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ABSTRACT

Coastal anthropization poses a severe threat to Mediterranean littoral ecosystems. This study provides a historical baseline for assessing long-term environmental changes in Bou Ismaïl Bay (central Algerian coast) across three sectors exhibiting varying anthropogenic pressures: Tipaza (Corne d'Or, reference), Bou Ismaïl (highly industrialized), and Sidi Fredj (urban/touristic), where comprehensive multi-compartment datasets remain scarce. Surface seawater, *Posidonia oceanica* sheaths/rhizomes, superficial matte sediments, and the sea urchin *Paracentrotus lividus* were concurrently sampled to assess physicochemical parameters, dissolved nutrients, fecal indicator bacteria, and trace element (Al, Cu, Fe, Hg, Mn, Zn) bioaccumulation. The results revealed marked spatial gradients associated with varying levels of anthropogenic pressure. Bou Ismaïl Bay exhibited elevated nutrient concentrations consistent with eutrophic conditions and fecal contamination, driven by massive ammonium (10.30 ± 8.70 μM) and reactive phosphate (2.40 ± 5.10 μM) enrichment alongside high mean total coliform counts ($5{,}000 \pm 6{,}925$ CFUs/100 mL), violating international bathing security margins. This multi-source pollution caused a substantial decline of *P. oceanica* meadows; shoot densities dropped into the "unsatisfactory" quality status in Bou Ismaïl and Sidi Fredj compared to the reference site. Concurrently, the meadow Conservation Index crashed from 0.80 to 0.40, signaling a pronounced ecological shift toward dead matte. Ecotoxicological analyses identified the organic-rich sedimentary matte as a major long-term geochemical sink, with iron ($73{,}03 \pm 39{,}900$ mg/kg dw) and zinc (500 ± 8.0 mg/kg dw) skyrocketing in the heavily impacted bay. Furthermore, a sharp localized mercury anomaly was detected in *P. oceanica* rhizomes at Sidi Fredj (0.700 ± 0.015 mg/kg), may reflect localized contamination associated with historical marina activities. Overall, these findings indicate a marked degradation of key biological indicators under increasing anthropogenic pressure and highlight the urgent need for local wastewater purification systems to safeguard southern Mediterranean coastal ecosystems.

KEYWORDS: Pollution, Algerian Coast, *Posidonia oceanica*, trace elements, *Paracentrotus lividus*, Bonitoring.

INTRODUCTION

Coastal ecosystems worldwide are under severe pressure due to escalating anthropogenic activities (Halpern *et al.* 2015). Because major urban centers and industrial zones are historically established along coastlines, marine environments frequently receive substantial loads of untreated industrial and domestic wastes (UNEP/MAP, 2012). The Mediterranean Sea, particularly along its southern margin, is highly vulnerable to this ongoing degradation (Lejeusne *et al.* 2010). In Algeria, where the vast majority of the population and economic infrastructure are concentrated within the narrow northern coastal fringe, littoral zones face critical environmental challenges driven by urban expansion and industrial discharge (Grimes *et al.* 2010; Aroua *et al.* 2023).

To accurately assess and monitor the ecological status of these impacted areas, integrated bio-monitoring approaches using both biotic and abiotic components are essential. In the Mediterranean, meadows formed by the endemic seagrass *Posidonia oceanica* (L.) Delile constitute the climax ecosystem and serve as an exceptional Biological Quality Element (BQE) under modern environmental frameworks such as the European Union Water Framework Directive (Lopez y Royo *et al.* 2010; Personnic *et al.* 2014). Due to its high sensitivity to environmental modifications, the health and structural vitality of *P. oceanica* are widely used as reliable indicators of coastal ecological status and pollution resilience (Pergent-Martini *et al.* 2005; Sengouga *et al.* 2024).

Evaluating environmental stress within this ecosystem requires a multi-compartment diagnostic approach. Beyond the physiological and structural traits of the seagrass itself, associated key species can provide critical complementary data. The purple sea urchin *Paracentrotus lividus* (Lamarck 1816), a dominant macroinvertebrate grazer in Mediterranean meadows, directly depends on *P. oceanica* for food and shelter. Consequently, it represents an effective bioindicator, notably for tracing the transfer and bioaccumulation of contaminants through the trophic web along the Algerian coast (Soualili *et al.* 2008; Boudeffa *et al.* 2023). Concurrently, the organic-rich sediment trapped within the seagrass matte acts as a long-term sink for persistent pollutants. Although the Mediterranean is characterized as a strictly oligotrophic system, concentration gradients of trace elements are often elevated in surface waters and coastal sediments due to industrial inputs, making the matte sediment a highly informative geochemical matrix (Copin-Montégut *et al.* 1986, El Sayed *et al.* 1994). Furthermore, nearshore pollution originating from urban sewage and local wadi discharges can be effectively

tracked by monitoring microbiological indicators, such as faecal coliforms and intestinal enterococci, which reflect immediate sanitary degradation and fecal pollution risks (Holcomb and Stewart 2020).

