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Intertidal gastropod diversity in hard-bottom habitats as an indicator of habitat quality along Tomini Bay Coastline, Gorontalo, Indonesia

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Abstract. *Kadim MK, Pasisingi N, Kasim F, Djunaidi S, Suciyono, Risjani Y, Roem M. 2026. Intertidal gastropod diversity in hard-bottom habitats as an indicator of habitat quality along Tomini Bay Coastline, Gorontalo, Indonesia. Biodiversitas 27 (2): d270207. https://doi.org/10.13057/biodiv/d270207.* Gastropods are reliable bioindicators for evaluating environmental quality. Therefore, understanding their species diversity, especially in hard-bottom habitats is essential for ecological assessment and coastal management. This study aimed to explore the spatial diversity of gastropods inhabiting hard-bottom substrates along the Tomini Bay Coastline in Gorontalo, Indonesia and assess their potential as indicators of coastal water quality. Surveys were conducted at five main stations comprising 21 sub-stations and community structure was analyzed using diversity indices and biotic metrics. A total of 195 species representing 33 families were recorded, with Muricidae, Conidae, and Neritidae as dominant families. *Planaxis sulcatus* together with *Nerita senegalensis* and *Littoraria scabra* contributed substantially to overall abundance. Gastropod diversity exhibited marked spatial variation in community structure among stations. This variation was primarily influenced by turbidity, dissolved oxygen and orthophosphate concentration, which were identified as the key drivers differentiating environmental conditions across sites. Habitat quality assessment indicated slightly polluted conditions but overall maintained good ecological status. These findings demonstrate the sensitivity of intertidal gastropod assemblages to environmental gradients and reinforce their value as effective bioindicators for long-term biodiversity monitoring and coastal ecosystems management in tropical hard-bottom environments.

Keywords: Bioindicator, hard-bottom habitat, intertidal gastropods, spatial diversity, Tomini Bay

INTRODUCTION

Gastropods are important components of tropical marine ecosystems, occurring across mangroves, seagrass beds, and coral reefs-associated habitats, where differences in structural complexity and resource availability shape patterns of diversity and abundance (Baharuddin et al. 2018; Isroni et al. 2023). In intertidal zones, epifaunal gastropods occupy dynamic habitats shaped by tidal exposure, hydrodynamic forces, and microhabitat variability, forming highly diverse communities (Islamy and Hasan 2020). Hard-bottom habitats (such as dead coral, rocky substrates, and coastal structures) provide refuges, feeding and nursery grounds (Marshall et al. 2018). The structural complexity of dead coral and rock surfaces supports biofilms, algae, and sessile fauna that function as food resources and shelter for many taxa, including members of Muricidae, Trochidae, and Cerithiidae (Samsi et al. 2017; Vandarwala et al. 2020).

As grazers and predators, gastropods help regulate algal growth and small invertebrate populations, thus maintaining ecosystem balance (Pinedo and Ballesteros 2019). Owing to their sedentary nature and sensitivity to habitat conditions, they are also effective bioindicators of environmental quality (Suratissa and Rathnayake 2017; Kadim et al. 2022). In hard-bottom systems, community composition and diversity are closely linked to physicochemical conditions (e.g., pH, salinity, oxygen, and temperature) and water quality dynamics (Leiwakabessy and Rumahlatu 2017; Persulessy and Arini 2019; Kadim et al. 2022). However, these habitats face increasing anthropogenic pressures, particularly pollution from maritime activities introducing heavy metals and antifouling compounds into benthic environments (Rumampuk et al. 2019; Natan et al. 2023).

Tomini Bay, located in Gorontalo Province, is part of Indonesia's tropical region and is renowned for its rich marine biodiversity, encompassing coral reefs, reef fishes, seagrass ecosystems and mangroves (Kadim et al. 2018). However, these coastal ecosystems are increasingly threatened by natural disturbances and anthropogenic activities (Kadim and Pasisingi 2018; Kadim et al. 2019; Olii et al. 2024). Understanding contaminant impacts on gastropod communities is therefore critical for the sustainable management of coastal resources. Previous studies in Gorontalo have primarily characterized gastropod assemblages within mangrove and estuarine ecosystems (Daulima et al. 2021; Abukasim et al. 2022; Kasim et al. 2022; Usman and Tuli 2022), with limited investigations in seagrass-associated habitats (Sianu et al. 2014; Laxmana et al. 2017; Saleh et al. 2017). Broader assessments of macrozoobenthic communities, including gastropods, have been undertaken by Kadim et al. (2022), providing important baseline information on species composition and habitat characteristics. However, most of these studies are largely descriptive and provide limited integration of water-quality variables for explaining spatial patterns in gastropod distribution.

The diversity of gastropods associated with hard substrates represents a key intersection of marine biodiversity research, habitat ecology, and environmental assessment (Baxter et al. 2023). Studies across eastern Indonesia and Asia have shown that hard substrates support distinct gastropod communities, with diversity patterns influenced by physicochemical parameters such as salinity and pH, where fluctuations may lead to calcification stress and diversity declines (Bugaleng et al. 2015; Leiwakabessy and Rumahlatu 2017; Persulessy and Arini 2019; Vandarwala et al. 2020; Natan et al. 2023). Nevertheless, most of these findings were derived from other regions such as Maluku, North Sulawesi, and India, and few have focused specifically on dead coral substrates, rocky outcrops, or artificial structures like breakwaters.

In Gorontalo, intertidal hard-bottom habitats along the Tomini Bay Coastline remain poorly documented, particularly regarding spatial community patterns linked to water-quality variation and habitat-quality assessment using biotic indices. This gap is increasingly important given recent reports of extensive dead coral coverage in parts of Gorontalo waters, attributed to combined anthropogenic disturbance and climate-related stressors (Hamzah et al. 2020; Hamzah and Nursinar 2021). Accordingly, this study examined intertidal epifaunal gastropods inhabiting dead coral, rocky outcrops, and breakwaters along the Tomini Bay Coastline in Gorontalo, Indonesia. The objectives were to quantify species richness, diversity, and dominant taxa across sites; describe spatial patterns in community composition in relation to key environmental variables; and assess habitat quality using community-based biotic indices. We expected that gastropod community composition and diversity vary among stations in response to spatial heterogeneity in habitat condition and water quality; that variation in assemblage structure is associated with environmental gradients; and that sites with comparatively degraded water quality tend to exhibit lower diversity and poorer habitat-quality classifications based on biotic indices.

MATERIALS AND METHODS

Study area

This study was conducted in the coastal waters of Tomini Bay, located in Gorontalo Province, Indonesia. Tomini Bay is a semi-enclosed tropical marine basin with high ecological significance, supporting diverse marine life and productive fisheries. The region is influenced by tidal dynamics, riverine input, and anthropogenic pressures, which collectively contribute to spatial heterogeneity in habitat quality and benthic community structure. The surveyed coastal areas are part of Gorontalo Bay, which is a locally recognized segment of Tomini Bay that encompasses both urban and rural coastlines with varying degrees of human disturbance.

The research area spans five administrative regions within Gorontalo Province: Gorontalo City, Bone Bolango District, Gorontalo District, Boalemo District, and Pohuwato District. These regions were designated as main sampling zones, each subdivided into five purposively selected sub-sites (except Gorontalo City and Boalemo District, there are only three sub-sites), resulting in total of 21 sub-sites. Selection was made based on the presence of hard substrates, such as dead coral, natural rocky outcrops, and breakwater structures, within the intertidal zone. Site selection was considered by contrasting levels of anthropogenic disturbance, ranging from areas exposed to intense maritime activities and coastal development to relatively undisturbed, natural environments. This stratification was designed to capture ecological variability and ensure representative coverage of the province's coastal landscape (Figure 1 and Table 1).

