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Research Article

Ecological status assessment of Musa Estuary using macrobenthos and biotic indices (Persian Gulf, Iran)

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Abstract

Macrobenthos are a key ecosystem indicator and are sensitive to changes in sediments. This study evaluated the ecological status of the Musa estuary located in the northwestern part of the Persian Gulf (Iran) by analyzing macrobenthic community structure and applying biotic indices. The sediment and water samples were collected from six creeks during the summer and winter of 2024 using a Peterson grab and Nansen bottle, respectively. The sediment grain size, total organic matter (TOM), and macrobenthic composition were analyzed. Concurrently, bottom-water physicochemical parameters, including salinity, temperature, pH, and dissolved oxygen concentrations, were measured to assess their potential influence on benthic habitat characteristics. The ecological indices, including AZTI's Marine Biotic Index (AMBI), Benthic Opportunistic Polychaetes Amphipods Index (BOPA), Shannon, Margalef, Pielou, and Simpson, were calculated to evaluate ecological quality. Seventy taxa from seven phyla were identified, with Annelida dominating (69.62%), notably *Melinna* sp. and *Capitella* sp. Jafari Creek exhibited the highest macrobenthic density in summer, while Odeleh Creek peaked in winter. Jafari Creek also showed the highest Shannon and Margalef diversity indices across seasons. AMBI and BOPA indicated predominantly unpolluted to slightly polluted conditions, except Ghazaleh Creek, which displayed moderate to severe pollution in winter. TOM positively correlated with the benthic abundance and diversity. Findings suggest that Musa estuary's ecological status is influenced by natural dynamics and anthropogenic pressures. The study underscores the importance of integrating multiple indices for robust ecosystem assessment.

Introduction

Estuaries are complex marine ecosystems characterized by high biodiversity and substantial primary production. These conditions render them optimal habitats for the spawning and early development of significant aquatic species (Lam-Gordillo *et al*., 2023; Choi *et al*., 2024). However, estuaries are facing increasing pressures from human activities and natural stressors, which endanger the resident organisms (Nayak *et al*., 2022). In response to these alterations, aquatic species within these regions frequently exhibit shifts in abundance and diversity (Souza *et al*., 2021). The Musa estuary, which is among the most extensive in the northwestern Persian Gulf, is especially susceptible to such impacts. The region is confronted with environmental challenges stemming from petrochemical industries, oil exports, and fishing activities (Heydari *et al*., 2024). Consequently, assessing its ecological health is imperative.

Macrobenthos are of particular significance in aquatic ecosystems, where they function as a primary food source for larger species. Their extended lifespans and constrained mobility render them particularly vulnerable to sediment contamination, thereby functioning as dependable indicators of prolonged ecosystem distress (Dong *et al*., 2023; Liang *et al*., 2024b). A variety of indices are utilized to evaluate the health of estuaries and coastal ecosystems. These indices, including the AMBI (AZTI's Marine Biotic Index) and the BOPA (Benthic Opportunistic Polychaetes Amphipods Index), employ a classification system that categorizes macrobenthos based on their tolerance to organic pollutants. This approach, as outlined in the works of Borja *et al*. (2000), Dauvin and Ruellet (2007), Lu *et al*. (2021), Dong *et al*. (2023), and Liang *et al*. (2024b), enables a comprehensive assessment of the ecological health of these environments. Furthermore, biodiversity indices (e.g., Shannon, Margalef, Pielou, and Simpson) quantify species diversity and distribution (Fu *et al*., 2022). A multitude of studies have demonstrated the efficacy of these indicators in evaluating ecosystem quality (Lu *et al*., 2021; Fu *et al*., 2022; Dong *et al*., 2023; Liang *et al*., 2024b). However, given the intricate dynamics of estuaries, reliance on a solitary index might prove inadequate (Liang *et al*., 2024b). The integration of multiple indicators has been demonstrated to enhance the precision of assessments (Dong *et al*., 2023).

Previous macrobenthos studies in the Musa Estuary focused on individual creeks (Dehghan Madiseh *et al*., 2012; Heydari *et al*., 2021; Heydari *et al*., 2024; Kianersi *et al*., 2024). These limited-scope studies, in conjunction with data that is no longer current, fail to reflect the present conditions of the ecosystem. A thorough evaluation is imperative to inform strategies for habitat and biodiversity conservation. The objective of this study is to evaluate the ecological health of the Musa estuary, which is comprised of six branches, employing a set of six biological indicators (AMBI, BOPA, Shannon, Margalef, Pielou, and Simpson) to establish a baseline for effective management and conservation efforts.

Materials and methods

Study area

The Musa estuary, situated in the northwestern Persian Gulf within the province of Khuzestan in Iran, consists of multiple tributaries. The present study centered on six creeks within the Musa estuary region, with the objective of providing a comprehensive representation of the area, taking into account human activities and physicochemical/biological parameters (Table 1 and Fig. 1). The depth of the sampling points was less than 2 meters.

