

Bivalve community structure in relation to soil and porewater properties in Benoa Bay, Bali, Indonesia

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Abstract. *Indrawan GS, Arthana IW, Suartini NM, Hendrawan IG, Sugiana IP. 2026. Bivalve community structure in relation to soil and porewater properties in Benoa Bay, Bali, Indonesia. Biodiversitas 27 (3): d270301. <https://doi.org/10.13057/biodiv/d270301>.* Coastal ecosystems support benthic communities that are sensitive to environmental changes, making bivalve community structure a reliable indicator of ecological condition. This study examined relationships between bivalve community structure and soil and porewater properties at seven stations in Benoa Bay, Bali (n: 7 stations). Bivalve sampling used a transect-quadrat approach and recorded 19 species, with spatial variation in richness and density. Soil parameters included total organic matter (TOM, 2.55-4.60%), pH (6.05-6.89), soil fractions (gravel, sand, silt, clay), and water content (0.32-0.59). Porewater properties measured at 30-60 cm depth included temperature (26.1-28.1°C), pH (6.27-7.17), salinity (23.1-28.9 ppt), redox potential (-51 to -98 mV), and dissolved oxygen (1.01-2.63 mg L⁻¹). Data normality was assessed using the Shapiro-Wilk test, followed by Pearson correlation analysis and linear regression. Bivalve density showed a significant positive correlation with sand fraction (r: 0.84, p<0.05) and dissolved oxygen (r: 0.85, p<0.05). Positive but non-significant trends were observed for salinity (r: 0.58, p: 0.172) and oxidation-reduction potential (r: 0.72, p: 0.068), while negative but non-significant relationships occurred with silt (r: -0.65, p: 0.114) and clay fractions (r: -0.73, p: 0.062). Community structure varied spatially, with Shannon diversity index values ranging from 0.58 to 1.80, indicating conditions from relatively balanced to stressed assemblages. Given the limited number of stations, these correlations should be interpreted as exploratory rather than definitive. These results indicate statistically significant associations between bivalve density and selected environmental variables. The findings suggest that bivalve community metrics, combined with soil and porewater measurements, may help describe spatial variation in estuarine ecosystem condition.

Keywords: Benoa Bay, bivalves, mangrove estuary, soil texture, porewater chemistry

INTRODUCTION

Coastal ecosystems are dynamic transition zones between land and sea, characterized by interactions among hydrological processes, sedimentation, and tidal dynamics. These systems support high biological productivity and play essential roles in coastal protection, soil stabilization, nutrient regulation, and the provision of habitats for benthic organisms (Alongi 2018; Hilmi et al. 2022). Spatial variation in substrate characteristics and water chemistry creates heterogeneous microhabitats that sustain diverse assemblages of molluscs, crustaceans, and other benthic fauna (Zvonareva and Kantor 2016). Because benthic organisms are in direct contact with soils and porewater, their community responses are widely recognized as sensitive indicators of environmental change in coastal ecosystems (Ernawati et al. 2024).

Among benthic fauna, bivalves occupy an important ecological position due to their dual role as suspension feeders and infaunal organisms (Yahya et al. 2020). Through

filtration activities, bivalves influence suspended particle concentrations, water clarity, and nutrient cycling, while their burrowing and bioturbation activities modify soil structure and oxygen penetration (Ferriss et al. 2016; Cranford 2019). Their limited mobility and close association with soil and porewater environments make bivalve communities highly responsive to changes in habitat quality, supporting their application as indicators of coastal ecosystem condition (Imamsyah et al. 2020; Safitri et al. 2025).

Soil and porewater properties jointly shape the structure and distribution of bivalve communities. Soil texture, organic matter content, and pH regulate permeability, microbial activity, and oxygen diffusion, which collectively determine habitat suitability for infaunal bivalves (Alongi 2018; Oncken et al. 2022). Sandy soils generally provide higher permeability and oxygen availability, whereas fine-grained, organic-rich soils tend to develop reductive conditions that restrict community composition to tolerant taxa (Kabir et al. 2014; Vahidi et al. 2021). In parallel,

porewater characteristics such as salinity, redox potential (ORP), and dissolved oxygen regulate physiological stress and survival thresholds of bivalves, reflecting the combined influence of tidal exchange, freshwater input, and soil biogeochemical processes (Hutchins et al. 2008; Volkenborn et al. 2012; Rao et al. 2014).

Despite the growing number of studies on mangrove-associated bivalves in Indonesia, most investigations remain descriptive and focus primarily on species inventories or basic diversity metrics without explicitly integrating sediment texture and porewater chemistry within a unified quantitative framework (Hasidu et al. 2020; Ernawati et al. 2024). Quantitative evaluations linking multiple environmental gradients to bivalve density and community structure using consistent statistical approaches are still limited, particularly in semi-enclosed tropical bays.

Benoa Bay, Bali, represents a complex estuarine-mangrove system exposed to heterogeneous hydrodynamic conditions, variable sediment composition, and increasing anthropogenic pressure from coastal development and land-based inputs (Suteja et al. 2024). However, systematic assessments integrating bivalve community metrics with sediment and porewater characteristics remain scarce for this area, despite its ecological and management relevance.

Therefore, this study aims to i) quantify spatial variation in bivalve composition, density, and community structure across seven stations in Benoa Bay, ii) examine their relationships with sediment properties (organic matter, texture, pH, water content) and porewater parameters (temperature, salinity, ORP, dissolved oxygen). Based on established ecological principles, we hypothesize that: (H1) bivalve density is positively associated with sand fraction and dissolved oxygen, (H2) bivalve density is negatively associated with fine sediment fractions (silt and clay) and high organic matter, (H3) community evenness decreases under low oxygen and highly reducing conditions, and (H4)

diversity indices show weaker direct relationships with single environmental variables due to multivariate habitat controls.

In this study, “ecosystem condition” is interpreted operationally using bivalve community metrics (density, diversity, evenness, dominance) as biological indicators of relative habitat quality, rather than as a formal ecosystem health index. This approach follows widely applied benthic ecological assessment frameworks and supports cautious, comparative interpretation among stations (Magurran 2013; Montero-Taboada et al. 2023).

MATERIALS AND METHODS

Research site

The study was conducted in Benoa Bay, southern Bali, Indonesia, an estuarine coastal system influenced by freshwater inflow from several rivers and a semi-diurnal tidal regime. Seven sampling stations were selected to represent variation in substrate characteristics, proximity to river mouths, and intensity of human activities (Dharmayasa et al. 2024; Sugiana et al. 2024). All station coordinates were recorded using a handheld GPS. Sampling was conducted during the dry season of 2024 at the lowest ebb tide to ensure consistent access to intertidal substrates and porewater. Station I is characterized by mangrove vegetation and sandy substrate associated with small-scale fishing activities. Station II is located near a port area with mixed sand-mud soils. Station III and Station IV are mangrove-dominated areas influenced by ecotourism and fishing activities. Stations V, VI, and VII represent mangrove zones with varying soil composition and conservation status (Figure 1, Table 1).