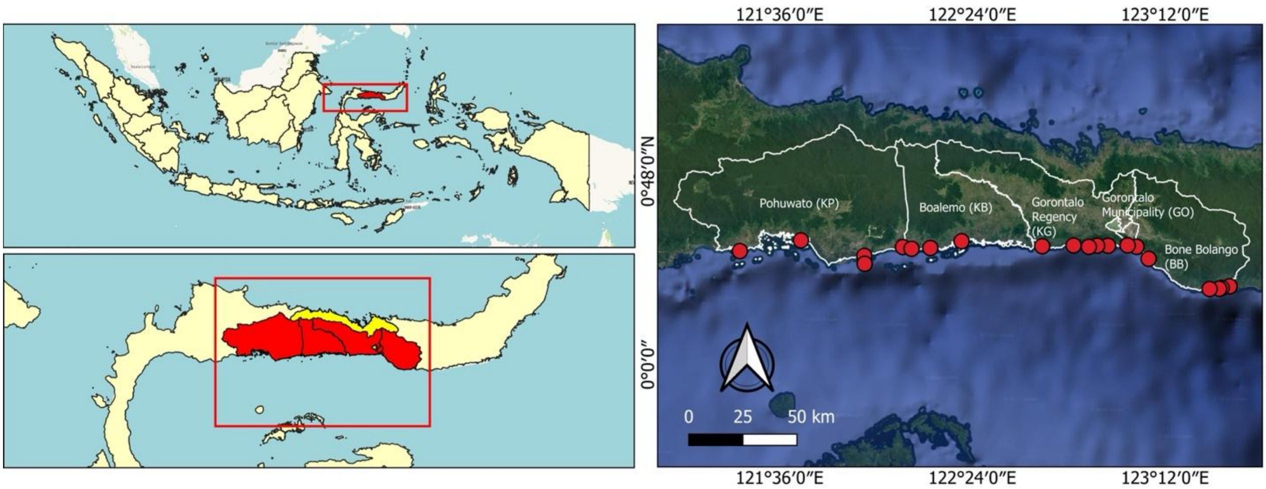

Figure 1. Location of the Research. The red dot (•) indicates the sub-site research location per Station

Table 1. The description of sampling location

Station/Sub-site	Coordinate	Location	Description (Type of hard-substrate)
Pohuwato (KP)			
KP 1	N00°28.17888' E121°26.13108'	Popayato, Torosiaje Laut	Located near the residential areas and adjacent to mangrove stands and aquaculture ponds, dominated by dead coral substrate.
KP 2	N00°30.8358' E121°41.34024'	Wanggarasi	A fishing settlement area with nearby mangrove vegetation and a small boat-landing zone, characterized by natural rocky substrates
KP 3	N00°26.995' E121°57.116'	East Pohuwato, Pohon Cinta Beach	Situated within a tourism area near the Marisa River estuary, composed mainly of rocky and breakwater substrate
KP 4	N00°25.0272' E121°57.21588'	Lahe Island	A small offshore island with minimal anthropogenic disturbance, primarily covered by dead coral substrates
KP 5	N00°29.18676' E122°6.73206'	Paguat, Bumbulan	A commercial harbor and sea-toll area, exposed to heavy shipping activity and dominated by rocky and artificial breakwater structures
Boalemo (KB)			
KB 1	N00°30.62808' E122°21.35454'	Tilamuta, East Pentadu	Fish Landing Site (TPI), located near a mangrove area (substrate type: dead coral)
KB 2	N00°28.9377' E122°13.57002'	Botumoitu, Dulangeya	Fish pond area, adjacent to mangrove vegetation (substrate type: dead coral)
KB 3	N00°28.75776' E122°8.88948'	Mananggu, Kramat	Fishing settlement, tourist area, TPI, and mangrove zone (rocky substrate type and breakwater structures)
Gorontalo District (KG)			
KG 1	N00°29.505' E122°57.851'	East Biluhu	Near a conservation area**,** with a seawall**,** adjacent to an atoll and residential area (substrate type: dead coral)
KG 2	N00°29.523' E122°55.109'	Langgula	Residential area, river mouth, and small jetty (substrate type: dead coral)
KG 3	N00°29.239' E122°53.046'	Olimo'o	Residential area (substrate type: dead coral and rocky substrate)
KG 4	N00°29.584' E122°49.256'	Botuboluo	Tourism area (substrate type: dead coral)
KG 5	N00°29.396' E122°41.444'	Taulaa	Area with minimal disturbance (substrate type: dead coral)
Gorontalo Municipality (GO)			
GO 1	N00°29.249' E123°04.924'	Leato Selatan	Tourism area and fishing settlement (substrate type: dead coral)
GO 2	N00°29.685' E123°02.678'	Leato Utara	Near a harbor and residential area (substrate type: dead coral and rocky substrate)
GO 3	N00°29.593' E123°02.722'	Tanjung Kramat	Fishing settlement and boat landing site (substrate type: dead coral)
Bone Bolango (BB)			
BB 1	N00°19.436' E123°28.109'	Moodulio	Area with minimal disturbance (substrate type: dead coral)
BB 2	N00°19.013' E123°26.134'	Sogitia	Boat landing site, harbor, near river mouth (substrate type: dead coral)
BB 3	N00°18.836' E123°25.489'	Monano	Low-disturbance area near river mouth (substrate type: dead coral)
BB 4	N00°18.770' E123°23.137'	Bilolantunga	Residential area (substrate type: dead coral and breakwater)
BB 5	0°26'16.1"N 123°07'56.4"E	Bintalahe	Tourism area and residential zone (substrate type: dead coral)

Sampling was carried out between December 2024 to February 2025. Spatially distributed sampling locations were selected across multiple districts to capture gradients of ecological pressure and habitat composition, thereby providing insights into how local environmental conditions shape gastropod assemblages on hard-bottom habitats.

Procedures

Sample collection

Gastropod samples were collected during low the tide conditions to ensure accessibility to dead coral substrates and intertidal structures. At each sub-site of station, three line transects (50 × 3 m) were systematically positioned perpendicular to the shoreline to capture shore-normal variability and patchy microhabitats on complex hard substrates while maintaining consistent sampling effort across sites. This design resulting in a total sampling area of 450 m² per sub-site. Transect intervals were ≥100 m to improve the independence of sampling units and to capture variability among discrete substrate patches and local disturbance conditions. Transect placement was guided by the presence of hard substrates, including transitions among dead coral patches, natural rock, and artificial structures. These fixed dimensions were used across all sites to standardize sampling effort, capture intertidal habitat heterogeneity and facilitate quantitative comparisons. Similar transect designs have been widely applied in intertidal macroinvertebrate benthic surveys (Leiwakabessy and Rumahlatu 2017; Kasim et al. 2022). Organisms within each transect were collected using a direct census method with handpicking techniques (Baderan et al. 2021). All observed specimens were initially identified based on shell morphology and diagnostic characteristics using identification keys provided by Baharuddin et al. (2019), Hamli et al. (2024), Islamy and Hasan (2020) as well as verified through the World Register of Marine Species (WoRMS) online database. Identified individuals were counted, photographed, and documented in situ before being returned to their original habitat. Specimens that could not be conclusively identified in the field were collected, stored in labeled plastic containers with 70% ethanol, and transported to the laboratory and retained as voucher specimens for further taxonomic examination and verification. Identification was conducted to the genus or species level when possible. Recorded data included the number of individuals per species, frequency of occurrence, and community structure at each sub-site.

Water quality and heavy metal measurement

Physicochemical water parameters including temperature, Dissolved Oxygen (DO), pH, salinity, and turbidity were measured in situ using a multiparameter water quality checker portable HI98194 series (Hanna, USA). Additional parameters: nitrate, orthophosphate, and lead (Pb); were analyzed ex situ from water samples collected at each station. For this purpose, 500 mL of seawater was collected into acid-washed polyethylene bottles and transported to the laboratory under cooled and dark conditions to preserve sample integrity. Seawater samples for Pb, nitrate, and orthophosphate analyses were processed and analyzed at the Balai Standardisasi dan Pelayanan Jasa Industri (BSPJI) Manado, Indonesia. Water samples were collected during high tide period on the same day and at the same locations as gastropod sampling. This approach was employed to ascertain the benthic water conditions that prevailed at each sub-site. The collected data were intended to characterize spatial variability in water quality and to examine potential correlations between environmental parameters and gastropod diversity patterns. Pb was analyzed by Atomic Absorption Spectrophotometer (AAS) following Indonesian national standard procedures (SNI 6989.46: 2009), while nitrate and orthophosphate were analyzed spectrophotometrically following SNI 19-6964.7-2003 and SNI 06-6989.31-2005, respectively. Calibration and internal quality control were conducted according to the BSPJI procedures.

