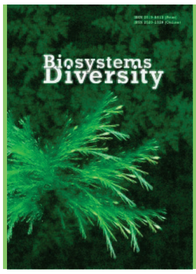

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Benthic macrofauna biodiversity on the East Coast of Algeria

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This study investigated the spatial and temporal variations in macrobenthic communities across three sites on the eastern coast of Algeria, El-Kala, Annaba, and Skikda, in 2021. These sites were selected to assess the impact of varying levels of human activity on marine biodiversity, with El-Kala experiencing minimal disturbance, while Annaba and Skikda were significantly affected by industrial and urban activities. Monthly sampling was conducted on both rocky and sandy substrates to capture a comprehensive picture of the biodiversity within these ecosystems. Water physicochemical parameters, including temperature, pH, salinity, and dissolved oxygen, were measured to evaluate the environmental conditions at each site. The results revealed a significant spatial variability in biodiversity among the sites. El-Kala exhibited the highest biodiversity, reflected in a Shannon-Wiener index of 2.51, followed by Annaba (2.06), and Skikda (1.89). Principal Component Analysis (PCA) was conducted to elucidate the relationships between the physicochemical parameters and ecological indices across the three sites. PCA revealed that higher salinity levels were strongly associated with Skikda, which was affected by industrial runoff. In contrast, temperature, dissolved oxygen, and pH were positively correlated with the ecological indices in El-Kala, indicating a healthier ecosystem with more stable environmental conditions. These findings highlight the urgent need for ongoing monitoring and conservation strategies to mitigate the adverse effects of anthropogenic activities on coastal marine ecosystems. This study highlights the critical importance of environmental management in regions facing significant industrial pressure, such as Skikda, in preserving biodiversity and maintaining ecological balance.

Keywords: biodiversity; ecological indices; Eastern Algerian coast; marine pollution; polychaetes.

Introduction

The Mediterranean Sea, renowned for its economic importance and extensive maritime activities, faces significant environmental challenges due to anthropogenic activities such as hydrocarbon pollution and heavy metal contamination (Chatzinikolaou et al., 2018; Hamoudi et al., 2024; Moumeni et al., 2024). Coastal regions, vital to global economic growth, are increasingly vulnerable to diverse human activities, including terrigenous pollution, aquaculture, fishing, transportation, and offshore oil exploration, which collectively degrade marine ecological environments (Ni et al., 2019; Hamdy et al., 2022). This degradation threatens biodiversity, climate regulation, and habitat protection (Forchino et al., 2011; Bonsignore et al., 2018; Ni et al., 2019). The Mediterranean coastal regions, including the Algerian and Tunisian coasts, face significant environmental challenges due to pollution from urban, industrial, and agricultural sources (Er-Raioui et al., 2012; Dauvin et al., 2013; Mosbahi et al., 2019). These pressures have led to biodiversity decline and ecosystem degradation in various areas (Benali et al., 2017; Rebai et al., 2022).

The Algerian coast, spanning 1622.8 km along the Mediterranean Sea, is experiencing unprecedented development across urban, industrial, tourist, and agricultural sectors (Tata et al., 2023). Effluents from these activities are continuously discharged into coastal waters, exacerbating pollution (Bouzahouane et al., 2018; Inal et al., 2018; Tata et al., 2023). Studies along the Algerian coast have revealed varying levels of contamination, with some areas showing high species richness and diversity (Dauvin et al., 2013), while others exhibit reduced biodiversity and altered community structures (Chabane et al., 2018; Rebai et al., 2022). The Algerian coastal zone faces escalating pressures from socioeconomic growth and inadequate environmental management, leading to biodiversity decline in specific coastal zones (Belhouchet et al., 2024). The use of biomarkers and ecological indices has proven valuable in assessing marine environmental quality and identifying pollution gradients (Guemouda et al., 2014; Snani et al., 2015; Chabane et al., 2018).