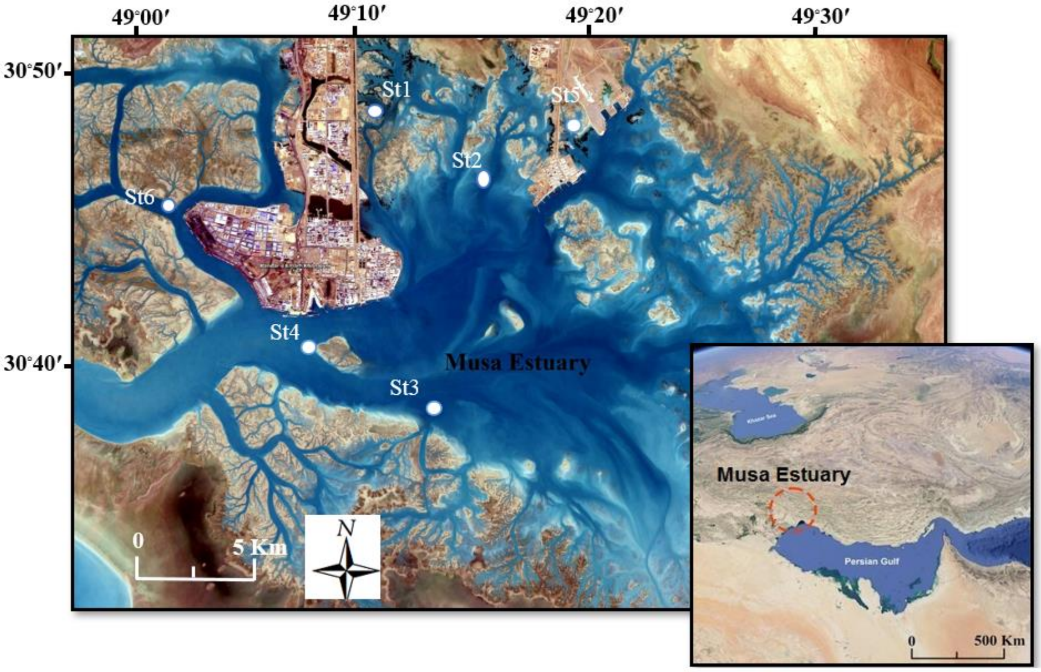

Figure 1: Map of Musa estuary indicating the locations where samples were collected.

Table 1: Geographic locations of the Musa estuary sampling sites.

Region	Latitude	Longitude
Jafari (St1)	30.4640 N	49.1157 E
Odeleh (St2)	30.4525 N	49.1577 E
Patil (St3)	30.3880 N	49.1382 E
Merinos (St4)	30.4038 N	49.0926 E
Ghazaleh (St5)	30.4733 N	49.1914 E
Doragh (St6)	30.4589 N	49.0279 E

Sampling and analysis of environmental parameters

Sediment and water samples were collected during two seasons, summer (August) and winter (December) of 2024, at high tide, with three replicates per creek. Sediment samples were collected using a Peterson grab with a coverage area of 0.125 m² from the top 4 cm of the benthic layer for macrobenthic identification, grain size analysis, and quantification of total organic matter (TOM). The physicochemical parameters, including salinity, temperature, pH, and dissolved oxygen (DO) levels in the vicinity of the bed, were collected using a Nansen bottle and analyzed with an HQ40d Multi-meter (Loveland, Colorado, USA). The sediment samples were stored in polyethylene containers at -20°C until analysis. For macrobenthic analysis, samples were sieved through a 500 µm mesh and preserved in a 4% formalin solution until further examination (Asl *et al*., 2023). The percentages of grain size and TOM in the sediments were assessed through combustion and by passing the samples through a series of sieves ranging from 63 µm to 4 mm, following the method outlined by Holme and McIntyre (1984). Particles measuring less than 63 µm were categorized as silt-clay (Shepard, 1954).

Analysis of macrobenthos

Macrobenthos samples were stained with a rose bengal solution (1 g/L) for 40 minutes and preserved in 70% alcohol (Khaledi, 2024). The samples were examined under a stereomicroscope (Nicon, SMZ800) and identified to the most precise taxonomic level possible, typically at the species level, using reliable taxonomic keys (Hutchings, 1984; Sharabti, 1984; Dudgen, 1999; Rouse and Pleijel, 2001; Al-Yamani *et al*., 2012).

Ecological indicators

This study employed a range of ecological indicators to evaluate the health of the region by examining macrobenthos. The calculation of species diversity was performed using diversity indices such as Shannon's Index (H'), Margalef's Species Richness (d), Pielou's Evenness (J'), and Simpson's Dominance (D) (Fu *et al*., 2022). Additionally, two biotic indices, AMBI (Borja *et al*., 2000) and BOPA (Dauvin and Ruellet, 2007), were used to assess ecological quality (Table 2). The AMBI v6.0 software (available at http://www.azti.es) was used to calculate AMBI, incorporating the most recent species classifications as of October 2024. For groups that could not be identified at the species level, classification information was obtained from closely related genera. The AMBI index is a classification system that categorizes macrobenthos into five ecological groups (EG) based on their tolerance to organic matter (Borja *et al*., 2008). Ecological indices such as AMBI, BOPA, and H′ are classified into five ecological quality states (EcoQs) based on their values (Table 3). These states are further categorized into acceptable (High and Good) and unacceptable (Moderate, Poor, and Bad) levels (Liang *et al*., 2024b).