Data analysis

Gastropod community data were analyzed using several biotic indices and community metrics to assess spatial patterns and ecological status (Kadim et al. 2022; Kasim et al. 2022) which included: species abundance and composition, diversity (Shannon_H, Simpson 1-D, and Evenness e^H/S) and dominance indices. These metrics were used to evaluate the stability, saturation level, and spatial configuration of benthic gastropod communities inhabiting hard substrates.

Gastropod data were also assessed using the AZTI's Marine Biotic Index (AMBI) and M-AMBI by AMBI software (version 5.0, AZTI-Tecnalis), which classifies environmental quality based on the abundance of species indicator and their tolerance to organic pollution (Borja et al. 2019). This biotic index was originally developed for soft-bottom benthic macroinvertebrates. Therefore, its application to hard-substrate gastropod assemblages involves assumptions and potential limitations. In hard-bottom intertidal habitats, community structure may also be strongly influenced by natural physical drivers (Pinedo and Ballesteros 2019), and AMBI/M-AMBI can potentially overestimate ecological status in rocky intertidal settings. Ecological group assignments followed the taxa list on AMBI software. Taxa not included in the AMBI list, classification information was verified and inferred from closely related genera (Zhang et al. 2022). When such as information was unavailable, the taxa were recorded as "unassigned". The proportion of unassigned taxa was reported and considered when interpreting index results. Consequently, AMBI/M-AMBI outcomes were interpreted cautiously and used together with physicochemical variables, the Pollution Index, and multivariate community analyses, focusing on relative comparisons among stations rather than as a stand-alone classification of ecological quality.

Water quality parameters were assessed by comparing measured values with the national marine water quality standards outlined in Indonesian Government Regulation No. 22 in 2021. The ecological condition of coastal waters was further evaluated using the Pollution Index (PI) method, previously applied to Gorontalo Bay (Kadim and Pasisingi 2018). To examine the relationships between environmental factors and gastropod community composition Canonical Correspondence Analysis (CCA) was used. *Cluster Analysis* (UPGMA method; Bray-Curtis coefficient) was used to classify the main station based on similarity in benthic community structure (Suciyono et al. 2024). All core statistical analyses were conducted using SPSS version 22, Microsoft Excel, and PAST version 4.0.

RESULTS AND DISCUSSION

Gastropods diversity and composition

A total of 195 species representing 33 families were successfully identified, encompassing 52,849 individual gastropods recorded across all sub-sites in the study area. Representative photographs of gastropods from each recorded family are provided in Figure 2. The spatial distribution of these taxa revealed notable variation in richness and abundance among districts (Figure 3). Family-level composition was dominated by Muricidae (16.4%), followed by Conidae (12.8%), and Neritidae (10.8%). The remaining families each accounted for less than 7% of the total species representation, with smaller contributions from Trochidae, Columbellidae, and Cypraeidae observed across scattered sub-sites. The pie chart map (Figure 3) summarizes family composition across sub-sites.

Figure 2. Representative photographs of gastropods from each recorded family. A. Bursidae: *Alanbeuella corrugata* (16 mm), B. Cerithiidae: *Cerithium atratum* (14 mm), C. Costellariidae: *Vexillum virgo* (9 mm), D. Neritidae: *Nerita plicata* (14 mm), E. Columbellidae: *Pyrene testudinaria* (16 mm), F. Olividae: *Oliva amethystina* (23 mm), G. Cypraeidae: *Cypraea arabicula* (47 mm), H. Conidae: *Conus ebraeus* (20 mm), I. Fissurellidae: *Fissurella maxima* (15 mm), J. Littorinidae: *Littoraria scabra* (17 mm), K. Lottiidae: *Scurria viridula* (18 mm), L. Patellidae: *Patella longicosta* (27 mm), M. Haliotidae: *Haliotis tuberculata* (24 mm), N. Mitridae: *Strigatella paupercula* (7 mm), O. Pisaniidae: *Engina zonalis* (3 mm), P. Muricidae: *Morula granulata* (19 mm), Q. Volutidae: *Cymbiola vespertilio* (29 mm), R. Nacellidae: *Cellana exarata* (18 mm), S. Siphonariidae: *Siphonaria pectinata* (13 mm), T. Planaxidae: *Planaxis sulcatus* (20 mm), U. Trochidae: *Monodonta labio* (12 mm), V. Strombidae: *Lambis lambis* (107 mm), W. Tegulidae: *Tectus niloticus* (64 mm), X. Nassariidae: *Tritia reticulata* (30 mm), Y. Turbinidae: *Lunella cinerea* (21 mm), Z. Vasidae: *Vasum turbinellus* (38 mm)

A small number of taxa dominated total abundance across the study area. The five most abundant taxa were *Planaxis sulcatus* (Born, 1778) (11,678 individuals recorded at station KP and 8,629 individuals at station KB), followed by *Nerita senegalensis* Gmelin, 1791 (5,602 individuals at station BB), *Littoraria scabra* (Linnaeus, 1758) (3,183 individuals) and *Nerita polita* (Linnaeus, 1758) (1,838 individuals at station KB), as well as *Littorina littorea* (Linnaeus, 1758) (1,386 individuals at station KP). Collectively, these five taxa accounted for approximately 64.62% of the total number of individuals recorded across all sampling stations. Among these taxa, *N. senegalensis* was the only species consistently found at all sampling locations. In terms of total abundance per station, KP exhibited the highest number of individuals (17,827), followed by KB (17,515), BB (11,161), GO (4,262), and KG with the lowest count of 2,084 individuals. A comparative overview of taxa richness and individual abundance across sampling stations is presented in Figure 4.

The spatial analysis of gastropod communities revealed distinct variations in biotic structure across the five administrative regions. Gastropod density ranged widely across the coastline, with highest concentrations observed in sub-sites of KB, KP and parts of BB, as shown in the gastropod density heatmap. These patterns are illustrated in the density distribution shown in Figure 5.A. Furthermore, radar plots embedded in the map indicate variations in environmental parameters that may influence community structure. Analyses of gastropod diversity in hard-substrate intertidal zones (stations KP, KB, KG, BB, GO) revealed marked spatial variations.