Macrobenthos, essential organisms inhabiting and burrowing in coastal sediments, play critical roles in energy and material transfer within marine food webs (Dauvin et al., 2006). These communities serve as effective indicators of pollution impacts and ecosystem health due to their ecological significance and sensitivity to disturbances (Li et al., 2016). Polychaetes, a major component of benthic communities, are crucial for assessing ecological conditions, influencing trophic webs, sedimentary processes, and organic matter cycles (Gambi & Giangrande, 1986; Mdaini et al., 2020; Quiroz-Martínez et al., 2021). However, environmental contaminants can significantly affect their diversity, abundance, dominance, and biomass (Pearson and Rosenberg, 1978). The trophic organization of benthic assemblages is also affected by anthropogenic activities, with more open coastal areas generally showing better ecological balance (Afli et al., 2008).

Benthic communities are directly exposed to contaminants adsorbed on particles and dissolved in water at the sediment-water in-terface. Consequently, they are used as bio-indicators in the biomonitoring of sediment toxicity (Meghlaoui et al., 2015; Tlili & Mouneyarc, 2019; Boumaza et al., 2021). Polychaete annelids, particularly those in the Nereididae family, are representative species of estuarine macrobenthos and play significant roles in biogeochemical processes (Scaps, 2002; Banta & Andersen, 2003; Amiard-Triquet, 2009). These organisms are integral to understanding and managing the impacts of pollution on coastal ecosystems.

This study employed an ecological approach to investigate the structure of macrobenthic populations along the eastern Algerian coast, providing essential baseline data for future environmental assessments and management strategies in the region.

Materials and methods

Sampling sites were selected on the eastern Algerian Mediterranean coast along the east coast of Algeria (Fig. 1 ; Table 1). The maximum tidal range in this region is 0.9 m. Site selection was based on the abundance of species and ease of access to the study area. El-Kala (36°54'0.14" N, 8°28'12.48" E) is close to the Tunisian border (10 km). This site is part of a national park and is not urbanized; therefore, it was considered to be a healthy reference site. Annaba (36°55'0.88" N, 7°46'5.96" E) is located approximately 80 km from the Tunisian border. This site is exposed to pollution by pesticides and/or heavy metals released from fertilizer factories and port activities (Sifi et al., 2007; Ouali et al., 2018). Skikda (36°53'49.51" N, 6°52'50.39" E) is located approximately 180 km from the Tunisian border. This site is near the port of Stora and is characterized by intense maritime traffic. It is also polluted by polycyclic aromatic hydrocarbons (PAH) due to the presence of petrochemical complexes and human activities.