Data analyze

Graphs were created using Microsoft Excel 2016, and statistical analyses were conducted using IBM-SPSS (version 26, Chicago, USA). The Shapiro-Wilk test was used to evaluate the normality of the data distribution. A one-way analysis of variance (ANOVA) was performed to analyze spatial (sampling points) and temporal (seasons) variations for normally distributed data. When significant differences were detected, the Tukey post-hoc test was used to determine specific differences between groups. Spearman's rank correlation test, a nonparametric method used due to the uneven distribution of macrobenthos abundance, was utilized to evaluate the relationships between density, different indices, and environmental factors.

Table 2: Overview of evaluated benthic indices, featuring calculation formulas (Fu *et al*., 2022; Liang *et al*., 2024b).

Indices	Equation	Note
AMBI	= [(0 × %EGI) + (1.5 ×% EGII) + (3 × %EGIII) +(4.5 ×% EGIV)(6 ×% EGV)]/100	EGI: species very sensitive; EGII: species indifferent; EGIII: species tolerant; EGIV: second-order opportunistic species; EGV: first-order opportunistic species
BOPA	= log[(*ƒ* P)/ (*ƒ* A + 1) + 1)]	*ƒ*P: opportunistic; polychaetes frequency; *ƒ*A: amphipods frequency
H´ (Shannon)	$= - \sum Pi \log_2 Pi$	Pi: probability of occurrence of the i^th^ species in a community
d (Margalef)	$= (S - 1)/\log_2 N$	S: number of species found; N: total number of individuals
J ´(Pielou)	$= H'/\log_2 S$	H: Shannon; S: number of species found
D (Simpson)	$= \sum Pi^2$	Pi: probability of occurrence of the i^th^ species in a community

EG: ecological group

Table 3: Thresholds for classifying ecological quality status based on the indicators used (Liang *et al*., 2024b).

EcoQs	AMBI	BOPA	H´ (Shannon)
High (no disturbance)	0.0–1.2	0–0.045	>4
Good (slight disturbance)	1.2–3.3	0.045–0.139	3–4
Moderate (moderate disturbance)	3.3–5.0	0.139–0.193	2–3
Poor (serious disturbance)	5.0–6.0	0.193–0.267	1–2
Bad (extremely serious disturbance)	>6.0	0.267–0.301	<1

EcoQs: ecological quality states

Quantitative values for biological indices were calculated using AMBI v.6 and Paleontological Statistics (Past; Version 4, National History Museum, Oslo, Norway) software. A significance level of 0.05 was adopted for all statistical tests, and results were presented as mean±standard deviation (SD). Prior to analyzing macrobenthos abundance data, a Log(x+1) transformation was applied to address non-normal distribution. The transformed data were assessed for distributional properties and homogeneity of variance using the Shapiro-Wilk and Levene tests, respectively, followed by the ANOVA test. Results are presented as mean±SD of the untransformed data, while all statistical analyses were conducted on the transformed data.

Results

Overall, certain environmental factors exhibited significant variations among the creeks ($P < 0.05$). Among the studied creeks, Odeleh Creek had the highest TOM at 9.40%, while Merinos Creek recorded the lowest TOM at 6.16 %. Bed texture analysis indicated that mud dominated the study area. Odeleh Creek had the highest concentration of silt-clay particles at 70.48 %, while Merinos Creek had the lowest at 64.46 % (Table 4).

Table 4: Environmental features of the studied Creeks in the Musa estuary area in 2024 (Mean ± SD). Different letters in each column indicate significant differences (*p<0.05*).

Region	Environmental Factors					
	TOM (%)	Silt-clay (%)	DO (mg/L)	pH	Temperature (c°)	Salinity (ppt)
Jafari	9.05 ± 1.24^{c}	69.12 ± 2.64^{b}	5.15 ± 0.34	7.11 ± 0.11	22.15 ± 0.55	44.11 ± 0.58
Odeleh	9.40 ± 0.45^{c}	70.48 ± 1.69^{b}	5.05 ± 0.27	7.19 ± 0.10	22.94 ± 0.34	44.34 ± 0.66
Patil	6.37 ± 0.98^{a}	66.82 ± 2.13^{ab}	5.13 ± 0.39	7.55 ± 0.23	23.05 ± 0.21	44.11 ± 0.43
Merinos	6.16 ± 1.09^{a}	64.46 ± 2.35^{a}	5.01 ± 0.11	7.44 ± 0.05	22.05 ± 0.22	43.05 ± 0.51
Ghazaleh	9.28 ± 1.11^{c}	67.76 ± 1.74^{ab}	5.43 ± 0.15	7.34 ± 0.31	22.44 ± 0.33	44.21 ± 0.71
Doragh	8.21 ± 0.97^{b}	67.38 ± 2.10^{ab}	5.11 ± 0.56	7.32 ± 0.12	22.01 ± 0.41	43.22 ± 0.62

The average density of macrobenthos during summer and winter was 4301 and 4788.66 individuals/m², respectively. Significant spatial variations in macrobenthos abundance were observed (*p<0.05*). In summer, Jafari Creek had the highest abundance, while Doragh Creek had the lowest. Conversely, in winter, Odeleh Creek recorded the highest abundance, and Merinos Creek exhibited the lowest (Fig. 2).