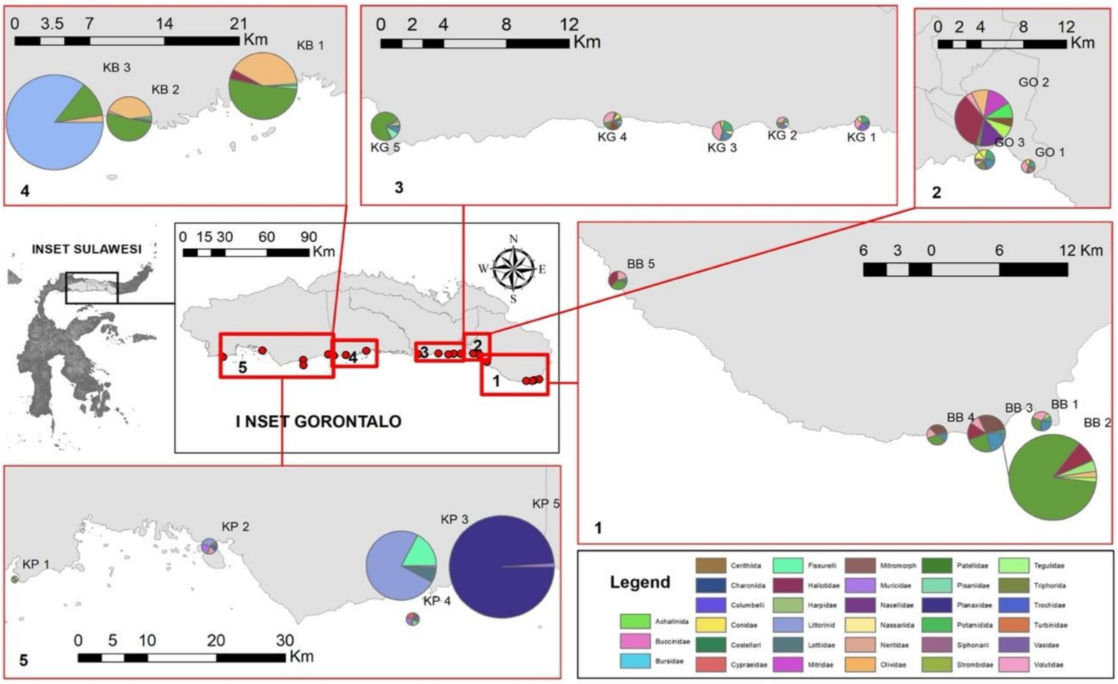

Figure 3. Spatial distribution of gastropod family composition across sub-sites along the Tomini Bay Coastlineal waters of Gorontalo Province, Indonesia. Pie charts represent the relative abundance of dominant families at each sub-site. The size of the pie reflects the total number of individuals recorded. Distinctive community structures indicate varying ecological conditions and habitat types, particularly differences in dead coral, natural rocky outcrops and breakwater substrates

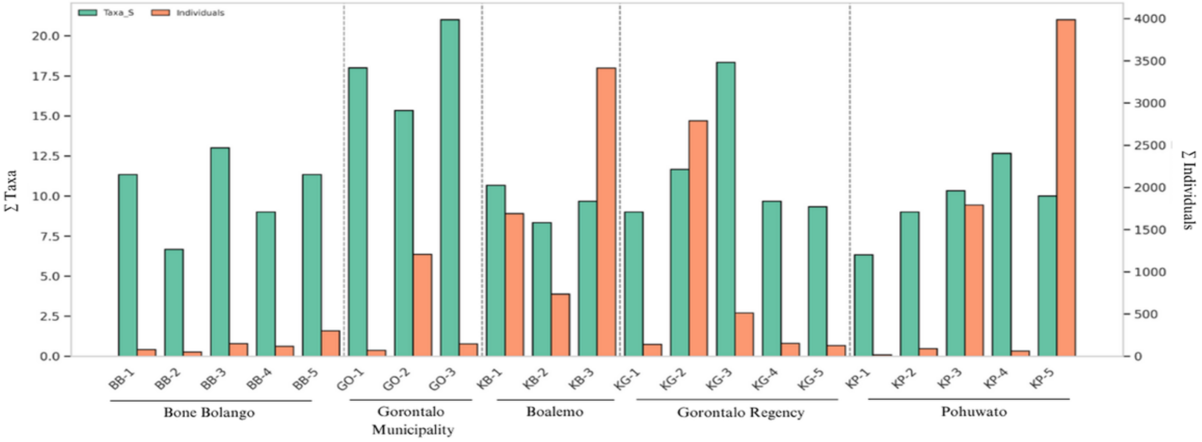

Figure 4. Comparison of the number of taxa and the number of individuals recorded accross observation station

In this study, diversity reflects the species composition of gastropod fauna at sampling locations. The Shannon_H ranged from 0.07 in Pohuwato (KP) to 1.76 in Gorontalo Municipality (GO). Most sampling stations (90.4%) exhibited moderate diversity, suggesting moderate ecosystem productivity and relatively balanced conditions (Sumekar and Widayat 2021), while the remainder (9.52%) fell into the low-diversity category. These findings align with Simpson 1-D (ranged from 0.02-0.95), which indicated that 87.3% of sampling stations supported highly diverse communities, whereas 12.6% exhibited less diverse assemblages. Meanwhile, the evenness e^H/S ranged from 0.09 to 1.07, spanning low to high categories. Approximately 50.8% of sampling sites demonstrated high evenness, 19% moderate, and about 30.2% low. The highest values observed at stations KG5 and KG4, and the lowest at KP5. GO exhibited the highest diversity and evenness, indicating a more balanced community structure. In contrast, Pohuwato (KP5) recorded the lowest evenness and dominance, suggesting a community skewed toward dominant species, possibly due to environmental stressors or reduced habitat heterogeneity. These findings are visually reinforced by the overlay bar charts and index-specific interpolation maps (Figures 5.B-5.D). Overall, the variation in diversity and composition among districts indicates localized differences in community structure.