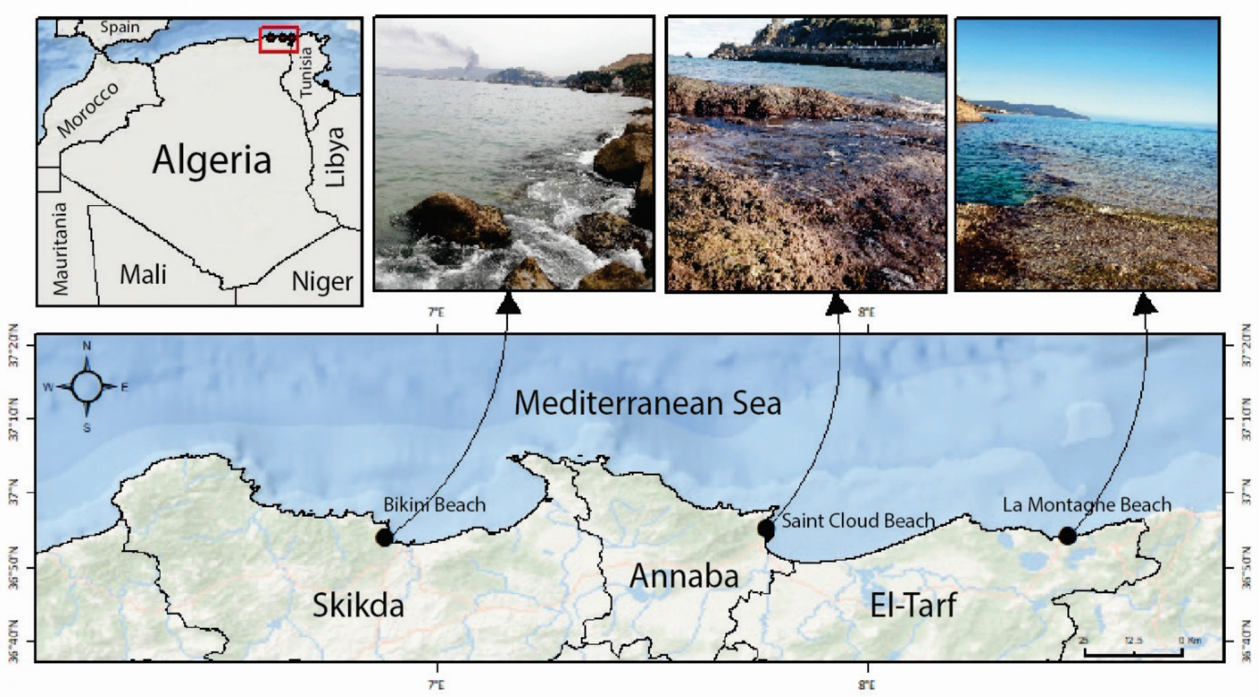

Fig. 1. Location of the study area showing the sampling stations at El-Kala, Annaba, and Skikda

Table 1
Nature of diverse human-induced stresses
at three monitoring sites (El-Kala, Annaba, and Skikda)

Sampling site	Latitude	Longitude	Human-induced stresses
El-Kala	36°54'0.14" N	8°28'12.48" E	Tourist activities and fishing
Annaba	36°55'0.88" N	7°46'5.96" E	Industrial and domestic effluents, domestic sewage disposal, boating, tourist activities and bathing
Skikda	36°53'49.51" N	6°52'50.39" E	Domestic and industrial effluents, tourist activities, fishing, agricultural, domestic, and aquacultural practices

In 2021, macroinvertebrates were collected from three sites on the Eastern Algerian coast: El-Kala, Annaba, and Skikda. Sampling was conducted on rocky and sandy substrates, both of which were covered with algae. At each site, one replicate of sampling was performed each month using a 25 × 25 cm quadrat and a 0.5 m depth scraper. In the laboratory, macroinvertebrates were fixed in the field using 4% formaldehyde solution and then preserved in 70% ethanol.

At each site, the environmental parameters (water temperature, pH, salinity and dissolved oxygen) were measured monthly using a multiparameter analyser (Multi 340i/SET).

To assess the spatial and temporal variations in the physicochemical parameters of water across the study sites (El-Kala, Annaba, and Skikda Sites), a one-way ANOVA was conducted. Tukey's test was used for post-hoc comparisons to identify any significant differences between the sites. Biodiversity was evaluated using a suite of diversity indices, including the Shannon-Wiener (Shannon, 1948), Piélou evenness (J) (Pielou, 1966), Simpson (Simpson, 1949), and Margalef (Margalef, 1958) indices, to analyze species diversity, evenness, dominance, and richness. All statistical analyses were performed using R (version 4.2.3; R Core Team, 2023) and RStudio (RStudio Team, 2024).

Results

The surface water temperatures varied seasonally across the El Kala, Annaba, and Skikda sites. The maximum temperatures are typically observed in summer, whereas the minimum temperatures occur in winter. Seasonal temperature variations exhibited a decline from autumn to winter, and an increase from spring to summer (Fig. 2a). The differences between the sites reflected the local coastal dynamics and seasonal influences. Salinity levels in El Kala, Annaba, and Skikda displayed seasonal fluctuations influenced by factors such as evaporation and precipitation. Higher salinity levels were generally observed during summer because of increased evaporation, whereas rainy seasons contributed to decreased salinity (Fig. 2b).