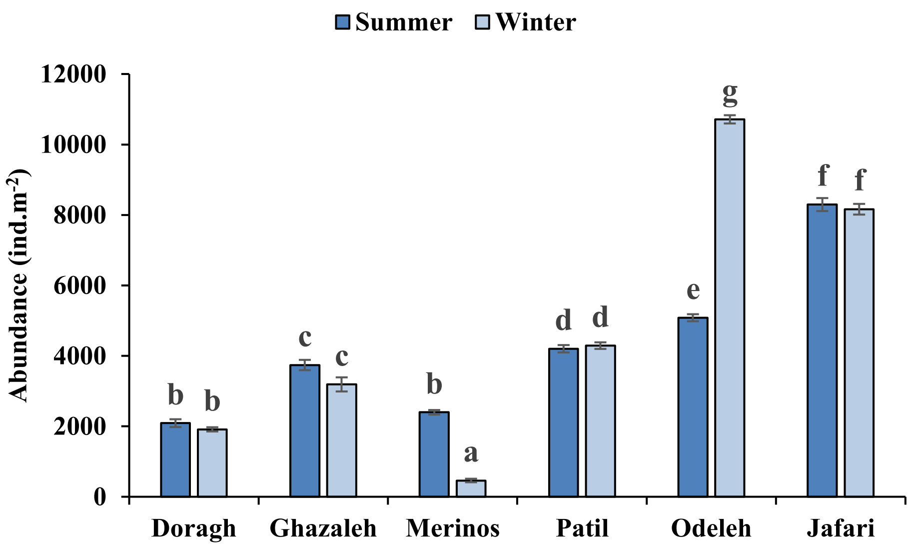

Figure 2: Changes in the abundance of macrobenthos (individual.m^{-2}) in different creeks in two seasons in the Musa estuary in 2024 (Mean±SD). Various letters represent significant differences (*p<0.05*).

Polychaetes were the most prevalent group, comprising 40-90% of the total macrobenthos across all creeks in both seasons, significantly outnumbering other taxonomic groups. However, differences were noted in the presence of important taxonomic groups among the various study creeks. Crustaceans were absent from Ghazaleh Creek, and mollusks were not present in Merinos Creek during the winter season (Fig. 3).

A total of 70 taxa across 7 phyla were identified, along with one larval stage of Megalopoda from Decapoda and one larval stage of Cnidaria.

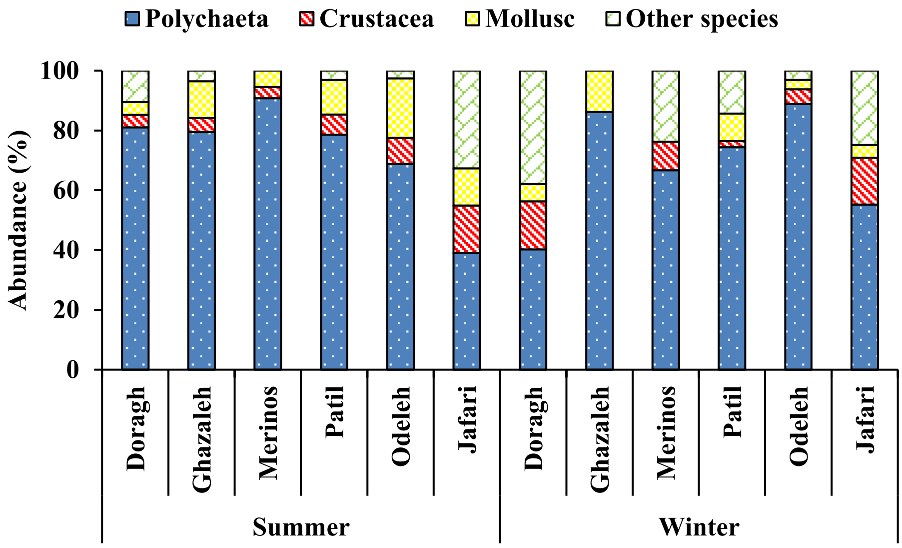

Figure 3: Relative abundance (%) of the key taxonomic groups across various creeks during two seasons in Musa estuary in 2024.

Among these, Annelida comprised the largest group with 35 taxa (69.62%), followed by Arthropoda with 17 taxa (8.79%), Mollusca with 10 taxa (8.87%), Cnidaria with 4 taxa (0.97%), Nemertea with 2 taxa (3.59%), Echinodermata with 1 taxa (0.69%), and Sipuncula with 1 taxa (1.13%). *Melinna* sp. was the most prevalent species in the area, accounting for 14% of the total species, followed by *Capitella* sp. at 6.09% (Table 5).

Table 5: List of dominant species in Musa estuary in 2024.

Taxonomic Group	Taxa	Abundance (%)
Polychaeta	*Melinna* sp.	14
	Capitella sp.	6.09
	Cossura sp.	4.60
	Eunice sp.	3.63
	Lumbrineris sp.1	4.03
	Lumbrineris sp.2	5.12
	Nephthys tulearensis	2.02
	Owenia fusiformis	3.99
	Sabella sp.	4.07
Crustacea	*Ampelisca* sp.	1.17
	Leptognathia sp.	1.33
	Kalliapseudidae	1.69
Bivalvia	*Tellina* sp.	4.44
Hydrozoa	*Hydra* sp.	3.87

The average changes in the Margalef index during summer and winter were 1.28–5.20 and 1.63–5.10, respectively. In both seasons, the highest value was observed at

Jafari Creek, while the lowest was noted at Merinos Creek. The average variations of the Pielou index during summer and winter were 0.51–0.82 and 0.76–0.33, respectively. In the summer, the maximum value was recorded at Doragh Creek, while the minimum was observed at Merinos Creek. Conversely, in the winter, the highest value was found at Merinos Creek, and the lowest values were recorded at Patil and Odeleh Creeks. The average changes in Simpson's index during the summer and the winter were 0.04–0.25 and 0.06–0.23, respectively. In the summer, Merinos Creek had the highest value, while Jafari Creek had the lowest. In winter, Patil Creek recorded the highest value, while Jafari Creek again had the lowest (Fig. 4). Notable differences were found in all diversity indices among the sampling stations during each season (*p<0.05*).

