose; Local name: Cera dada, Lakling merah), C. *Holothuria* (*Metriatyla*) *scabra* (FAO: Sandfish; Local name: Trepang gososk, Pasir), D. *Actinopyga miliaris* (FAO: Blackfish/Hairy blackfish; Local name: Lotong, Kapuk, Sepatu), E. *Pearsonothuria graeffei* (FAO: Blackspotted sea cucumber; Local name: Bintik merah, Gomboyok), F. *Bohadschia argus* (FAO: Leopardfish/Holothurie leopard; Local name: Bintik, Patola, Cempedak), G. *Stichopus horrens* (FAO: Selenka's sea cucumber; Local name: Kacang goreng), H. *Stichopus naso* (Local name: Gamet emas, Gamet kacang, I. *Thelenota anax* (FAO: Amberfish, Local name: Donga, Duyung, Babi)