In this context, Bou Ismaïl Bay represents a critical area of study along the central Algerian coast, characterized by intense anthropogenic pressure from local industrial zones, agricultural runoff, and urban sewage. This study aims to establish a historical environmental baseline for Bou Ismaïl Bay using a multi-compartment biomonitoring approach integrating seawater quality, *Posidonia oceanica*, sediments, and *Paracentrotus lividus*. This baseline provides a valuable reference for future assessments of long-term environmental changes along the central Algerian coast.

MATERIALS AND METHODS

Study Area and Sampling Stations

Field sampling was conducted in May 2010 across three distinct coastal areas exhibiting varying degrees of anthropogenic pressure along the central Algerian coast (Figure 1). A total of 23 sampling sites were monitored. The environmental and geographical characteristics of these studied areas are summarized in Table 1.

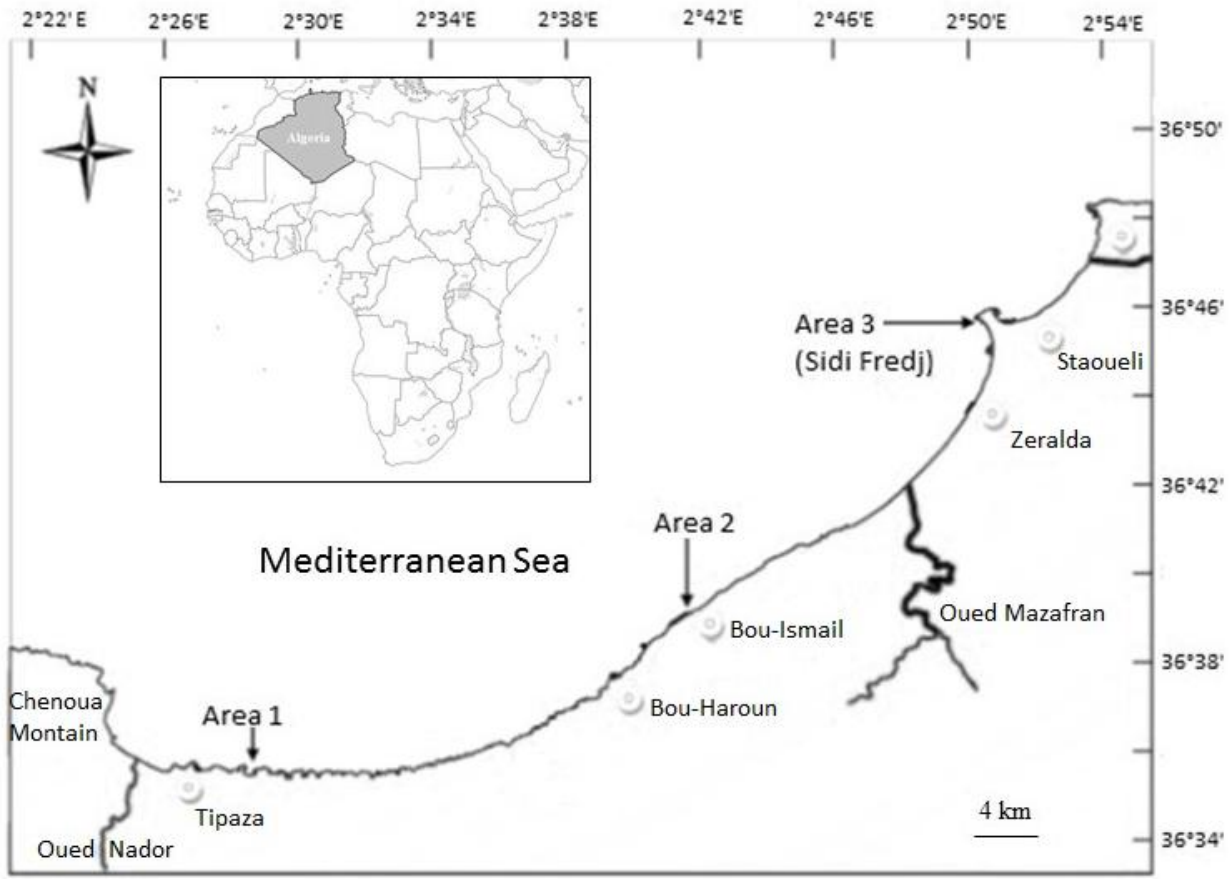


Fig 1. Geographical location of the study area.

Tab 1. Environmental and geographical characteristics of the three sampled areas along the central Algerian coast.

Area	Location	Coastal Morphology & Habitat	Anthropogenic pressure
1. Tipaza (corne d'or)	$36°35'30''$ N, $2°28'30''$ E (~60 km west of Algiers)	Open zone, sandy coast, low turbidity, high-density *P. oceanica* meadow.	Low pressure; seasonal tourism, low local population density.
2. Bou Isamaïl	$36°38'33''$ N, $2°41'24''$ E (~45 km west of Algiers)	Open zone, rocky and sandy coast, high turbidity, low-density *P. oceanica* meadow.	High pressure; intensive agriculture, industrial zones, high population density, urban sewage outfall.
3. Sidi Fredj	$36°45'51''$ N, $2°50'38''$ E (~30 km west of Algiers)	Open zone, rocky and sandy coast, intermediate turbidity, low-density *P. oceanica* meadow.	Medium pressure; tourism infrastructure, marina proximity, moderate population density.