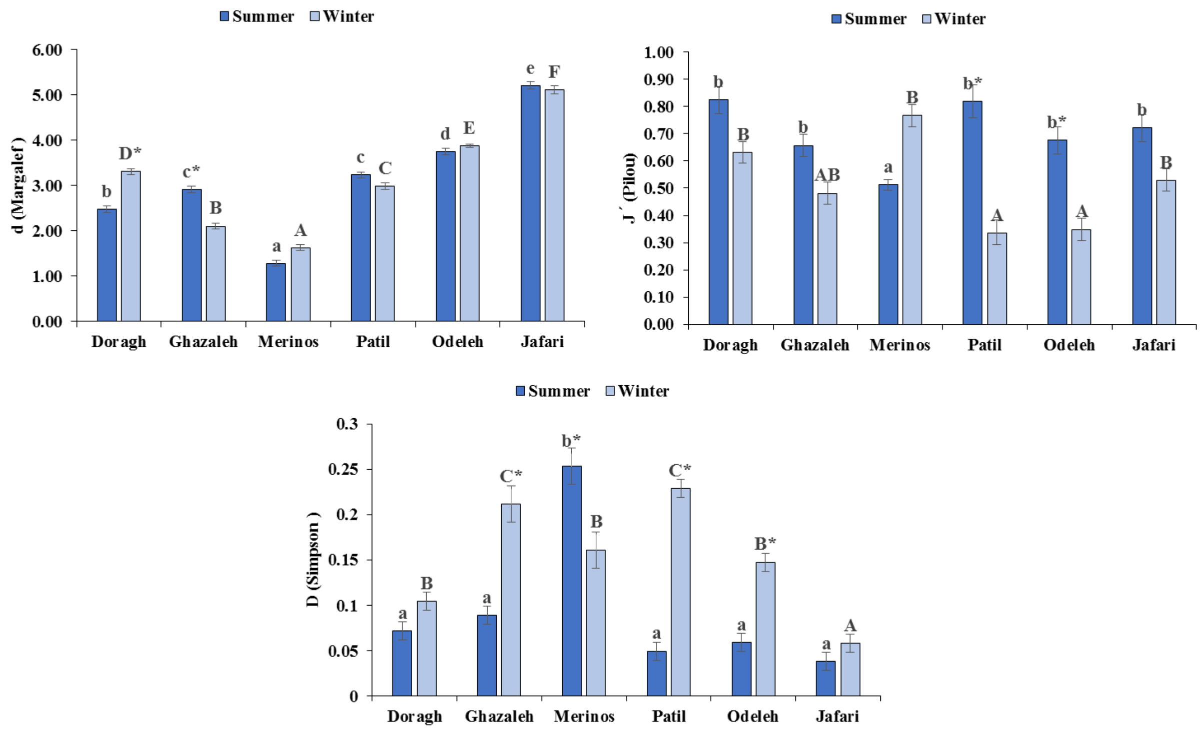

Figure 4: The diversity index values for the species examined in the Musa estuary region during two seasons in 2024 (Mean ± SD). Statistical differences (*p<0.05*) between stations and seasons are denoted by different letters (a, b, c, etc.) and symbols (* and none), respectively.

Fewer than 4% of individuals in the region were not assigned to ecological groups. During summer, EGII was the most prevalent in Doragh, Ghazaleh, and Odeleh Creeks, while EGI was the most common in Merinos, Patil, and Jafari Creeks. In winter, EGI dominated Doragh Creek, EGIV was the most prominent in Ghazaleh Creek, and EGIII was the leading group in the remaining creeks (Fig. 5).

The mean variations in the Shannon index for summer and winter were 2.01–3.54 and 2.13–3.21, respectively. In both seasons, the highest values were observed at Jafari Creek, while the lowest were found at Merinos Creek.