Dissolved oxygen levels varied during the study period. Maximum values were typically recorded during cooler months, with minimum values observed during warmer months. Oxygen levels generally decreased during summer and increased during winter across all sites, which was influenced by seasonal variations in water temperature and biological activity (Fig. 2c).

The pH values at El Kala, Annaba, and Skikda were consistently alkaline at all the sites. Slight variations in pH levels were observed between sites, reflecting local environmental conditions (Fig. 2d). The ANOVA single controlled factor analysis indicated that there were significant differences only between the dissolved oxygen levels at the three study sites ($P < 0.05$).

During the study period, 4,242 individuals were sampled from the three sites. Individuals were distributed across 20 families and 30 species (Table 2). Among these 30 species, 9 belonged to the family Neredidae.

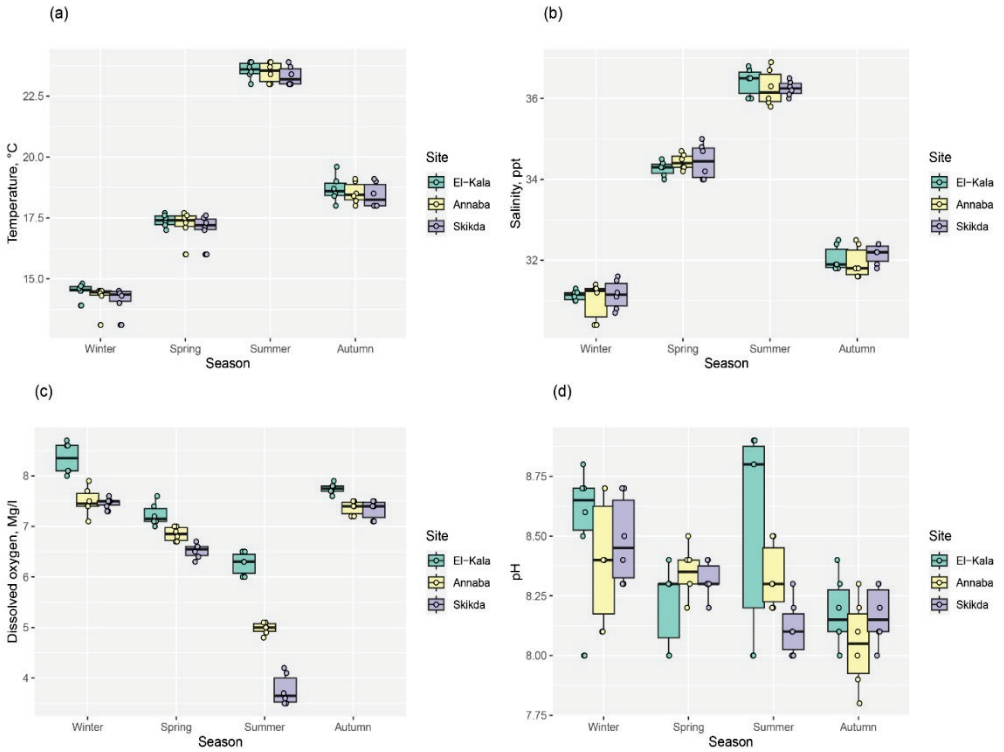

Fig. 2. Variations in water physicochemical parameters at different study sites during the study period

A total of 1,944 specimens, representing 30 different species across 20 families, were identified at La Montagne Beach in El-Kala (Table 2). The most abundant families were Neredidae (37.6%), Mytilidae (21.8%), and Patellidae (9.4%) (Fig. 3a). Among the species found at this site, *Perinereis cultrifera* (26.5%), *Mytilus galloprovincialis* (21.8%), and Amphipoda sp. (8%) were the most abundant (Fig. 3b). A total of 1,383 specimens were identified at Saint Cloud beach in Annaba, consisting of 19 different species belonging to 14 families (Table 2). The most abundant family was Neredidae (42.7%, Fig. 3a). The dominant species at this site were *Perinereis cultrifera* (28.6%), *Mytilus galloprovincialis* (28%), and *Nereis falsa* (12.4%, Fig. 3b). Finally, 909 specimens were sampled at Bikini Beach in Skikda, representing 17 different species from 13 families (Table 2), with Neredidae (38.3%), Mytilidae (33.7%), and Patellidae (10.8%) being the most frequently encountered (Fig. 3a). The most dominant species at this site were *Mytilus galloprovincialis* (33.7%), *Perinereis cultrifera* (30.4%), and Amphipoda sp. (8%), respectively (Fig. 3b).