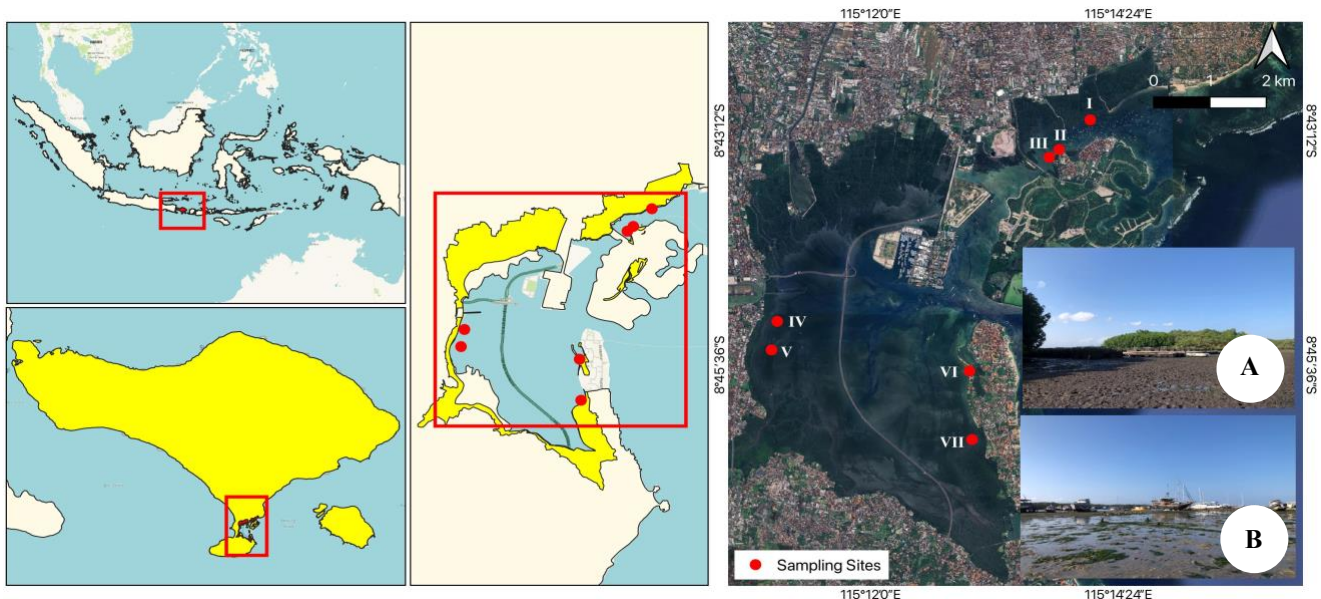
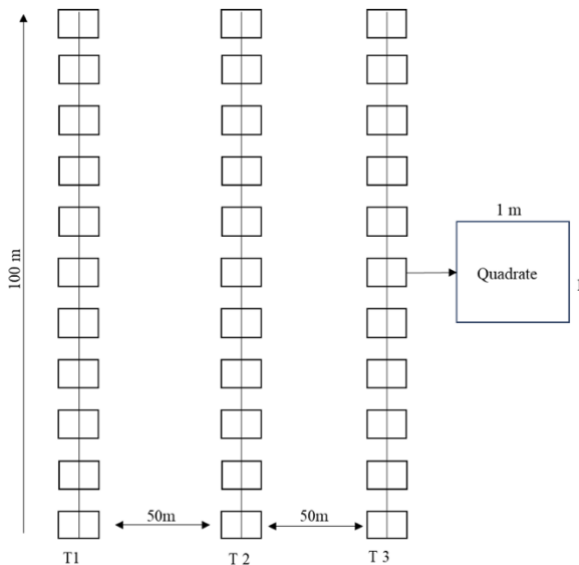


Figure 1. Distribution of data collection stations and documentation of several field conditions. A. Station V near the mangrove ecosystem, B. Station II, which is located in a port area with intensive fishing activities

Table 1. Characteristics, utilization types, and environmental conditions of sampling stations in Benoa Bay, Bali, Indonesia

Station	Utilization	Condition	Coordinate
I	Fishermen's activities	Mangroves, sand	-8.71814°, 115.23547°
II	Port, fishing activities	Without mangroves, sand and mud	-8.72318°, 115.23045°
III	Ecotourism, conservation	Mangroves, sand and mud	-8.75743°, 115.18403°
IV	Fishermen's activities	Mangroves, sand and rocky mud	-8.75255°, 115.18495°
V	Ecotourism, fishing activities	Mangroves, sand and mud	-8.72453°, 115.22885°
VI	Ecotourism, conservation	Mangroves, sand and mud	-8.76103°, 115.21598°
VII	Fishermen's activities, conservation	Mangroves, sand and mud	-8.77273°, 115.21638°

**Figure 2.** Illustration of bivalve data collection

Sampling design and bivalve data collection

Sampling locations were determined using purposive sampling to capture spatial heterogeneity in soil characteristics and environmental conditions across Benoa Bay. At each station, three transects of 100 m length were established parallel to the shoreline with 50 m spacing between transects. Along each transect, eleven quadrats (1×1 m) were placed at 10 m intervals, resulting in a total of 33 quadrats per station (Figure 2).

The number of stations and transects was selected to represent spatial variability across the bay and follows sampling designs commonly applied in tropical benthic community studies (English et al. 1994; Hasidu et al. 2020; Wiraatmaja et al. 2022). This design provides sufficient replication to detect spatial differences in community structure using correlation and regression-based analyses. All bivalves found within each quadrat were collected. Individuals buried in the soil were excavated to a depth of approximately 20 cm using an iron shovel. Live specimens were counted and photographed in situ. Specimens that could be confidently identified in the field were returned to their habitat, while individuals with uncertain morphological characteristics were preserved in 70% ethanol and transported to the laboratory for further identification. Although bivalve abundance was recorded at the quadrat level, environmental parameters were measured

and averaged at the station level; therefore, all statistical analyses were conducted using station-level means (n: 7 stations) to maintain consistency between biological and environmental datasets and to avoid pseudo-replication. The implications of limited sample size on statistical power are acknowledged and interpreted cautiously.

Bivalve identification

Bivalve identification was conducted consistently at the species level based on external shell morphology. Identification followed standard taxonomic references, including “Recent and Fossil Indonesian Shells” (Dharma et al. 2005) and the “World Register of Marine Species” (WoRMS 2025, www.marinespecies.org). These operational taxonomic units were retained in abundance-based indices (density, H', E, D).

Data analysis

Bivalve density

The density of *Bivalvia* animals is determined using the following formula (English et al. 1994):

$$\text{Density} = \frac{ni}{A}$$

Where, ni: number of bivalve individuals of each transect, A: total sampled area per station (33 quadrats × 1 m²: 33 m², which converted to 100 m²).

Bivalve density per station was calculated as the total number of individuals recorded across 33 quadrats (33 m²) divided by the sampled area and scaled to 100 m². Because abundance values were derived from whole-individual counts, resulting densities appear in discrete increments reflecting the scaling factor. Mean density and standard deviation (SD) reported in the results were calculated from transect-level densities (three transects per station), each based on 11 quadrats.