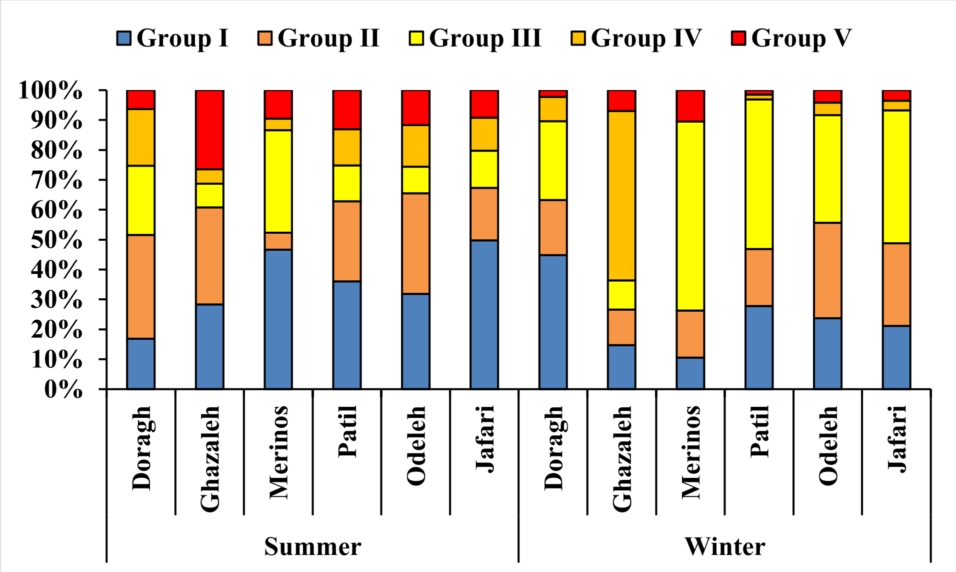

Figure 5: Proportion of ecological groups (I-V) in the examined creeks of the Musa estuary region during the two seasons in 2024.

The Shannon diversity index, a measure of ecological diversity, revealed that the sampled locations and seasons exhibited a moderately polluted condition, with the exception of Patil and Odeleh Creeks during summer and Jafari Creek in both seasons, which were categorized as slightly polluted. The mean variations in the AMBI index during summer and winter were 1.55–2.47 and 1.57–3.39, respectively. The maximum value was documented at Ghazaleh Creek during the winter, while the minimum was recorded at Jafari Creek in the summer season. Across both seasons, the AMBI values in all creeks remained below 3.3, indicating a slightly polluted status. However, during the winter, Ghazaleh Creek was classified as moderately polluted. The mean variations in the BOPA index during summer and winter were 0.05–0.11 and 0.01–0.21, respectively. The maximum value was documented at Ghazaleh Creek during the winter, while the minimum was recorded at Patil Creek in the same season. During the summer, the BOPA values across all creeks ranged from 0.045 to 0.139, indicating a condition of slight pollution. During the winter, the BOPA values of all creeks fell below 0.045, thus classifying them as unpolluted, with the exception of Ghazaleh Creek, which was designated as severely polluted (Fig. 6).

The Spearman correlation analysis demonstrated a positive correlation between the abundance and diversity indices (Shannon and Margalef) and the organic matter percentage ($p<0.01$). Conversely, the Simpson index negatively correlated with sediment organic matter ($p<0.05$). The Pielou index had a positive correlation with DO levels ($p<0.05$), yet a negative correlation with salinity (p<0.01) (Table 6).

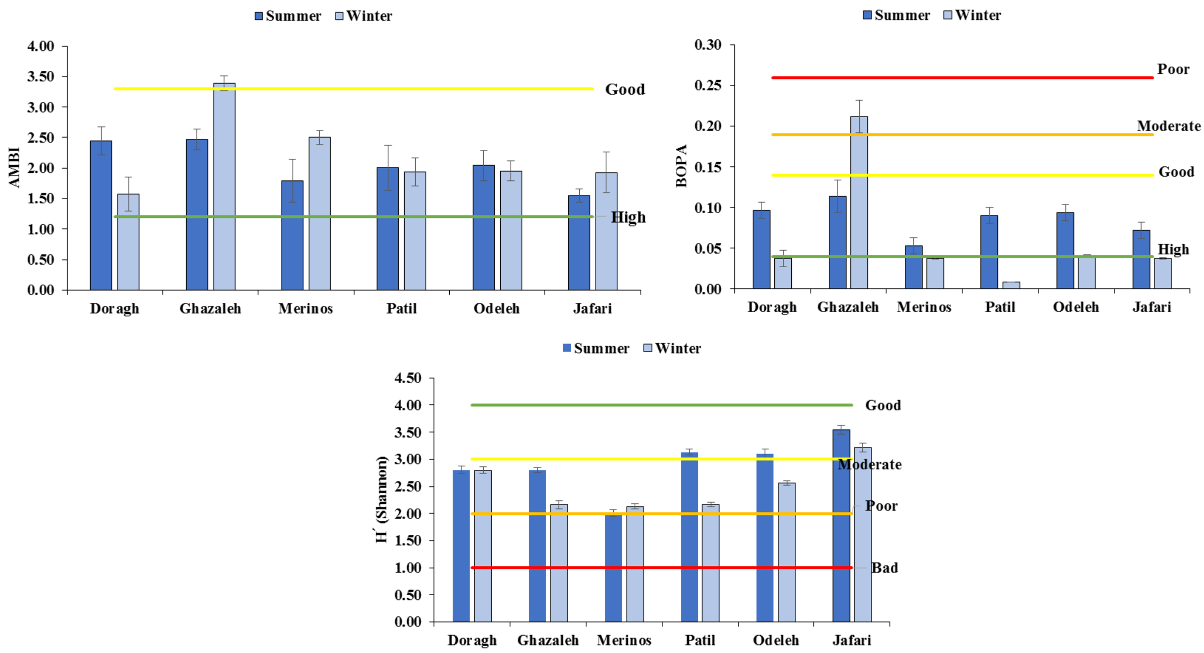

Figure 6: Values of biotic indices and the ecological quality status in the examined creeks of the Musa estuary region during the two seasons in 2024 (Mean±SD).