Table 2
Taxonomic list of benthic macrofauna collected at various sampling sites during the study period

Families	Species	Site			Total
		El-Kala	Annaba	Skikda	
Nereidae	*Perinereis cultrifera* (Grube, 1840)	516	396	276	1188
	P. floridana (Ehlers, 1868)	53	19	0	72
	P. macropus (Claparède, 1870)	17	0	0	17
	P. marioni (Audouin & Milne Edwards, 1833)	14	3	3	20
	P. oliveira (Horst, 1889)	12	0	0	12
	Pseudonereis anômala (Gravier, 1899)	8	0	0	8
	Platynereis dumerilii (Audouin & Milne Edwards, 1833)	9	0	0	9
	Nereis falsa (de Quatrefages, 1866)	95	172	69	336
	Nereis virens (M Sars, 1835)	7	0	0	7
Patellidae	*Patella rustica* (Linnaeus, 1758)	111	79	58	248
	P. caerulea (Linnaeus, 1758)	39	23	17	85
	Cymbula safiana (Lamarck, 1819)	33	23	23	79
Muricidae	*Stramonita haemastoma* (Linnaeus, 1767)	64	33	21	118
Siphonariidae	*Siphonaria pectinata* (Linnaeus, 1758)	27	17	7	51
Fissurellidae	*Diodora graeca* (Linnaeus, 1758)	19	5	3	27
Eriphiidae	*Eriphia verrucosa* (Forskål, 1775)	18	9	4	31
Grapsidae	*Pachygrapsus marmoratus* (Fabricius, 1787)	28	18	7	53
Cirolanidae	*Eurydice pulchra* (Leach, 1816)	30	17	9	56
Arbaciidae	*Arbacia lixula* (Linnaeus, 1758)	24	7	3	34
Parechinidae	*Paracentrotus lividus* (Lamarck, 1816)	11	0	0	11
Polynoidae	*Lepidonotus clava* (Montagu, 1808)	17	0	0	17
Pisinae	*Pisa* sp.	6	0	0	6
Majidae	*Maja* sp.	3	0	0	3
Mytilidae	*Mytilus galloprovincialis* (Lamarck, 1819)	423	387	306	1116
Chitonidae	*Acanthochitona* sp.	34	0	0	34
Trochidae	*Gibbula* sp.	99	36	17	152
Gammaridae	*Amphipoda* sp.	155	105	73	333
Acriniidae	*Anemonia viridis* (Forsskål, 1775)	3	0	0	3
Phascolosomatidae	*Phascolosoma* sp.	63	31	13	107
Holothuroidea	Holothuroidea spp.	6	3	0	9
	Total site	1944	1383	909	
	Total sites		4242		