Diversity, evenness, and dominance indexes

The structure of the macrozoobenthos community was measured using the diversity index (Shannon-Wiener index, H'), the evenness index (Pielou's index, J), and the dominance index (Simpson's index, C). The diversity index describes species richness and the distribution of individuals among taxa; the evenness index measures how evenly individuals are distributed among the observed species, while the dominance index measures the extent to which some species dominate the community. All calculations are based on species-level abundance data

obtained from macrozoobenthos counts. The Shannon-Wiener diversity index (H') is calculated as:

$$H' = - \sum_{i=1}^S p_i \ln p_i$$

Where, S : total number of species, $p_i \ln p_i$: proportion of individuals belonging to species- i relative to the total abundance. Criteria: $H' < 1.0$: low diversity (unstable/ impacted community), $1.0 \leq H' \leq 3.0$: moderate diversity (moderately stable community), $H' > 3.0$: high diversity (stable community) (Magurran 2013).

Pielou's evenness index (J) was calculated as:

$$J = \frac{H'}{\ln S}$$

Where, H' : Shannon-Wiener diversity index, S : total number of species. Criteria: $J < 0.4$: low evenness (domination by few taxa), $0.4 \leq J \leq 0.6$: moderate evenness, $J > 0.6$: high evenness (balanced community structure).

The Simpson's dominance index (C) was calculated as:

$$C = \sum_{i=1}^S p_i^2$$

Where, $p_i \ln p_i$: proportion of individuals belonging to species- i . Criteria: C close to 0: low dominance (no single taxon dominates), C around 0.5: moderate dominance, C close to 1: high dominance (community strongly dominated by one or a few taxa).

Soil and porewater measurement

Soil samples were collected using a 5 cm-diameter soil auger, with a drilling depth of 0-100 cm. Soil pH was measured in the laboratory using a calibrated Lutron pH meter on a soil-water slurry prepared at a 1:5 (w/v) ratio, after homogenization to ensure representative measurements. Approximately 300 g of soil was stored in plastic containers for further chemical analysis. To determine the water content, 100 g of soil was dried at 70°C for approximately 48 hours until it reached a stable weight. Another 100 g was dried at 105°C to determine the volume density of the soil. The dried soil was then used for various tests: 10 g for particle size analysis, 3 g for soil organic matter (TOM) measurement.

For particle size analysis, soil fractions were classified following the Wentworth scale (Wentworth 1922), where gravel > 2 mm, sand: 2 mm-75 µm, silt: 75-2 µm, and clay < 2 µm. Sand fractions were determined using dry sieving, while silt and clay fractions were determined using a settling method in distilled water at room temperature. TOM was measured by the loss-on-ignition (LOI) method, burning the sample at 550°C, following Chen et al. (2014).

Porewater samples were collected at 30-60 cm below the soil surface during low tide. Temperature, pH, salinity, and oxidation-reduction potential (ORP) were measured using a COM-600 water quality multimeter, while dissolved oxygen (DO) was measured using a Lutron DO-5519 meter. Although bivalves were excavated primarily from the upper 20 cm, deeper porewater chemistry was used as a proxy for integrated subsurface biogeochemical

conditions that influence oxygen diffusion, redox gradients, and organic matter mineralization affecting surface infaunal habitats. Although bivalves were excavated primarily from the upper ~20 cm of soil, porewater was sampled at 30-60 cm depth to capture integrated subsurface biogeochemical conditions influenced by tidal flushing and organic matter mineralization. In mangrove sediments, redox gradients and oxygen diffusion are vertically structured, and deeper porewater chemistry often reflects broader sedimentary processes that regulate oxygen availability and organic matter turnover in overlying layers. However, we acknowledge that partial decoupling between surface microhabitats and deeper porewater conditions may occur. Therefore, the results should be interpreted as associations between community patterns and integrated subsurface conditions rather than direct measurements of the immediate bivalve microenvironment.

Statistical analysis

Prior to statistical analysis, all environmental and biological variables were tested for normality using the Shapiro-Wilk test. Pearson correlation analysis was applied to evaluate relationships between bivalve community metrics and individual environmental variables. Given the limited sample size ($n = 7$), emphasis was placed on effect size (Pearson's r) and confidence intervals rather than p -values alone. To evaluate robustness, Spearman rank correlations were performed as sensitivity analyses. Multiple comparisons were not adjusted formally due to the exploratory nature of the study; therefore, results are interpreted cautiously. Simple linear regression models were fitted separately for sand fraction and dissolved oxygen as predictors of bivalve density. Variables with $r > 0.7$ were not included simultaneously to avoid multicollinearity. All analyses were performed using RStudio version 4.0.2.

RESULTS AND DISCUSSION

Composition and richness of bivalve communities

Species richness of bivalves varied across the seven sampling stations in Benoa Bay, ranging from 5-11 species, indicating marked spatial heterogeneity within the study area (Table 2). Station I recorded the highest species richness (11 species), followed by Station II with 10 species. Stations III and IV supported seven and 6 species, respectively, whereas Stations V and VI contained fewer taxa, with 4 and 3 species. Station VII supported 6 species, as indicated in Table 2. Detailed presence-absence information for each species is presented in Table 2.

Across all stations, the family Veneridae was the most consistently represented, with *M. hiantina* occurring at all sampling locations. Other families, including Arcidae, Pinnidae, Tellinidae, and Semelidae, exhibited more restricted spatial distributions and were recorded only at certain stations. Several species showed station-specific occurrence, such as *I. ephippium* at Station III and *Q. palatum* at Station VII, reflecting differences in local assemblage composition within the bay.

The relative composition of bivalve assemblages also differed markedly among stations (Table 3). At Station I, the assemblage was dominated by *M. hiantina* and *M. opima*, while Station II was characterized by high contributions of *M. opima* and *A. squamosa*. Station III showed a strong contribution of *I. ehippium*, accompanied by *M. hiantina* and *G. tumidum*. In contrast, Station IV was dominated by *M. opima*, with *M. hiantina* and several other

taxa present in lower proportions. A distinct pattern was observed at Station V, where *E. spengleri* accounted for the majority of individuals, whereas Station VI displayed a more heterogeneous assemblage, including *S. regularis*, *T. timorensis*, and *P. bicolor*. At Station VII, the assemblage consisted mainly of *T. radiata*, *Q. palatum*, and *G. tumidum*, with other taxa contributing minimally. Documentation of each species can be seen in Figure 3.