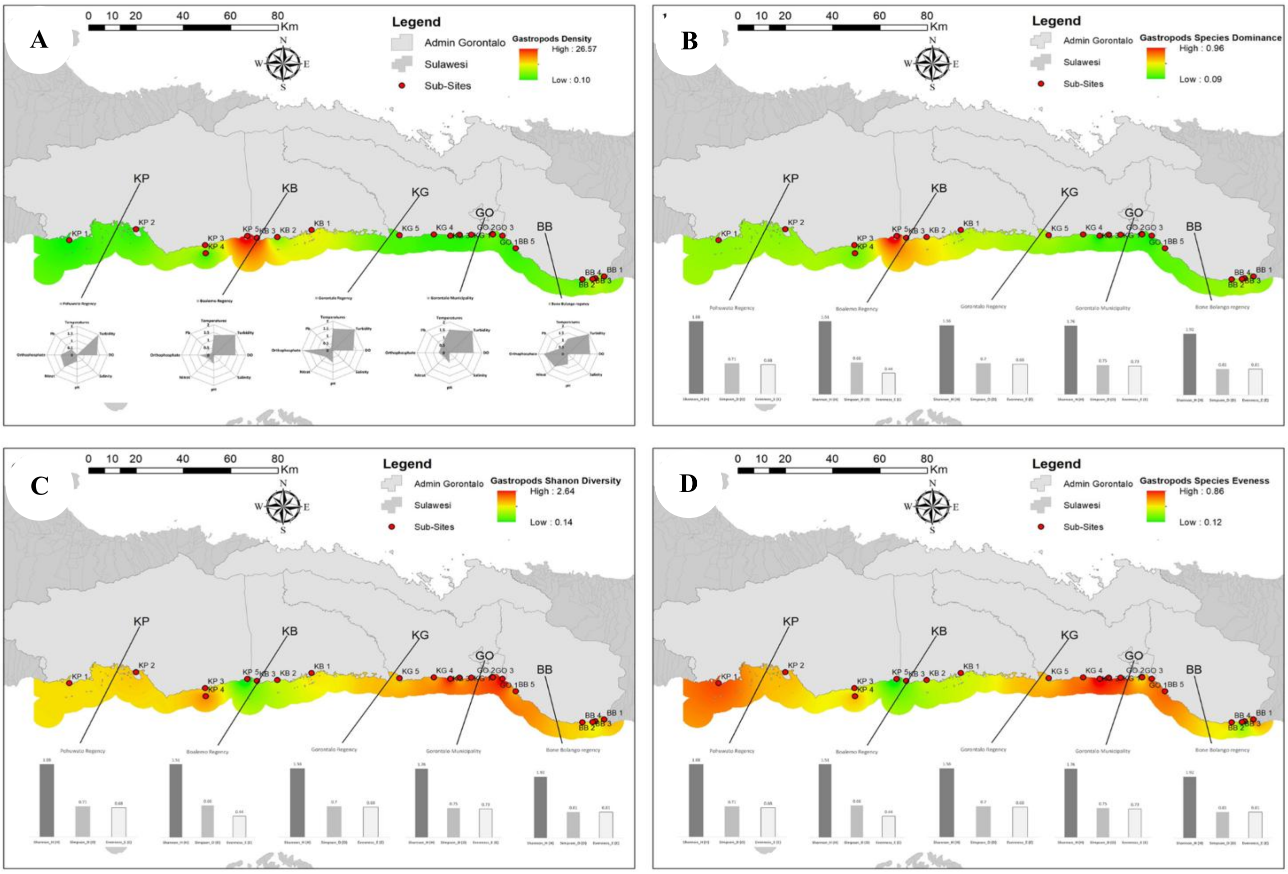

Figure 5. Integrated spatial maps of intertidal gastropod community attributes in Tomini Bay, Gorontalo, Indonesia. Panels show interpolated gradients with station codes and district-level summary plots: A. (Top-Left): Spatial interpolation of gastropod density (individuals·m^{-2}), highlighting areas of high abundance in western Boalemo and eastern Pohuwato. Radar plots illustrate the corresponding water quality parameter averages per district; B. (Top-Right): Dominance Index (Simpson's 1-D), showing localized dominance patterns in Boalemo and KP5. Accompanying bar charts indicate regional dominance trends; C. (Bottom-Left): Shannon_ H, highest in Gorontalo Municipality and Bone Bolango, lowest in Boalemo; D. (Bottom-Right): Evenness, indicating the degree of uniformity in species distribution. Highest in Gorontalo Municipality and KP sites, and lowest in Boalemo. The spatial heterogeneity across panels suggests a combined influence of habitat substrate (dead coral vs breakwater), anthropogenic gradients, and physicochemical parameters on gastropod assemblages

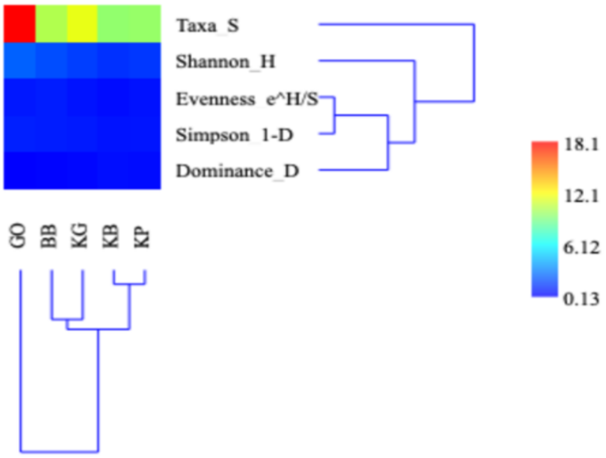

Figure 6. Heatmap and hierarchical clustering of community structure indices across five administrative stations. The color gradient indicates index values, while dendrograms visualize ecological similarity among sites and metrics

To explore spatial similarity in community structure, a heatmap with hierarchical cluster analysis was employed (Figure 6), which divided the sampling stations into three distinct groups, thereby reflecting spatial variations in community structure. The resulting dendrogram demonstrated that stations KG and BB were grouped within the same cluster, as well as KB and KP. Station GO formed a separate branch in the dendrogram relative to other sites.

Environmental conditions and their correlation with Gastropod communities

Water quality parameters were employed to characterize the hydrographic conditions at the sampling stations. The recorded physical and chemical parameters during sampling reflected the water quality of Tomini Bay, Gorontalo Province, at the time of observation. Despite the relatively variable parameter values, the water quality at each observation station remained supportive of gastropod life. The results of water quality measurements are presented in Table 2.

Table 2. Summary of the physicochemical water quality parameters measured accross observation stations during the study period

Stations	**Concentration (Mean ± SD; min - max)**							
	Temperature (°C)	**pH**	**DO (mg·L^{-1})**	**Salinity (ppt)**	**Turbidity (NTU)**	**Ortophosphate (mg·L^{-1})**	**Nitrate (mg·L^{-1})**	**Pb (ppm)**
KP	27.4 ± 4.0	7.7 ± 0.3	6.6 ± 1.3	31.6 ± 1.2	2.53 ± 2.60	0.0137 ± 0.009	0.0507 ± 0.019	0.0145 ± 0.004
	19.9 - 31.4	7.1 - 8	4.3 - 8.1	30 - 34	0.44 - 7.73	0.0027 ± 0.03	0.03 - 0.09	0.011 - 0.023
KB	30.63 ± 0.49	7.89 ± 0.12	6.79 ± 0.053	31.67 ± 0.31	2.64 ± 4.43	0.017 ± 0.012	0.162 ± 0.181	0.044 ± 0.074
	30.1 - 31.4	7.7 - 8.12	5.6 - 7.2	31 - 33	0.41 - 14.2	0.0083 - 0.041	0.05 - 0.62	0.013 - 0.024
BB	30.18 ± 0.79	8.1 ± 0.46	7. 45 ± 0.92	31.02 ± 1.15	1.32 ± 1.79	0.009 ± 0.005	0.047 ± 0.022	0.013 ± 0.002
	29.1 - 32.4	6.6 - 8.5	6.1 - 9.5	29. 7 - 33.7	0.16 - 7	0.0026 - 0.02	0.002 - 0.0011	0.11 - 0.21
GO	31.02 ± 0.54	8.00 ± 0.36	7.38 ± 0.69	31.11 ± 0.93	2.33 ± 2.34	0.022 ± 0.018	0.148 ± 0.176	0.012 ± 0.002
	30.1 - 30.8	7.74 - 8.75	6.01 - 8.05	30 - 32	0.42 - 7.49	0.0054 - 0.057	0.05 - 0.61	0.007 - 0.014
KG	30.97 ± 0.98	8.26 ± 0.15	6.59 ± 1.10	30.25 ± 2.06	1.39 ± 1.51	0.007 ± 0.005	0.095 ± 0.075	0.044 ± 0.059
	29.3 - 32.9	8 - 8.5	4.2 - 8.5	24.2 - 33	0.025 - 5.3	0.0025 - 0.022	0.03 - 0.33	0.009 - 0.21
Limit*	28 - 30	7 - 8.5	>5	33 - 34	5	0.06	0.015	0.008

Note: Water quality standards for marine biota based on Indonesian Government Regulation No. 22 in 2021

Dissolved Oxygen (DO) levels were generally >5 mg·L^{-1}, providing adequate respiratory support for benthic macroinvertebrates (Musale et al. 2015), including gastropods (Croijmans et al. 2021). However, several sub-sites (KP1, KG2) approached lower thresholds, indicate reduced water mixing or localized organic decomposition. Water temperature ranged from 19.9-32.9°C, with the highest values recorded in KG, reflecting typical fluctuations associated with tidal exposure and local environmental conditions. Temperature influences metabolic rates, feeding patterns, and tolerance to emersion stress, thereby shaping competition and survival ratios which ultimately affect community structure and evenness (Prayudi et al. 2024). Salinity varied from 24.2-34 ppt, lowest across most KG sites. Salinity is a primary controlling factor for macrozoobenthic distribution in coastal ecosystems (Dolbeth et al. 2019; Kadim et al. 2022). Freshwater input (Suciyono et al. 2024) and the bay's open, wide, indented mouth (Izegaegbe et al. 2023) accounted for local salinity gradients among sampling points in KP, GO, and KG, although these values remained within optimal tropical marine ranges. pH ranged 6.6-8.8 (neutral to alkaline), but the low pH at BB1 could impair shell calcification in gastropods (Samsi et al. 2017). Turbidity (0.03-14.2 NTU) generally allowed adequate light penetration, although several points in KP, GO, and KG exceeded the quality standard (>5 NTU).

Nitrate (0.02-0.62 mg·L^{-1}) and orthophosphate (0.0025-0.057 mg·L^{-1}) concentrations indicate predominantly oligotrophic to mesotrophic conditions (Le et al. 2022), consistent with Herawati et al. (2025) who reported <0.05 mg·L^{-1} in minimally impacted areas. Slightly elevated phosphate values at GO, KB, and KP indicate emerging anthropogenic input with a potential to alter benthic assemblages, including gastropods (Lei et al. 2025). Lead (Pb) in water ranged 0.007-0.24 mg·L^{-1}, with maxima in parts of KB and KG. The widespread occurrence of Pb suggests chronic exposure plausibly linked to shipping, antifouling paints, and urban runoff (Rozirwan et al. 2025). Sedimentary Pb accumulation could pose long-term risks to epibenthic fauna, including gastropods.