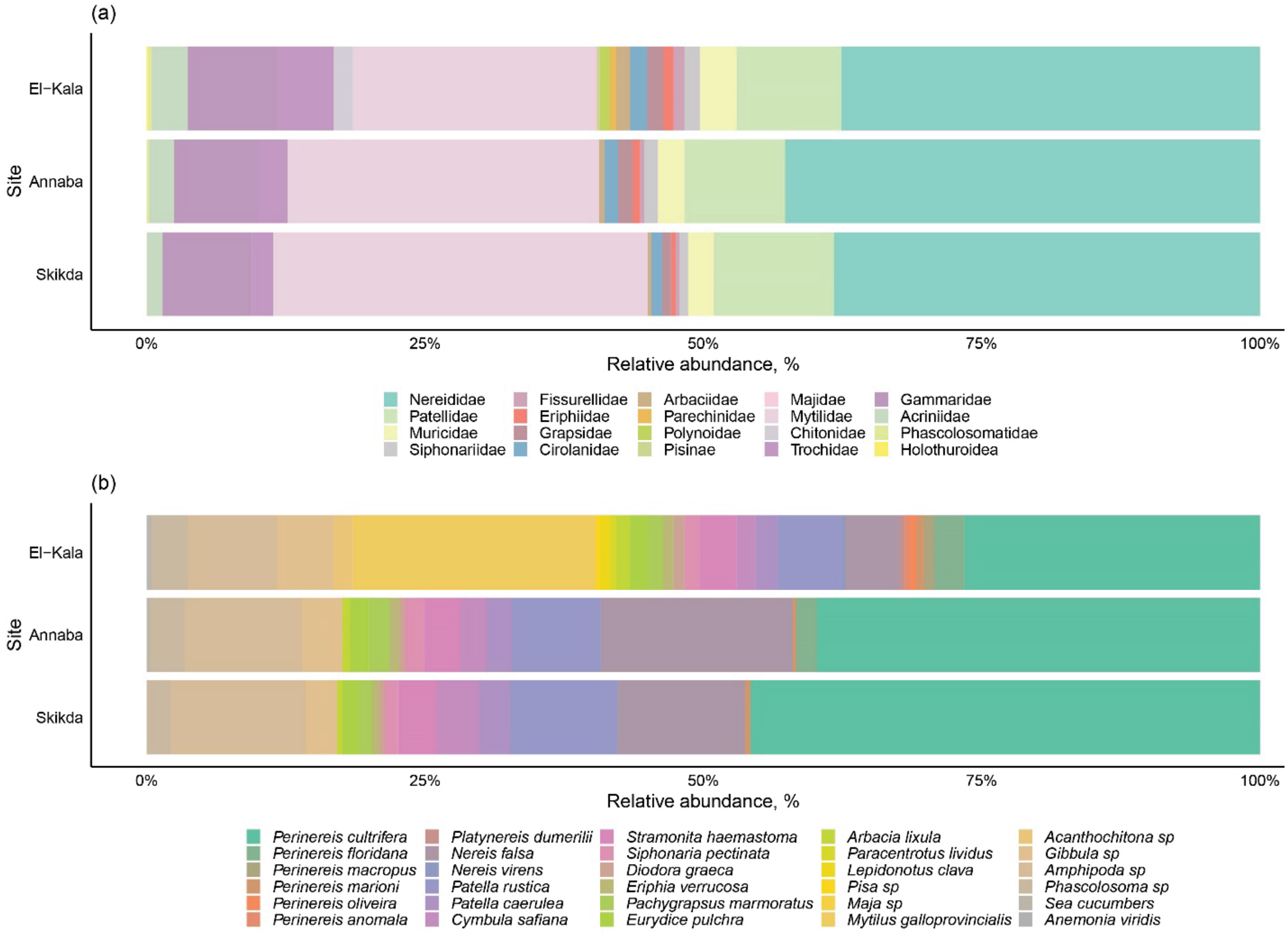

Fig. 3. Relative abundance of macroinvertebrates at three sites on the eastern coast of Algeria during the study period: *a, b* – relative abundance (%) of different macroinvertebrate groups in El-Kala, Annaba, and Skikda

The Shannon-Wiener index is a commonly used measure of biodiversity that considers both the number of species and their evenness in a community. A higher Shannon-Wiener index value indicated a more diverse and balanced ecosystem. In this study, the Shannon index was highest in El-Kala (2.51), followed by Annaba (2.06), and Skikda (1.89) (Table 3). This suggests that El Kala had the highest level of biodiversity among the three study sites, whereas Skikda had the lowest.