Table 2. Bivalve checklist data of each station

Family	Genera	Species	Stations						
			I	II	III	IV	V	VI	VII
Arcidae	<i>Anadara</i>	<i>Anadara antiquata</i>	+	+	-	+	-	+	-
	<i>Tegillarca</i>	<i>Tegillarca granosa</i>	-	+	-	+	-	-	-
Isognomonidae	<i>Isognomon</i>	<i>Isognomon ehippium</i>	-	-	+	-	-	-	-
Laternulidae	<i>Exolaternula</i>	<i>Exolaternula spengleri</i>	-	-	-	-	+	+	-
Mactridae	<i>Mactra</i>	<i>Mactra grandis</i>	-	-	-	-	-	+	-
Pinnidae	<i>Pinna</i>	<i>Pinna bicolor</i>	+	+	-	+	-	+	-
Semelidae	<i>Semele</i>	<i>Semele cordiformis</i>	-	+	-	+	-	-	-
	<i>Semele</i>	<i>Semele solida</i>	+	-	-	-	-	-	-
Solenidae	<i>Solen</i>	<i>Solen regularis</i>	+	-	-	-	+	+	-
Tellinidae	<i>Cyclotellina</i>	<i>Cyclotellina remies</i>	-	+	-	+	-	-	-
	<i>Quidnipagus</i>	<i>Quidnipagus palatum</i>	-	-	-	-	-	-	+
	<i>Tellina</i>	<i>Tellina timorensis</i>	+	+	-	+	+	+	-
	<i>Tellina</i>	<i>Tellina radiata</i>	-	+	-	+	-	-	+
Veneridae	<i>Anomalocardia</i>	<i>Anomalocardia squamosa</i>	+	+	-	+	-	+	-
	<i>Dosinia</i>	<i>Dosinia fibula</i>	-	-	-	-	+	-	-
	<i>Gafrarium</i>	<i>Gafrarium tumidum</i>	+	-	+	-	-	+	+
	<i>Gafrarium</i>	<i>Gafrarium pectinatum</i>	+	-	-	+	-	-	+
	<i>Marcia</i>	<i>Marcia hiantina</i>	+	+	+	+	+	+	+
	<i>Marcia</i>	<i>Marcia opima</i>	+	+	-	+	-	-	+

Note: +: present, -: absent

Table 3. Composition of bivalves from each Station (Note: Percentage composition was calculated as (number of individuals per species / total individuals per station) × 100. Percentages are based on total abundance recorded at each station)

Family	Genera	Species	Stations						
			1	2	3	4	5	6	7
Arcidae	<i>Anadara</i>	<i>Anadara antiquata</i>	3.70%	0.90%	0.00%	3.70%	0.00%	5.45%	0.00%
	<i>Tegillarca</i>	<i>Tegillarca granosa</i>	0.00%	5.70%	0.00%	5.50%	0.00%	0.00%	0.00%
Isognomonidae	<i>Isognomon</i>	<i>Isognomon ehippium</i>	0.00%	0.00%	34.90%	0.00%	0.00%	0.00%	0.00%
Laternulidae	<i>Exolaternula</i>	<i>Exolaternula spengleri</i>	0.00%	0.00%	0.00%	0.00%	85.10%	3.64%	0.00%
Mactridae	<i>Mactra</i>	<i>Mactra grandis</i>	0.00%	0.00%	0.00%	0.00%	0.00%	12.12%	0.00%
Pinnidae	<i>Pinna</i>	<i>Pinna bicolor</i>	3.00%	0.90%	0.00%	0.90%	0.00%	7.27%	0.00%
Semelidae	<i>Semele</i>	<i>Semele cordiformis</i>	0.00%	0.90%	0.00%	0.90%	0.00%	0.00%	0.00%
	<i>Semele</i>	<i>Semele solida</i>	4.50%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Solenidae	<i>Solen</i>	<i>Solen regularis</i>	2.20%	0.00%	0.00%	0.00%	2.10%	27.47%	0.00%
Tellinidae	<i>Cyclotellina</i>	<i>Cyclotellina remies</i>	0.00%	2.80%	0.00%	2.80%	0.00%	0.00%	0.00%
	<i>Quidnipagus</i>	<i>Quidnipagus palatum</i>	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	20.80%
	<i>Tellina</i>	<i>Tellina timorensis</i>	9.70%	0.90%	0.00%	0.90%	3.10%	22.02%	0.00%
	<i>Tellina</i>	<i>Tellina radiata</i>	0.00%	12.30%	0.00%	11.90%	0.00%	0.00%	25.00%
Veneridae	<i>Anomalocardia</i>	<i>Anomalocardia squamosa</i>	9.00%	17.90%	0.00%	17.40%	0.00%	3.64%	0.00%
	<i>Dosinia</i>	<i>Dosinia fibula</i>	0.00%	0.00%	0.00%	0.00%	0.70%	0.00%	0.00%
	<i>Gafrarium</i>	<i>Gafrarium tumidum</i>	2.20%	0.00%	14.00%	0.00%	0.00%	3.64%	20.80%
	<i>Gafrarium</i>	<i>Gafrarium pectinatum</i>	0.00%	2.80%	0.00%	2.80%	0.00%	0.00%	8.30%
	<i>Marcia</i>	<i>Marcia hiantina</i>	42.50%	3.80%	51.20%	3.70%	9.00%	14.75%	16.70%
	<i>Marcia</i>	<i>Marcia opima</i>	23.10%	50.90%	0.00%	49.50%	0.00%	0.00%	8.30%

The spatial distribution of bivalve assemblages in Benoa Bay reflects clear differentiation in community composition among stations, rather than a uniform pattern across the bay. Stations characterized by higher species representation were specifically associated with a broader taxonomic mix, whereas other locations were defined by a more limited set of recurrent taxa. For example, assemblages at stations with mixed sandy-mud substrates were characterized by combinations of Veneridae and Tellinidae taxa, while stations with fewer species were dominated by only one or two species. Similar patterns of uneven bivalve distribution across mangrove and estuarine settings have been reported in other Indonesian coastal systems, where local habitat characteristics influence assemblage composition (Wiratmaja et al. 2022; Syahrial et al. 2025).

At the family level, Veneridae emerged as the most consistently represented group across sampling locations, with *M. hiantina* and *M. opima* occurring in multiple stations. In contrast, families such as Pinnidae, Isognomonidae, and Solecurtidae showed more restricted occurrence, appearing only in specific parts of the bay. The presence of certain taxa at individual stations, such as *I. ehippium* or *P. bicolor*, contributed to distinctive local assemblage identities, while other stations were characterized by numerical dominance of a single species. Comparable family-level patterns have been observed in mangrove-associated bivalve communities elsewhere in Indonesia, where habitat heterogeneity leads to spatially uneven assemblage structures (Hasidu et al. 2020). Overall, these observations emphasize that bivalve composition in Benoa Bay is spatially heterogeneous, with different taxa prevailing locally in response to site-specific environmental conditions.