Table 6: Spearman correlation coefficients between abundance and biological indices of macrobenthos and environmental parameters.

	TOM (%)	Silt-clay (%)	DO (mg/L)	pH	Temperature (c°)	Salinity (ppt)
Abundance	0.54**	0.11	0.10	-0.05	-0.06	0.54
Shannon	0.55**	0.43	0.48	-0.69	0.40	-0.15
Margalef	0.51**	0.39	0.30	-0.32	0.01	-0.32
Pielou	0.15	0.15	0.67*	-0.66	0.55	-0.71**
Simpson	-0.57*	-0.33	-0.50	0.69	-0.38	0.24
AMBI	0.17	-0.16	0.28	0.32	-0.18	0.06
BOPA	0.45	0.16	-0.10	-0.02	0.21	-0.17

*: p<0.05; **: p<0.01

Discussion

In this study, 7 phyla were identified in the Musa estuary, with polychaetes dominating (69% of the macrobenthos). Similar results have been reported in the northwestern Persian Gulf (e.g., Jafari Creek) (Heydari *et al*., 2024) and Pangpang Bay, Indonesia (Suciyono *et al*., 2024), where polychaetes were abundant in muddy sediments. Several factors explain their prevalence in muddy beds, including their ability to consume organic matter in fine-grained sediments, their agility and ability to hide in the mud, and their physiological adaptations that allow them to thrive in low-oxygen conditions, aided by specialized respiratory structures (Rabalais and Baustian, 2020; Wiesebron *et al*., 2021; Miri *et al*., 2023). Muddy sediments (dominated by silt and clay) are ideal for polychaetes due to their high organic content, which serves as a nutritious food source (Lourido *et al*., 2023). In the Musa estuary, the dominant sediment type was silt-clay, consistent with polychaete dominance. Similarly, in Zangi Creek (northwestern Persian Gulf), polychaetes comprised >50% of the benthic biomass in sediments with >80% silt-clay (Heydari *et al*., 2021). Furthermore, a study conducted in Onagawa Bay, Japan, found that polychaetes were the dominant group in the benthic macrofauna, accounting for 86.3% of the total abundance (Deen *et al*., 2024).

In the current study, two polychaete species, *Melinna* sp. and *Capitella* sp., were identified as the dominant species in the Musa estuary. *Melinna* is known to be a surface deposit feeder that thrives in moderately polluted conditions (Shokat *et al*., 2010; Massé *et al*., 2019). The high abundance of this species in the muddy beds of the Musa estuary may be due to the abundance of organic matter available and its ability to tolerate moderate pollution. *Capitella* is a non-selective subsurface deposit feeder that is recognized as an indicator of pollution. A high population of this species typically indicates the presence of organic pollution in the environment (Sanchis *et al*., 2021). The coexistence of these two species suggests a pollution gradient and the presence of organic matter in the Musa estuary region, with *Capitella* sp. occurring in more polluted areas and *Melinna* sp. found in areas with lower pollution levels. Thus, the coexistence of these species reflects the estuary's complex environmental gradients of the estuary.

In this study, the highest average macrobenthos densities were recorded in Jafari Creek during the summer and in Odeleh Creek during the winter. The increased abundance in these creeks is likely due to greater food availability and finer substrate texture, which is consistent with the TOM and sediment grain size results. Organic matter serves as the primary food source for macrobenthos, particularly polychaetes, while fine-grained sediments provide stable habitat (Naser, 2022; Lourido *et al*., 2023). These conditions promote macrobenthic settlement and feeding. We found a positive TOM-macrobenthos abundance correlation, indicating that organic matter directly affects population density. Naser (2022) studied macrobenthos in the coastal mudflats of Bahrain (Persian Gulf) and found that increases in organic matter led to increases in macrobenthos, particularly polychaetes. A recent study found that higher levels of organic matter in coastal sediments at Karimunjawa Island, Jepara District, Indonesia, were positively associated with increased polychaete abundance (Putro *et al*., 2025).

The Shannon index classified the ecological status of Musa estuary as unacceptable (moderately polluted) at some stations and seasons. In contrast, Patil and Odeleh creeks were acceptable (slightly polluted) in summer, as was Jafari creek in both seasons. This variation may reflect better environmental management or the distance of Jafari Creek from pollution sources. Jafari Creek had the highest biodiversity in both seasons, with Margalef's richness and Shannon's diversity indices supporting each other. Its higher biodiversity was probably due to more species, balanced distribution and improved substrate. Diversity and richness indices were positively correlated with TOM levels, reflecting the prevalence of sediment-feeding polychaetes that thrive on organic matter (Lourido *et al*., 2023).

Consistent with our findings, Haque *et al*. (2021) found an increase in macrobenthic biodiversity in the mudflat of the east coast of Bangladesh, which they attributed to favorable conditions for polychaetes. A recent study of macrobenthic communities in the coastal mudflat of Hwangdo Island, South Korea, yielded similar results (Liang and Me, 2025).