The Piélou evenness (equitability) index measures the relative evenness of species abundance in a community, with higher values indicating greater evenness. In this study, the Piélou index was highest in El-Kala (0.74), followed by Annaba (0.70), and Skikda (0.66) (Table 3). These results suggest that El-Kala and Annaba had more even distributions of species abundance than Skikda.

The Simpson index is another measure of biodiversity that assesses the dominance of a few species in a community. The Simpson index values ranged from 0.77 at Skikda to 0.86 at El-Kala, with Annaba having an intermediate value of 0.81 (Table 3). This suggests that El-Kala has a more diverse ecosystem than Skikda, whereas Annaba is somewhere in between. The Margalef index measures community richness by considering the number of species present. The Margalef index was highest at El-Kala (3.83), followed by Annaba (2.48) and Skikda (2.34) (Table 3). This suggests that El-Kala had higher species richness than the other two sites.

Table 3
Biodiversity indices at different study sites in 2021

Diversity indices	Site		
	El-Kala	Annaba	Skikda
Taxa (S)	30	19	17
Individuals	1944	1383	909
Shannon-Wiener (H')	2.51	2.06	1.89
Piélou (J)	0.74	0.70	0.66
Simpson (1-D)	0.86	0.81	0.77
Margalef (d)	3.83	2.48	2.34

The Sørensen coefficient measures the similarity of species composition between different sites. The highest similarity was found between Skikda and Annaba (0.94), followed by El-Kala and Annaba (0.77), and finally El-Kala and Skikda (0.72) (Fig. 4). These results suggest that Annaba shares a greater similarity in species composition with both El Kala and Skikda, whereas El-Kala and Skikda are less similar.

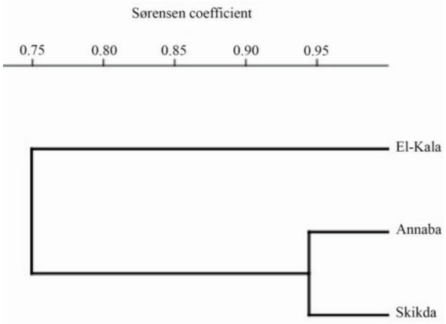

Fig. 4. Sørensen similarity dendrogram of study sites: El-Kala, Annaba, and Skikda

Principal Component Analysis (PCA) was conducted to investigate the relationships between ecological indices and physicochemical parameters in the study area. The dataset consisted of 10 columns representing environmental and biotic parameters and three rows corresponding to sampling stations (La Montagne Beach, Saint Cloud Beach, and Bikini Beach). PCA revealed that the first two dimensions, Dim1 (88.7%) and Dim2 (11.3%), accounted for the majority of the total variance, accumulating 100% of the total inertia (Fig. 5).

PCA results identified two distinct groups of parameters. The first group showed a correlation between salinity (Sal) and the Skikda site.

The second group demonstrated positive correlations between several ecological indices, including the Piélou index (J), Shannon-Weaver index (H), Margalef index (d), Simpson (D-1) coefficient, specific richness (S), Nerididea (N), Other families (OF) and abundance (N), and physicochemical parameters such as temperature (Temp), pH, and dissolved oxygen (DO). These characteristics were observed primarily at the El-Kala site.

Overall, PCA highlighted the relationships between biotic and abiotic parameters in the study area, revealing clear distinctions between the different sampling stations.

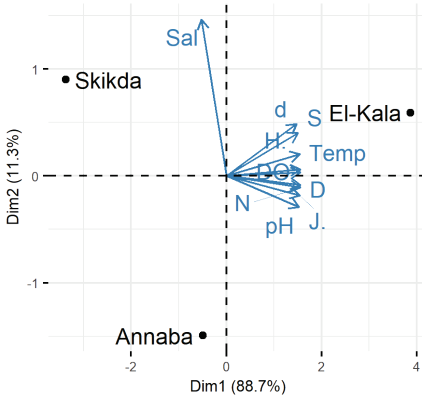

Fig. 5. Principal Component Analysis (PCA) biplot showing relationships between ecological and physicochemical parameters across multiple sampling stations