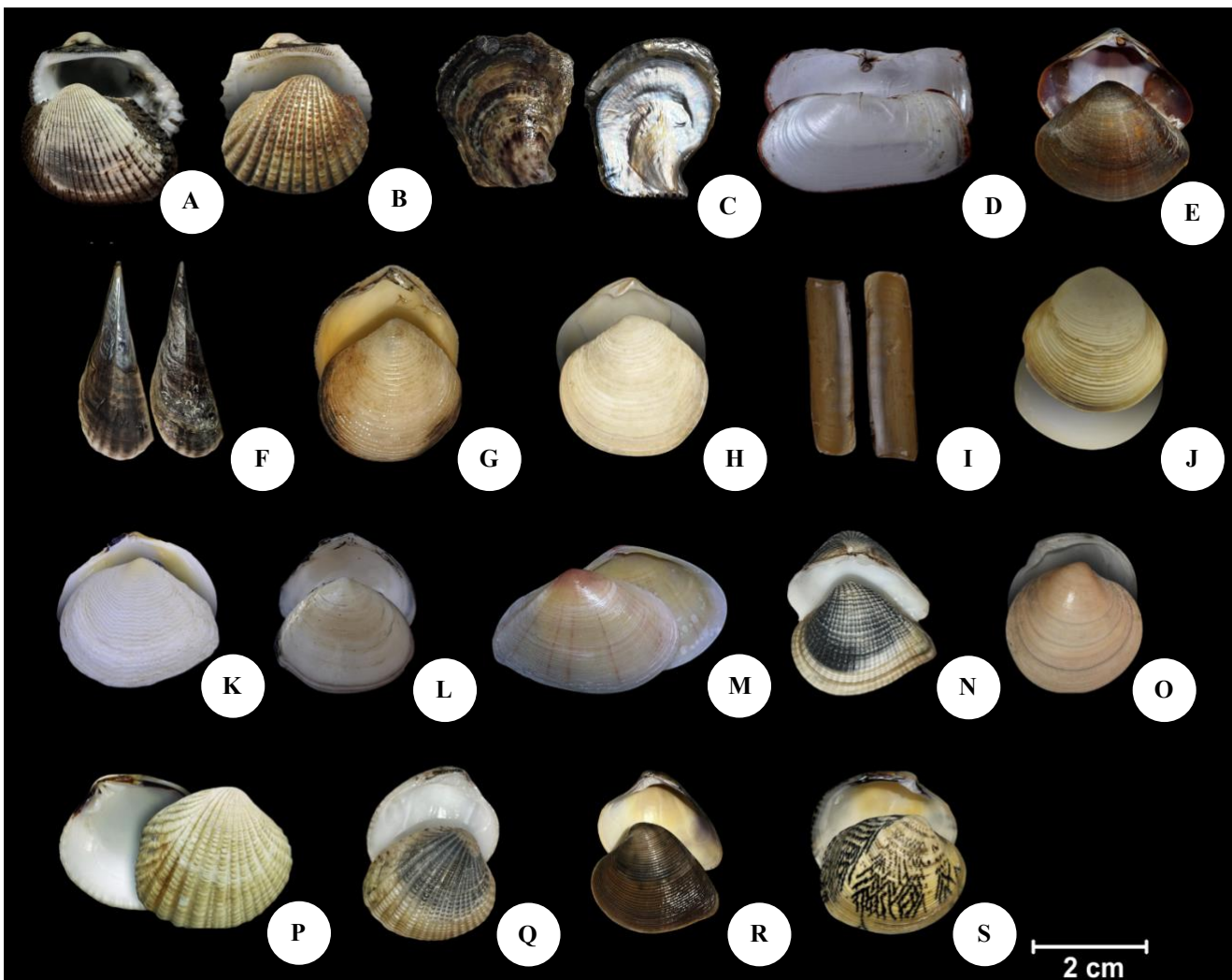


Figure 3. Documentation of bivalves found from all research stations. A. *Anadara antiquata*, B. *Tegillarca granosa*, C. *Isognomon ehippium*, D. *Exolaternula spengleri*, E. *Mactra grandis*, F. *Pinna bicolor*, G. *Semele cordiformis*, H. *Semele solida*, I. *Solen regularis*, J. *Cyclotellina remies*, K. *Quidnypagus palatum*, L. *Tellina timorensis*, M. *Tellina radiata*, N. *Anomalocardia squamosa*, O. *Dosinia fibula*, P. *Gafrarium tumidum*, Q. *Gafrarium pectinatum*, R. *Marcia hiantina*, S. *Marcia opima*

Spatial variation of bivalve density

The mean density of bivalves varied substantially among sampling stations, indicating pronounced spatial heterogeneity (Table 4, Figure 4). The highest mean density was recorded at Station V (873±1189 ind/100 m²), reflecting strong numerical dominance by *E. spengleri* and high variability among transects. Stations I and IV also showed relatively high mean densities (406±289 and 400±453 ind/100 m², respectively). Moderate mean densities were observed at Station VI (285±335 ind/100 m²), followed by Station III (130±106 ind/100 m²) and Station II (124±36 ind/100 m²). The lowest mean density occurred at Station VII (55±64 ind/100 m²).

The internal distribution of bivalve densities across stations revealed striking contrasts, with a few species exerting a disproportionately high numerical influence at specific locations. At Station V, the assemblage was heavily shaped by *E. spengleri*, whose contribution far exceeded that of other taxa and elevated the Station's overall total. A similar but less extreme pattern was noted at Station I and IV, where relatively high numbers of *M. hiantina*, *M. opima*, and *T. timorensis* together drove dense communities without a single species monopolizing the counts (Hasidu et al. 2020).

By contrast, Station II was shaped mainly by *M. opima* in combination with *A. squamosa*, while Station III was marked by a concentration of *I. ephippium*, highlighting site-specific dominance even at locations with lower totals (Wiraatmaja et al. 2022). These variations demonstrate that numerical disparities among species are central in defining the profile of each Station rather than the presence or absence of taxa alone. At intermediate and low-density stations, narrower assemblages further emphasized this

uneven internal pattern. Station VI, though not as rich in numbers as Stations I, IV, or V, was distinctly influenced by *S. regularis* and *T. timorensis*, while the sparse records of *M. hiantina* still contributed measurable representation. Station VII showed the lowest overall counts, comprising only a handful of individuals, including *Q. palatum*, *T. radiata*, and *G. tumidum*. These results indicate that numerical dominance can arise from either extreme concentrations of a single taxon or the combined effect of a few species at moderate levels (Sarong et al. 2019; López-Alonso et al. 2022). Thus, the observed heterogeneity in densities reflects internal differences in how particular bivalves establish local prevalence, producing distinct assemblage structures across Benoa Bay (Ernawati et al. 2024).