Overall, the data indicate that hydrographic conditions among the sampling stations were relatively similar. To quantitatively assess the environmental status of the study area, the Pollution Index (PI) method was applied, using the national marine water quality standards (Indonesian Government Regulation No. 22, 2021) as reference thresholds. This approach facilitates a multi-parameter evaluation of water pollution, integrating both nutrient and heavy metal indicators. Pollution Index scores were calculated based on eight key parameters: temperature, turbidity, Dissolved Oxygen (DO), salinity, pH, nitrate (NO_3^-), orthophosphate (PO_4^{3-}), and lead (Pb). The index values for each sub-site indicated that the majority of sites fell within the "slightly polluted" (PI 1.0-5.0) category, consistent with slight deviations above threshold values for nitrate and Pb in certain locations, particularly in KB and KG (Table 3).

To further evaluate ecological drivers underlying these biotic patterns, a Canonical Correspondence Analysis (CCA) was conducted using 8 environmental variables. Axis 1 reflected gradients in dissolved oxygen, temperature, turbidity, and nutrients (nitrate, orthophosphate), while Axis 2 captured differences in species dominance and diversity, indicated by Shannon_H′ and Simpson 1-D indices. The ordination indicated a positive association of species evenness with turbidity and Dissolved Oxygen (DO), while Shannon diversity (H′) was influenced by salinity and orthophosphate levels. Pb concentration and temperature were negatively correlated with both indices (Figure 7.A). As illustrated in Figure 7.B, spatial similarity patterns among stations were also reflected. A high similarity was observed between stations KG and BB, which were subsequently grouped with station GO and KB. In contrast, station KP diverged into a separate branch.

Table 3. The water quality status at the study sites based on the analysis using the Pollution Index (PI) method

Stations	IP score	Status
KP	1.6 - 3.84	Slightly polluted
KB	2.38 - 2.76	Slightly polluted
BB	1.5 - 4.47	Slightly polluted
GO	2.37 - 4.13	Slightly polluted
KB	2.35 - 8.51	Slightly polluted-Moderate

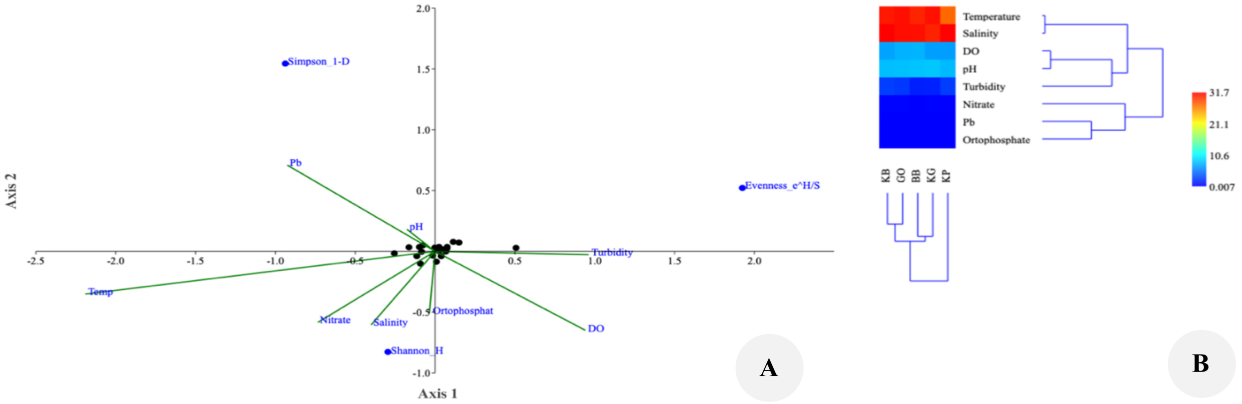

Figure 7. Overview of: A. Canonical Correspondence Analysis, Axis 1 and Axis 2 explained 84.7% and 15.3% of the community response to environmental variation. The ordination was significant (F=2.197, p=0.015); B. Heatmap and hierarchical clustering of water quality parameters. The dendrograms visualize ecological similarity among sites and metrics

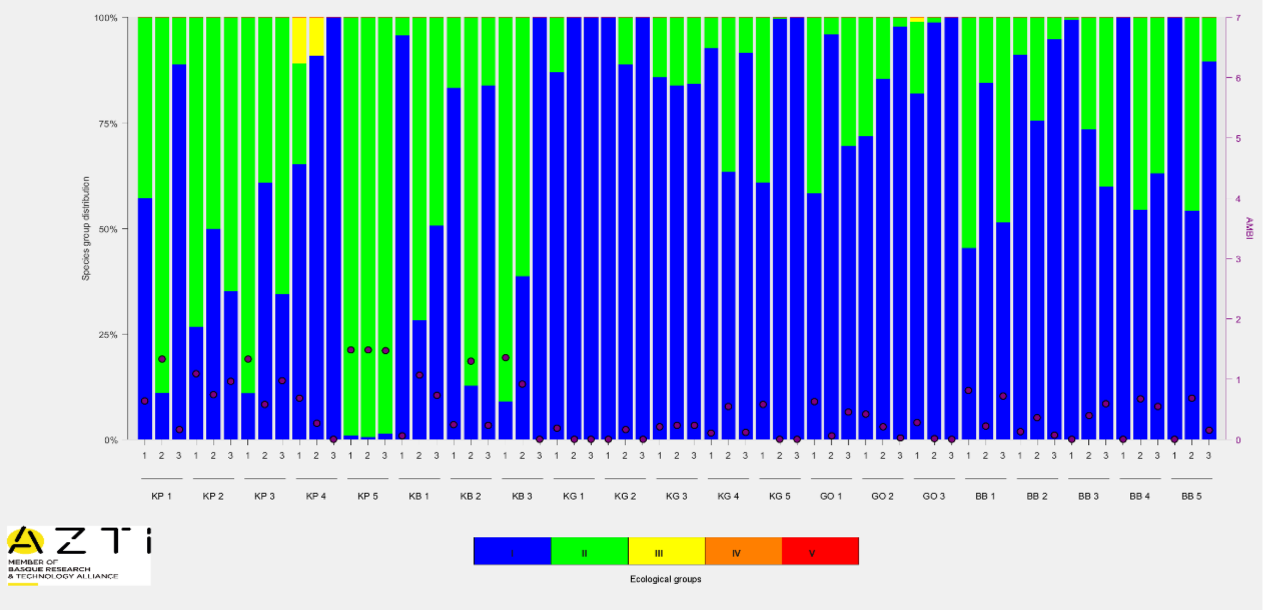

Figure 8. Classification of gastropod species into Ecological Groups (EG) derived from AMBI analysis

Bioindicator assessment using AMBI

The ecological condition of intertidal habitats across 5 stations (21 sub-sites) was assessed using the AZTI's Marine Biotic Index (AMBI), which classified benthic community responses to organic enrichment and environmental disturbance. AMBI has been adapted for molluscan communities, including gastropods, in tropical benthic assessments (Pruden et al. 2021). The Gastropod samples identified along the coastal zone of Tomini Bay, Gorontalo, during this study were subsequently classified into five Ecological Groups (EG) based on their responses to stress gradients resulting from organic enrichment (Borja et al. 2019; Lu et al. 2021). These groups represent responses to the initial environmental conditions and subsequent transitions toward mild to severe ecological imbalance (Hartati et al. 2024). The AMBI analysis results are shown in Figure 8.