Discussion

Physicochemical parameters of water play a crucial role in understanding aquatic ecosystems and their biodiversity. Temperature, pH, salinity, and dissolved oxygen are key factors influencing the behavior and distribution of aquatic organisms (Boudeffa et al., 2020; Houmani et al., 2023). These parameters exhibit spatial and temporal variations in coastal waters, estuaries, and lagoons (Aknaf et al., 2017; Qarri & Shehu, 2023; Koubaa et al., 2024). Anthropogenic activities, such as urban discharges and industrial effluents, can significantly alter water quality and impact aquatic life (Kies & Kerfouf, 2014).

Temperature is critical, influencing the survival, distribution, growth rate, activity, and reproduction of aquatic organisms (Abdel-Satar et al., 2010). Although the observed thermal values did not vary significantly among the three study sites, they still shape the distribution patterns of aquatic organisms in the Mediterranean region.

Water pH significantly affects the survival, growth, and physiology of aquatic organisms. Low pH can increase the toxicity of metals and other elements to aquatic life (Qu et al., 2013; Wang et al., 2016). pH influences metal bioavailability and bioconcentration, with lower pH generally increasing toxicity (Riba et al., 2003). Different species show varying pH tolerances; for example, *Daphnia magna*'s optimal pH range is 7.9–8.3 (Ghazy et al., 2011). The pH values observed at the study sites did not show significant variation.

Salinity is a decisive abiotic factor that modulates the physiology of aquatic organisms, determining species distribution and dy-namics (Teske & Wooldridge, 2003; Pasquaud, 2006). Despite influences such as anthropogenic activities and climatic factors, salinity values observed at the three study sites did not vary significantly, reflecting stability amidst external pressures (Bal et al., 2022).

Dissolved oxygen (DO) is crucial for nearly all aquatic organisms, influencing biological processes and survival (El-Zokm et al., 2018). Variations in dissolved oxygen conditions can lead to shifts in species composition and ecosystem health (Ekau et al., 2010). Bikini Beach (Skikda) exhibited significantly lower mean dissolved oxygen values compared to El-Kala and Annaba, likely due to biodegradable organic matter and industrial discharges impacting oxygen consumption and content. Oxygen plays a pivotal role in controlling life within coastal and estuarine ecosystems, regulated by atmospheric exchange, respiration, and photosynthesis (Cravo et al., 2020; Espinosa-Díaz et al., 2021).

Regarding biodiversity, El Kala showed the highest species richness, abundance, and diversity indices (Shannon and Piélou), indicating a robust ecosystem with balanced species distribution. Annaba exhibited lower species richness and abundance but moderate Shannon and Piélou indices, suggesting a somewhat stable ecosystem. Skikda, with the lowest species richness, abundance, and diversity indices, indicates a less diverse and uneven species distribution. These findings are consistent with previous research in the region (Rezzag Mahcene et al., 2022).

Grimes (2010) proposed a classification system for interpreting the H' index, indicating balanced population structures. Our results suggest balanced population structures in El-Kala and less balanced structures in Annaba and Skikda, possibly due to pollution impacts in these areas. This aligns with findings of high pollution levels in Annaba and Skikda reported by Ramdani et al. (2020), Belfetmi et al. (2021a, b) and Sebbih et al. (2023).

Conclusion

The study demonstrated significant variations in macrobenthic biodiversity among the sites of El-Kala, Annaba, and Skikda, influenced by anthropogenic activities and local environmental conditions. El-Kala, as a relatively undisturbed reference site, showed higher species diversity and more even distribution of species abundance compared to the more polluted sites of Annaba and Skikda. The results highlight the need for stringent environmental management to protect and restore marine biodiversity in Algeria's coastal areas. Regular monitoring and the application of biomarkers and ecological indices are essential to assess pollution impacts and guide conservation strategies.

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