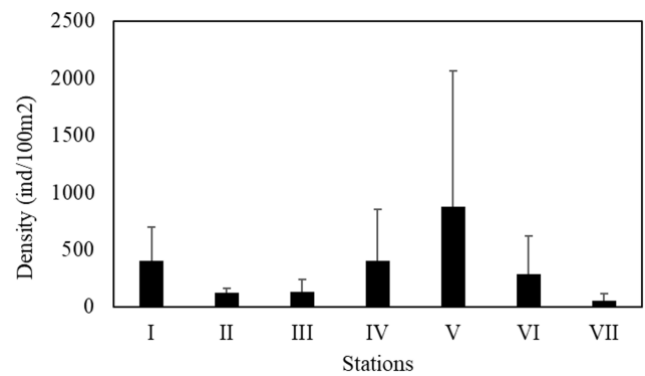


Figure 4. Density of bivalve around the sampling stations

Table 4. Density of bivalve species from each Station

Family	Genera	Species	Density of each Station (ind/100 m ²)						
			I	II	III	IV	V	VI	VII
Arcidae	<i>Anadara</i>	<i>Anadara antiquata</i>	45	9	0	36	0	27	0
	<i>Tegillarca</i>	<i>Tegillarca granosa</i>	0	55	0	55	0	0	0
Isognomonidae	<i>Isognomon</i>	<i>Isognomon ephippium</i>	0	0	136	0	0	0	0
Laternulidae	<i>Exolaternula</i>	<i>Exolaternula spengleri</i>	0	0	0	0	2227	18	0
Mactridae	<i>Mactra</i>	<i>Mactra grandis</i>	0	0	0	0	0	6	0
Pinnidae	<i>Pinna</i>	<i>Pinna bicolor</i>	36	9	0	9	0	36	0
Semelidae	<i>Semele</i>	<i>Semele cordiformis</i>	0	9	0	9	0	0	0
	<i>Semele</i>	<i>Semele solida</i>	55	0	0	0	0	0	0
Solenidae	<i>Solen</i>	<i>Solen regularis</i>	27	0	0	0	55	136	0
Tellinidae	<i>Cyclotellina</i>	<i>Cyclotellina remies</i>	0	27	0	27	0	0	0
	<i>Quidnipagus</i>	<i>Quidnipagus palatum</i>	0	0	0	0	0	0	45
	<i>Tellina</i>	<i>Tellinides timorensis</i>	118	9	0	9	82	109	0
	<i>Tellina</i>	<i>Tellina radiata</i>	0	118	0	118	0	0	55
Veneridae	<i>Anomalocardia</i>	<i>Anomalocardia squamosa</i>	109	173	0	173	0	18	0
	<i>Dosinia</i>	<i>Dosinia fibula</i>	0	0	0	0	18	0	0
	<i>Gafrarium</i>	<i>Gafrarium tumidum</i>	27	0	55	0	0	18	45
	<i>Gafrarium</i>	<i>Gafrarium pectinatum</i>	0	27	0	27	0	0	18
	<i>Marcia</i>	<i>Marcia hiantina</i>	518	36	200	36	236	73	36
	<i>Marcia</i>	<i>Marcia opima</i>	282	491	0	491	0	0	18

Bivalve community structure (H', J, C)

Community structure indices showed clear spatial contrasts among stations (Table 5). Stations I, II, IV, VI, and VII exhibited moderate to high diversity (H' : 1.56-1.80) and relatively high evenness (J : 0.66-0.96), indicating balanced assemblages without strong dominance. In contrast, Station V showed low diversity (H' : 0.58), low evenness (J : 0.36), and high dominance (C : 0.73), reflecting numerical dominance by *E. spengleri*. The relatively high H' and J values at Station VII are consistent with its moderate species richness and relatively even abundance distribution, rather than extremely low richness as previously stated.

Variation in the diversity index (H') among stations highlights this contrast at the bay scale. Stations showing moderate to high H' values indicate relatively stable and complex assemblages, while lower values reflect reduced diversity associated with numerical dominance. Similar ranges of diversity have been reported from mangrove ecosystems in Pacitan, East Java, where molluscan communities exhibited moderate diversity values (Wiratmaja et al. 2022), and from the Kampung Jawa mangrove ecosystem, where H' ranged between 0.69 and 1.37 with dominance by specific taxa such as *A. transversa* (Ramadhaniaty et al. 2021). These references are provided to place the Benoa Bay values within a broader regional context, rather than to imply direct ecological equivalence among sites.

Evenness (J) and dominance (C) patterns observed in Benoa Bay further emphasize station-level contrasts in community organization. Stations with high evenness and low dominance reflect more balanced species representation, whereas those with lower evenness and higher dominance indicate assemblages structured by the prevalence of a few taxa. Comparable patterns of relatively uniform molluscan distribution have been reported from other Indonesian mangrove systems, including Nusa Lembongan and Perancak (Simanullang et al. 2024). Taken together, the indices of H' , J , and C confirm that bivalve community structure within Benoa Bay is spatially heterogeneous, with each station exhibiting a distinct balance between diversity, evenness, and dominance driven primarily by the local distribution and abundance of species recorded in this study.

Soil and porewater characteristics across stations

Variations in TOM values between stations indicate differences in organic matter accumulation at each location. Some stations show higher organic content, while others show relatively lower conditions. A similar pattern is observed in soil pH, which ranges from fairly acidic to near-neutral. Water content also varies between stations, reflecting differences in the ability of soils to store or release water (Table 6).

Differences in TOM between stations are specifically influenced by litter decomposition intensity, mangrove vegetation type, and local sedimentation levels (Simpson et al. 2021). Stations with higher litter accumulation tend to

have higher TOM values. Variations in pH reflect the chemical dynamics of mangrove soil, driven by redox processes and the contribution of organic acids from litter (Silva et al. 2024). Meanwhile, differences in water content are closely related to texture fraction, where fine soils tend to have higher water retention than sandy soils (Kamal et al. 2020).

The soil fraction composition shows a predominance of sand at most stations, with greater contributions from the silt and clay fractions at specific locations. Some stations contain small amounts of gravel, but this is not a significant fraction. Variations in the fine fraction are clearly visible at several places, where higher silt and clay content is observed than at other stations (Figure 5).

Table 5. Community structure indices of bivalves from each Station

Station	Diversity (H')	Uniformity (J)	Dominance (C)
I	1.68	0.77	0.26
II	1.57	0.66	0.31
III	0.71	0.65	0.4
IV	1.8	0.87	0.2
V	0.58	0.36	0.73
VI	1.56	0.71	0.32
VII	1.71	0.96	0.19

Table 6. Soil properties between sampling stations

Station	Soil properties		
	TOM (%)	pH	Water content (%)
I	3.02	6.89	32%
II	3.96	6.41	45%
III	4.6	6.37	59%
IV	2.55	6.05	33%
V	3.14	6.47	40%
VI	4.42	6.88	56%
VII	3.98	6.71	51%

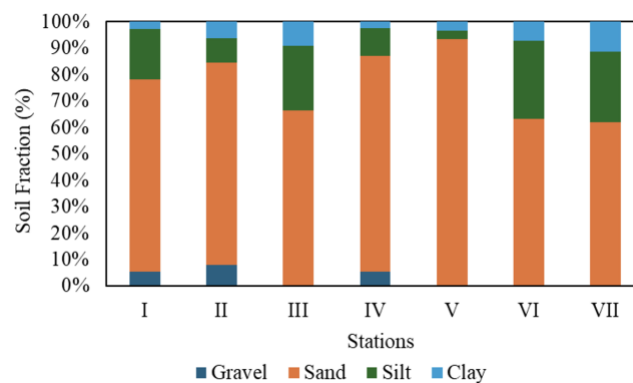


Figure 5. Soil fraction composition between sampling stations

The dominance of sand indicates that most mangrove areas are located in environments with relatively higher water energy, resulting in more coarse particles being retained (Risanti and Marfai 2020). Stations showing a dominance of fine fractions are areas with lower hydrodynamic energy, allowing for the deposition of small particles. The combination of these soil fractions is crucial in determining bivalve habitats, as each fraction provides different conditions for burrowing, filtering, and species that require stable substrates (Kabir et al. 2014; Vahidi et al. 2021).