The AMBI analysis generally indicates that Gastropod EG falls within the EG-I category, comprising species that are highly sensitive to organic enrichment and typically inhabit unpolluted environments, or species that are sensitive to disturbance (Zhou et al. 2018). EG-II, representing species unaffected by organic enrichment, was observed in small populations with negligible differences. EG-II was detected at several sampling sites, specifically at Pohuwato (KP4) and Gorontalo Municipality (GO). Standard deviations for AMBI scores across sub-sites are presented in Table 4. The results indicate that most sub-sites (20 out of 21) were classified as "high or undisturbed" (AMBI < 1.2), suggesting that gastropod communities at these locations were dominated by species tolerant to minimal or no disturbance. These include all sub-sites in Boalemo (KB), Bone Bolango (BB), Gorontalo Municipality (GO), and Gorontalo District (KG), with mean AMBI scores ranging from 0.056 to 0.968.

As shown in Table 4, only one sub-site (KP 5) in Pohuwato District (KP) was classified as "Slightly disturbed" category (AMBI = 1.483±0.006). The low standard deviations at most sub-sites (e.g., GO3 = 0.101±0.16, KG2 = 0.056±0.096) reflect consistent benthic community composition within those sites. In contrast, higher variability at sub-sites such as KB3 (0.76±0.695) and KP1 (0.714±0.587) may suggest localized habitat heterogeneity or patchy disturbances. These results affirm the utility of AMBI in characterizing ecological conditions using intertidal gastropods, especially when combined with supporting environmental metrics and diversity indices. Moreover, the AMBI findings align with previous assessments of coastal water quality in Tomini Bay (Kadim and Pasisingi 2018), confirming the generally low anthropogenic pressure in most surveyed locations.

Discussion

Benthic ecosystems exhibit high species diversity (approximately 90%) compared to pelagic ecosystems and play a critical role through complex trophic interactions in benthic material cycling and energy flow (Pruden et al. 2021). The diversity of macrobenthic communities, including gastropods, is also a key indicator for evaluating benthic ecological quality status (Roveri et al. 2020). The hydrographic conditions across stations in the present study were generally within ranges suitable for benthic macroinvertebrates. The CCA performed in this study revealed strong associations between environmental gradients and gastropod community structure in hard-substrate habitats along Tomini Bay. Spatial variation among five stations was driven by physical, chemical, and habitat factors. The first two axes explained most of the constrained variation (Figure 7.A). Turbidity, dissolved oxygen (DO), and orthophosphate were the primary drivers structuring hard-substrate intertidal gastropod communities in Tomini Bay, with temperature, salinity, and Pb acting as secondary modifiers. Although Pb showed weaker influence relative to other parameters, its ordination pattern indicates that moderate concentrations may still contribute to variation in assemblage composition. Given gastropods susceptibility to metal accumulation, even moderate Pb levels may alter species composition and reduce ecological stability. Combined effects of turbidity/nutrients and heavy metals may accelerate local community homogenization. Gastropods, as mollusks, are vulnerable to heavy metal accumulation through water, sediments, and the food chain (Sembel et al. 2022; Izegaegbe et al. 2023). Contaminated sites commonly show reduced diversity with increasing representation of tolerant taxa (Sahidin et al. 2018).

The spatial patterns of the three indices in this study reveal a gradient of decreasing diversity from the eastern to the western coastline of Tomini Bay, where the eastern to central areas (BB, GO, and KG) tend to exhibit higher index values compared to the western sites (KP and KB). Bone Bolango displayed the most balanced community structure. Although it did not have as many species as GO, its distribution was more even. Interestingly, stations GO and BB were located near port activities and settlements and influenced by river mouths, which theoretically could increase turbidity, nutrient loads, and organic matter, potentially reducing habitat quality and benthic biodiversity. This pattern is likely driven by water circulation and tidal mixing. Tomini Bay is characterized by strong cross-bay currents with semi-cyclic circulation from west to east, driven by tidal patterns and monsoon winds. GO and BB, located in the northeastern part of the bay, likely benefit from this circulation system, where suspended materials from river mouths are efficiently dispersed into the open sea rather than accumulating locally.

In port areas and densely populated coastal zones such as GO and BB, the presence of artificial structures (breakwaters, piers, and coastal armoring) provides new microhabitats for epibenthic organisms, including gastropods. These hard structures not only increase substrate heterogeneity but also help trap fine sediment particles (Ríos-Jara et al. 2020), maintaining suitable surfaces for the colonization of grazer and filter-feeder species (Baxter et al. 2023). Studies by Bishop et al. (2022) and Afzali and Nasrolahi (2025) have shown that engineered rocky structures can enhance benthic diversity compared to natural substrates in areas under high anthropogenic pressure, provided that adequate water exchange occurs.

Based on the research data, stations GO and BB occupy multivariate positions that reflect relatively balanced environmental conditions between physicochemical parameters and substrate heterogeneity, thereby supporting higher species diversity. These stations exhibited relatively higher DO and lower turbidity and nutrient levels, consistent with conditions known to support diverse benthic assemblages in tropical hard-substrate environments (Mustapha and Marshall 2021). DO stability is a key determinant for the sustainability of benthic communities in tropical intertidal ecosystems, as it influences energy availability for species sensitive to oxygen deficits (He et al. 2025). Heterogeneous micro-niches at these stations may support species with varied ecological strategies, contributing to diverse community structure (Croijmans et al. 2021; Neubauer et al. 2021). The occurrence of *N. senegalensis* at all stations may reflect broad habitat tolerance and wide ecological amplitude in intertidal hard-substrate environments.

Table 4. AMBI scores and classification of ecological quality status at the sampling stations

Stations	Sub-sites	AMBI score (Mean ± SD)	Classification
Pohuwato (KP)	KP1	0.714 ± 0.587	Undisturbed
	KP2	0.94 ± 0.176	Undisturbed
	KP3	0.968 ± 0.374	Undisturbed
	KP4	0.319 ± 0.345	Undisturbed
	KP5	1.483 ± 0.006	Slightly disturbed
Boalemo (KB)	KB1	0.625 ± 0.516	Undisturbed
	KB2	0.599 ± 0.613	Undisturbed
	KB3	0.76 ± 0.695	Undisturbed
Bone Bolango (BB)	BB1	0.592 ± 0.316	Undisturbed
	BB2	0.192 ± 0.153	Undisturbed
	BB3	0.335 ± 0.3	Undisturbed
	BB4	0.412 ± 0.362	Undisturbed
	BB5	0.28 ± 0.359	Undisturbed
Gorontalo Municipality (GO)	GO1	0.381 ± 0.29	Undisturbed
	GO2	0.224 ± 0.195	Undisturbed
	GO3	0.101 ± 0.16	Undisturbed
Gorontalo District (KG)	KG1	0.065 ± 0.113	Undisturbed
	KG2	0.056 ± 0.096	Undisturbed
	KG3	0.23 ± 0.016	Undisturbed
	KG4	0.26 ± 0.249	Undisturbed
	KG5	0.196 ± 0.337	Undisturbed

In contrasts, KB and KP which have semi-enclosed coastal morphologies and shallow waters, exhibited lower diversity and more uneven community structures. Consistent with previous studies, reduced water movement in semi-enclosed systems is often associated with increased nutrient and sediment retention (Man et al. 2025). Parts of stations KP and KB exhibited lower species richness but recorded the highest gastropod abundance among the other stations along the Tomini Bay Coastline. At both stations, an average of nine taxa and nine species were found at each sub-site, dominated by a few tolerant taxa. Quantitatively, station KP recorded a total abundance of 17,872 individuals, with a community dominated by *P. sulcatus* (65.5%), followed by the family of Littorinidae, particularly *L. littorea* (22.7%). A similar pattern was observed at station KB, with a total of 17,515 individuals, dominated by *P. sulcatus* (49.2%), followed by *Nerita* sp. (28.0%) and *L. scabra* (18.2%). The dominance of one or two species with high proportions at these stations indicates a relatively uneven community structure, resulting in overall lower diversity index (H′) values compared to other stations in the study area, suggesting environmental filtering in response to localized stressors.