Higher Simpson index values in Merinos Creek (summer) and Patil/Ghazaleh Creeks (winter) may indicate species vulnerability to stressors and the presence of pollution-resistant species. These results were consistent with Pielou's evenness index findings. As certain species populations increased, distribution evenness decreased. Alsamadany *et al*. (2020) found that human activities reduced biodiversity while increasing resilient species in Saudi Arabian mudflats. The decline in abundance and biodiversity in some creeks, particularly Merinos Creek, was likely due to poor conditions (low organic matter, unsuitable sediment) combined with local species characteristics.

In this study, the ecological conditions assessed using the AMBI and BOPA indices indicated that all creeks were in an acceptable state in terms of pollution (ranging from unpolluted to slightly polluted) during both seasons. However, Ghazaleh Creek was found to be in an unacceptable state (moderately polluted to heavily polluted) during winter. The increase in pollution levels in Ghazaleh Creek can be attributed to the influx of pollutants and urban and industrial wastewater, particularly during the winter rainy season. In contrast, other creeks may be in better condition due to their natural self-purification processes. The differences observed between the AMBI and BOPA indices and the Shannon and Margalef indices could be attributed to variations in the evaluation criteria, the species composition in the environment, and the presence of various stressors beyond pollution (Liang *et al*., 2024b). According to the findings of Dehghan Madiseh *et al*. (2012), the Musa estuary was found to be slightly polluted, as indicated by the AMBI index. The study also noted the presence of ecologically imbalanced conditions in the area. Furthermore, research conducted by Hawizawi *et al*. (2014) on the macrobenthos along the Khuzestan coast revealed that the BOPA index at sites proximate to the oil and petrochemical wharf in the Musa estuary region reflected a moderate to poor condition. Kianersi *et al*. (2024) demonstrated that a year-long sampling of macrobenthos indicated that Odeleh Creek was in a slightly polluted ecological condition according to AMBI indices. The enhancement in water quality in the Musa estuary after a period of more than ten years can be attributed to a combination of factors, including a reduction in human pollution, natural recovery of the ecosystem, and alterations in environmental variables. A research study was conducted to compare the environmental impacts of various industrial zones along South Korea's coast. The study revealed that the ecological quality, as measured by the AMBI, was significantly lower in areas near shipyards compared to areas near ironworks. This finding serves to underscore the deleterious effects of industrial activities on marine environments (Liang *et al*., 2024a).

During the summer, groups I and II, which are sensitive to pollution, were predominant in the area. Pollution-resistant and second-order opportunistic groups were observed to thrive in winter conditions, with Group III predominating in most creeks and Group IV being dominant in Ghazaleh Creek. Doragh Creek exhibited exceptional characteristics, with a persistent prevalence of group I species. This seasonal variation was likely a consequence of the interaction between physicochemical changes in the environment (temperature, water flow velocity, and dissolved oxygen) and the responses of species to environmental stresses, heightened human activities, or the influx of pollutants associated with seasonal rainfall (Khatri *et al*., 2023; Ge *et al*., 2025). The exception of Doragh Creek is likely attributable to the region's distinct sedimentary and hydrological characteristics, as well as the prevalence of the Hydridae family. These variations serve to illustrate the intricate interplay between physicochemical factors and how species respond ecologically to environmental pressures.

To enhance the environmental quality of the Musa estuary, a series of management strategies have been proposed. Key measures include the regulation of pollutants from industrial, agricultural, and urban sources, as well as the improvement of wastewater management. The establishment of protected areas and artificial habitats is instrumental in ensuring the preservation of biodiversity. Furthermore, community engagement initiatives play a pivotal role in fostering environmental stewardship. It is imperative to implement additional critical actions, including the following: first, the public must be made aware of the pertinent issues; second, ecological assessments must be conducted on a regular basis and utilize standardized indicators; and third, hydrological and sedimentary conditions must be improved. High-biodiversity zones such as Jafari Creek necessitate targeted protection measures, while fishing pressures must be sustainably managed. It is imperative to implement enhanced monitoring procedures for human activities, with a particular focus on the Merinos and Ghazaleh Creeks, to effectively mitigate the environmental stressors that have been identified. The implementation of these strategies is expected to enhance ecological conditions, reduce pollution, and ensure the long-term health of the estuary's ecosystems.

Conclusions

The Musa estuary exemplifies a multifaceted ecological dynamic, a consequence of both natural processes and anthropogenic activities. Spatial variations in macrobenthos abundance and diversity were more pronounced than seasonal changes, with Jafari Creek exhibiting high biodiversity and stability, while Merinos Creek experienced environmental stress. Ghazaleh Creek exhibited a decline in biodiversity during the winter, attributable to contamination. Key factors, including TOM and sediment texture, exerted a substantial influence on the composition of macrobenthos communities. The Shannon index classified the region as slightly to moderately polluted, while AMBI and BOPA indices indicated unpolluted to slightly polluted conditions, with the exception of Ghazaleh Creek, which exhibited moderately to seriously polluted conditions during the winter. These discrepancies underscore the importance of using multiple ecological indicators for accurate ecosystem assessment. The findings underscore the imperative for sustainable water resource management, pollution control, and regular monitoring to safeguard biodiversity and ecological balance. Subsequent research endeavors should concentrate on the repercussions of pollutants, including heavy metals, microplastics, and polycyclic aromatic hydrocarbons, on macrobenthos. This will facilitate the attainment of a more comprehensive comprehension of the estuary's ecological well-being.

Conflicts of interest

The authors declare no conflicts of interest

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