Porewater parameters showed consistent variation between stations. Porewater temperature ranges within the warm zone typical of tropical ecosystems. pH tends to be slightly acidic to near neutral. Salinity shows differences between stations, reflecting variations in seawater influence. ORP values are entirely reductive, while DO is very low at all locations, indicating hypoxic or low-oxygen conditions (Table 7).

Relatively uniform temperatures indicate the thermal stability of mangrove areas, while differences in pH reflect variations in organic matter decomposition and soil biogeochemical processes (Lathif et al. 2025). Salinity

variations between stations may reflect tidal levels, evaporation, and the intensity of seawater intrusion. Negative ORP and very low DO conditions are characteristic of organic-rich mangrove soils, where microbial activity causes high oxygen consumption. These patterns strongly influence the distribution of bivalves sensitive to salinity, low oxygen, and reductive conditions (Wang et al. 2024; Shi et al. 2025).

Relationship between community patterns and environmental gradients

The regression analysis results show that bivalve density is clearly related to several soil and porewater parameters (Figure 6). Density tends to increase at stations with a higher proportion of sand, while decreasing in soils dominated by fine fractions such as silt and clay. A similar pattern is observed in porewater parameters: stations with higher salinity and dissolved oxygen conditions exhibit higher bivalve density. Conversely, organic matter content and overly reductive soil conditions appear to be associated with a decrease in the number of individuals.

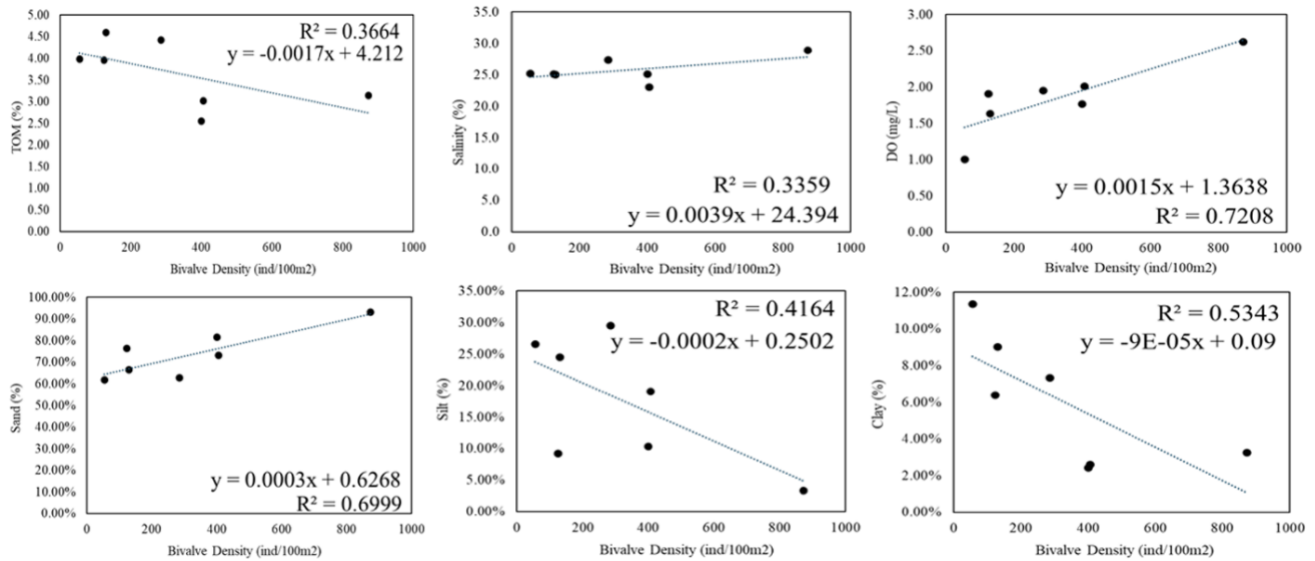


Figure 6. Relationship between environmental parameters and bivalve abundance

Table 7. Porewater properties between sampling stations

Station	Porewater properties				
	Temperature (°C)	pH	Salinity (ppt)	ORP (mV)	DO (mg/L)
I	26.8	7.17	23.1	-54	2.01
II	26.1	6.63	25.1	-67	1.91
III	27.3	6.97	25	-68	1.64
IV	26.3	6.27	25.1	-55	1.77
V	28.1	6.58	28.9	-51	2.63
VI	27.9	6.68	27.3	-75	1.95
VII	28.1	6.82	25.2	-98	1.01

Relationship between community patterns and

Pearson correlation analysis revealed that bivalve density was significantly positively correlated with sand fraction (r: 0.84, p: 0.018) and dissolved oxygen (r: 0.85, p: 0.015) (Table 8). Positive but non-significant relationships were observed for salinity (r: 0.58, p: 0.172) and ORP (r: 0.72, p: 0.068), while negative but non-significant relationships occurred with silt (r: -0.65, p: 0.114) and clay fractions (r: -0.73, p: 0.062). Among community indices, only evenness (E) and dominance (D) showed statistically significant associations with dissolved oxygen (E: r: -0.85, p: 0.015; D: r: 0.77, p: 0.043), whereas diversity (H') did not show significant correlations with any measured parameter. Borderline associations (e.g., dominance with salinity, p: 0.052) are interpreted cautiously. Broad claims of overall index sensitivity were therefore avoided. Regression analyses supported these patterns, indicating that sand fraction and DO explain a substantial proportion of variance in bivalve density (Figure 6, Table 8). All statistical relationships are interpreted as exploratory due to the limited number of stations (n: 7).

Interestingly, evenness (J) showed a significant negative association with dissolved oxygen, while dominance (D) was positively associated with DO. Although higher oxygen availability is generally expected to support more balanced assemblages, this pattern appears to be influenced by station-specific dominance dynamics, particularly at Station V, where a single species (*Exolaternula spengleri*) numerically dominated under relatively higher DO conditions. Thus, rather than indicating poorer environmental conditions, the observed relationship likely reflects local shifts in species dominance structure. Given the small sample size (n: 7), potential outlier influence cannot be excluded and results should be interpreted cautiously.

The positive relationship between bivalve density and sand fraction reflects the preference of many species for higher-energy substrates that provide stability and adequate space for filtration and shallow burrowing activities. Sandy substrates specifically have better water movement, thereby supporting the availability of suspended food and reducing

the risk of microhabitat hypoxia. Conversely, soils dominated by silt and clay often form more reductive environments with low permeability, thereby limiting the presence of sensitive species and supporting only a few tolerant groups (van der Geest et al. 2019; Effendi et al. 2025). The response of bivalve density to porewater parameters indicates that porewater chemistry plays a key role in regulating community structure. Higher salinity and dissolved oxygen tend to support the abundance of particular species that require more stable water conditions and better oxygenation. Conversely, lower ORP values and anoxic conditions can inhibit most bivalves, except those tolerant of reductive conditions (Kong et al. 2023). These findings indicate that the variability of bivalve communities in Benoa Bay is determined not only by substrate availability but also by environmental gradients reflecting mangrove hydrological dynamics and biogeochemical processes. These interpretations represent plausible ecological mechanisms rather than causal inference, given the observational nature of the study.