The low gastropod diversity at stations KP and KB can be attributed to high turbidity levels and increased nitrate and orthophosphate concentrations observed at these sites. Such conditions may reduce light penetration to the seabed, influence food availability and alter gastropods species compotition in hard-substrate habitats (Tuttle-Raycraft et al. 2017). Simultaneous increases in turbidity and nutrients can shift gastropod community composition (Lajtner et al. 2022; Sahu and Haldar 2022) from herbivorous species such as *Littoraria* sp. toward dominance by tolerant species such as *Nerita* sp. or *Cerithium* sp. (Serranito et al. 2022; Keerthana et al. 2023), which were also recognized as indicator species for heavy metal pollution (Cheng and Yap 2015; Ismail et al. 2017) and effective bioindicators of metal exposure in intertidal zones (Haris et al. 2020), Both species were found at all sampling stations. Similar phenomena are often observed in intertidal ecosystems experiencing anthropogenic disturbances or physical stress from increased sedimentation and turbidity (Olii and Pasisingi 2022; Lei et al. 2025). The dominance of *P. sulcatus* and *Littorina* spp. in dominating these areas may be linked to their physiological and morphological adaptations to environmental stress (elevated turbidity and nutrient levels), including efficient aerial respiration, thick shells, and aggregative behavior to minimize water loss during low tide phases. Consistent with their known tolerance to variable intertidal conditions (Marshall and Tsikouras 2023).

The gastropod diversity exhibited a clear spatial gradient in the present study. This pattern reflects an ecological gradient from more stable and complex conditions in the east toward more degraded conditions in the west. The gradient also reinforces the relationship between environmental conditions and community structure identified through biotic index analysis (AMBI), as shown in Table 4 and Figure 8. Although AMBI is widely recognized for assessing benthic ecological quality, its development for soft-bottom macrofauna may limit its applicability to tropical hard-bottom habitats dominated by gastropods. Previous research (Pruden et al. 2021) demonstrated that applying AMBI exclusively to molluscan assemblages introduces constraints, primarily due to the incomplete representation of tolerant taxa. In contrast, the multimetric M-AMBI approach, which integrates richness and diversity, substantially improves classification accuracy. Accordingly, a M-AMBI analysis was conducted to further assess benthic habitat quality. Detailed graphical results for all observation stations are presented in Figure 9.

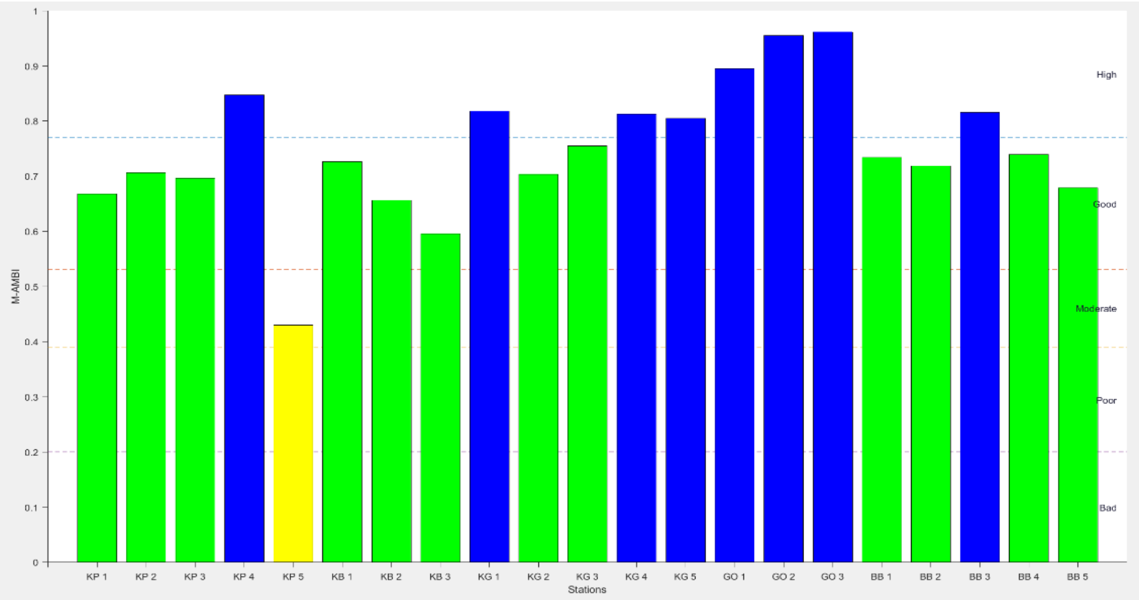

Figure 9. Graphical representation of M-AMBI analysis results showing the benthic habitat quality status. Note: Green: g=Good, Blue: High, Yellow: Moderate

The analysis revealed that M-AMBI values ranged from 0.43 to 0.96, indicating that only about 38.1% of sites were classified as excellent, 57.1% as good, and 4.8% as moderately disturbed. The application of AZTI's Marine Biotic Index (AMBI), M-AMBI, and Pollution Index (PI) in this study provided converging yet complementary insights into the ecological status of intertidal habitats. AMBI scores across the 21 sub-sites predominantly, showed that KP5 differed from other sub-sites in its AMBI classification and score (Table 4). As shown in Figure 9, GO and BB exhibited relatively better habitat quality. Meanwhile KP5 showed slight disturbance with moderate habitat quality. This sub-site showed a reduced number of sensitive taxa and increased dominance of tolerant/opportunistic gastropods, indicating the early signs of organic enrichment or localized anthropogenic pressure. This pattern was also supported by higher nutrient and turbidity levels observed in KP5 (see Table 2), further corroborating the ecological signal detected by the AMBI. Moreover, the AMBI results align with previous assessments of coastal water quality in Tomini Bay (Kadim and Pasisingi 2018), confirming the generally low anthropogenic pressure in most surveyed locations.

However, to complement the taxonomic approach of AMBI, we incorporated Pollution Index (PI) analysis based on physicochemical parameters (Table 3). The PI values indicate spatial variation in water quality, where sub-sites such as KP5, KB3, and GO2 registered moderate to high pollution levels, mainly driven by elevated concentrations of Pb, nitrate, and turbidity. These findings correspond with the lower evenness and dominance indices found in those sites and reinforce the interpretation that water quality degradation directly influences benthic stability and biodiversity. This integration of biotic and abiotic indicators provides a more comprehensive and validated assessment of ecological health. AMBI, while reliable for identifying biological responses, may under-represent chemical stressors like heavy metals if not mirrored by changes in community structure. Conversely, PI highlights contaminant loads but cannot reflect ecological consequences without biological data. The synergy between both indices enhances the diagnostic power for environmental monitoring, especially in transitional coastal zones where substrate heterogeneity and pollution sources intersect.

Overall, this study demonstrates that spatial variability in gastropod communities along the Tomini Bay Coastline is strongly shaped by differences in water quality, flushing capacity, and substrate heterogeneity. Stations with higher water exchange and stable hard-bottom microhabitats (GO and BB) supported more diverse and even assemblages, whereas semi-enclosed areas with elevated turbidity and nutrient loading (KP and KB) were characterized by reduced richness and the dominance of tolerant taxa. These patterns highlight the value of gastropods as sensitive bioindicators for detecting early ecological change in hard-substrate intertidal systems. Integrating biotic metrics (AMBI, M-AMBI, Shannon, Simpson, Evenness) with multimetric CCA and physicochemical assessments (Pollution Index) provides a robust approach for identifying areas where anthropogenic pressure and limited hydrodynamic renewal may compromise ecological stability. The spatial baseline established here offers a foundation for long-term monitoring, particularly in tracking shifts related to sedimentation, nutrient enrichment, and coastal development. These findings can help inform coastal management in Tomini Bay by identifying priority zones for conservation, guiding placement of monitoring sites, and supporting decisions on habitat protection or restoration in areas vulnerable to environmental degradation.

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