Overall, among the multiple environmental variables examined, only sand fraction and dissolved oxygen showed statistically supported associations with bivalve density. Other relationships were weaker or non-significant and therefore should be interpreted cautiously given the limited number of stations (n: 7). Accordingly, the correlation analysis is framed as exploratory, highlighting potential environmental gradients rather than implying direct causal relationships.

In relation to the proposed hypotheses, H1 was supported, as bivalve density showed significant positive associations with sand fraction and dissolved oxygen. H2 received partial support, with negative but non-significant trends observed for silt and clay fractions. H3 was partially supported, as evenness and dominance were significantly associated with dissolved oxygen, although diversity (H') did not show strong direct relationships. H4 was supported in that diversity indices exhibited weaker and less consistent associations with individual environmental variables, suggesting multivariate habitat controls.

Table 8. Pearson correlation analysis between bivalve community structure and environmental parameters (Values represent Pearson correlation coefficients (r) followed by p-values in parentheses. Asterisks (*) indicate statistically significant correlations at p<0.05*)

Media	Parameter	Pearson correlation coefficient			
		Density	H'	J	C
Soil	TOM	-0.61 (p: 0.146)	-0.30 (p: 0.513)	-0.03 (p: 0.949)	-0.00 (p: 1.000)
	Gravel	-0.13 (p: 0.781)	0.54 (p: 0.211)	0.20 (p: 0.667)	-0.40 (p: 0.374)
	Sand	0.84 (p: 0.018*)	-0.40 (p: 0.374)	-0.64 (p: 0.122)	0.64 (p: 0.122)
	Silt	-0.65 (p: 0.114)	0.25 (p: 0.589)	0.54 (p: 0.211)	-0.50 (p: 0.315)
	Clay	-0.73 (p: 0.062)	-0.00 (p: 1.000)	0.33 (p: 0.468)	-0.30 (p: 0.513)
	Soil pH	-0.10 (p: 0.831)	0.18 (p: 0.700)	0.08 (p: 0.864)	-0.10 (p: 0.831)
Porewater	Water content	-0.54 (p: 0.213)	-0.30 (p: 0.513)	-0.01 (p: 0.981)	0.02 (p: 0.965)
	Temperature	0.23 (p: 0.634)	-0.40 (p: 0.374)	-0.22 (p: 0.633)	0.42 (p: 0.349)
	Water pH	-0.27 (p: 0.558)	-0.10 (p: 0.831)	0.06 (p: 0.898)	-0.10 (p: 0.831)
	Salinity	0.58 (p: 0.172)	-0.60 (p: 0.154)	-0.66 (p: 0.107)	0.75 (p: 0.052)
	ORP	0.72 (p: 0.068)	-0.30 (p: 0.513)	-0.57 (p: 0.182)	0.46 (p: 0.299)
	DO	0.85 (p: 0.015*)	-0.50 (p: 0.253)	-0.85 (p: 0.015*)	0.77 (p: 0.043*)

Implications for coastal ecosystem health

The spatial variability of bivalve community structure in Benoa Bay indicates that ecosystem condition within the mangrove landscape is heterogeneous rather than uniform. Stations characterized by higher diversity and evenness, such as Stations I, II, IV, and VII, exhibited diversity values ranging from H' : 1.57-1.80 and evenness values of J : 0.66-0.96, reflecting relatively balanced assemblages with no single taxon strongly dominating the community. In contrast, Station V showed markedly lower diversity (H' : 0.58) and evenness (J : 0.36) together with high dominance (C : 0.73), indicating a simplified assemblage structure shaped by a limited number of taxa. These numerical contrasts consistently coincided with differences in soil composition and porewater conditions, highlighting clear associations between bivalve community metrics and local environmental gradients at the station scale (Aoki et al. 2011; Montero-Taboada et al. 2023).

Correlation analyses further show that variation in bivalve density and community structure is closely linked to soil texture and porewater dissolved oxygen. Stations with higher mean densities and uneven assemblages, particularly Station V (873 ± 1189 ind/100 m²), were associated with finer soil fractions and lower oxygen availability, whereas stations with moderate densities and more even communities tended to coincide with mixed soil textures and relatively higher dissolved oxygen levels. Although these relationships do not demonstrate direct causal mechanisms, they indicate that shifts in abiotic conditions are consistently linked to changes in dominance patterns and assemblage balance. Given the functional role of bivalves in biofiltration and soil reworking, such quantitative differences in abundance, evenness, and dominance may influence the capacity of benthic systems to sustain associated ecological processes and habitat functioning (Cranford 2019). Future studies should incorporate shallow porewater or surface sediment oxygen measurements to better resolve fine-scale vertical coupling between bivalve microhabitats and redox dynamics.

From a management perspective, the results emphasize the value of combining bivalve community indices with basic measurements of soil and porewater properties as practical indicators of mangrove and estuarine condition. Stations exhibiting relatively low diversity ($H' < 1.0$), low evenness ($J < 0.4$), and high dominance ($C > 0.7$) may warrant closer monitoring. These threshold values are derived from commonly used benthic assessment frameworks (Magurran 2013) and are applied here as heuristic reference points rather than validated ecosystem health criteria for Benoa Bay. Accordingly, they should be interpreted as comparative screening indicators within the study area rather than prescriptive management benchmarks. Conversely, stations supporting moderate to high diversity ($H' > 1.5$) and evenness ($J > 0.6$) provide important reference conditions for conservation and spatial planning. Anchoring ecosystem assessment and management actions to these observed ecological thresholds allows the routine monitoring program in Benoa Bay to more effectively detect early signs of degradation and support adaptive coastal management under increasing environmental pressures (Rodrigues et al.

2023). Rather than defining a formal ecosystem health index, these thresholds are used operationally to describe relative ecological condition and community status, following commonly applied benthic assessment frameworks (Magurran 2013; Montero-Taboada et al. 2023). Accordingly, interpretations avoid overgeneralization and emphasize comparative spatial patterns within the study area.

In conclusion, bivalve communities in Benoa Bay exhibit pronounced spatial heterogeneity in species richness, composition, density, and community structure, driven primarily by local environmental conditions. Stations with sandy substrates and higher dissolved oxygen supported greater bivalve densities, while fine sediments, high organic matter, and reductive conditions were associated with lower abundance. Community indices further highlighted contrasts between balanced assemblages and those dominated by a single species, particularly at Station V. Although statistical relationships were limited by sample size, the findings suggest that substrate characteristics and porewater quality are key factors shaping bivalve distribution, emphasizing the importance of environmental gradients in structuring mangrove-associated benthic communities.

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