- **Area 1 (Tipaza - Corne d'Or):** Five sampling sites were established within this sector. The coast features a localized tourism complex consisting of 76 bungalows and basic restaurant amenities. The marine habitat is characterized by well-developed, high-density *Posidonia oceanica* meadows, abundant populations of the sea urchin *Paracentrotus lividus*, shallow bathymetry (less than 10 m depth), and quartz-rich sandy sediments.
- **Area 2 (Bou Ismaïl):** Eleven sampling sites were selected near this urban center, which hosts approximately 42,000 inhabitants (population density: 2,977 inhabitants/km²). This sector is heavily impacted by diverse agricultural runoff and industrial effluents. Sampling sites were specifically positioned adjacent to the main municipal wastewater outfall. The environment exhibits elevated turbidity, severe organic and domestic waste loading, shallow depths (4 to 5 m), and mixed sandy-rocky substrates.
- **Area 3 (Sidi Fredj):** Seven sampling sites were monitored around this major tourist peninsula, which features dense hotel infrastructures and an active recreational marina. The stations are characterized by shallow waters (less than 5 m depth), low-density *P. oceanica* patches, and biogenic sandy sediments.

Four distinct matrices were concurrently collected at each sampling site: coastal seawater, leaves of *P. oceanica*, superficial matte sediments, and adult individuals of *P. lividus*.

These matrices were selected because they provide complementary information on short-term environmental conditions (seawater), long-term contaminant accumulation (sediments), ecological status (*P. oceanica*), and biological exposure to trace elements (*P. lividus*).

In Situ Physicochemical and Seagrass Descriptors

Physicochemical parameters of the water column—including temperature, pH, and salinity—were recorded in situ at each site using a multi-parameter submersible probe system (Wissenschaftlich Technische Werkstätten - WTW, Weilheim, Germany).

For the *P. oceanica* meadows, structural features were quantified via SCUBA diving. Shoot density (expressed as the number of shoots per square meter) was determined by counting living shoots inside a 20×20 cm quadrat, using 5 independent replicates per station to calculate the mean value. The percentage of meadow cover was assessed using the Line Intercept Transect (LIT) method (Montefalcone 2006). Four 10-meter-long transects were randomly deployed at each site. Divers recorded the transition points between distinct bottom covers to the nearest centimeter. The linear cover length (L_x) for each substrate category was obtained by subtraction. The percentage of relative cover ($R\%$) along each 10 m transect was calculated as follows:

$$R\% = \sum \left(\frac{L_x}{10} \times 100 \right)$$

Meadow health was further evaluated through the Conservation Index (CI) proposed by Montefalcone (2006). This index tracks the proportional abundance of dead matte relative to living *P. oceanica* using the following formula:

$$CI = \frac{P}{P + D}$$

Where P represents the percentage cover of living *P. oceanica* and D represents the percentage cover of dead matte.

Laboratory Processing and Trace Element Analysis

Trace element concentrations (Cu, Fe, Hg, Mn, and Zn) were quantified in three distinct matrices: *P. oceanica* rhizomes, superficial matte sediments, and the gonads of *P. lividus*.

Sample Preparation and Acid Digestion

Superficial matte sediments (approx. 100 g per site) were collected in sterile PVC containers and stored at $-20°C$. For the biotic matrices, 15 complete *P. oceanica* plants and 50 adult *P. lividus* individuals were collected per site. Sea urchins were weighed (precision: 0.1 g), dissected to isolate gonadal tissues, and pooled. Five seagrass rhizomes were similarly pooled and weighed (approx. 10 g wet weight). All samples were thoroughly frozen and dehydrated using a laboratory freeze-dryer (Christ Alpha 1-4 LDplus, Osterode am Harz, Germany).

Once completely dried, samples were pulverized and homogenized. Acid digestion was performed following established procedures (Pinta 1979, Pergent *et al.* 2015). Briefly, 500 mg of lyophilized tissue or sediment powder was treated with 7 mL of aqua regia (HCl: HNO_3, 3:1 v/v). The mixture was heated in a laboratory oven at $90°C$ for 3 hours, then allowed to cool at room temperature for 20 minutes. Digested solutions were subsequently diluted to a final volume of 50 mL with ultra-pure deionized water.

Spectrometric Quantification

Trace element analyses were performed using Cold Vapor Atomic Absorption Spectrometry (CV-AAS) on a PerkinElmer AAnalyst 700 spectrometer (PerkinElmer Life and Analytical Sciences, Shelton, USA). Total Mercury (Hg) concentrations were determined via a FIAS 400 flow injection analysis system coupled with an AS 800 autosampler. Copper, iron, manganese, and zinc were quantified using a standard flame atomization system. To assess and compare the cumulative metallic burden across different stations, the Metal Pollution Index (MPI) was calculated according to Usero *et al.* (2005):

$$MPI = \left(C_{f1} \times C_{f2} \times \ldots \times C_{fn}\right)^{1/n}$$

Where C_{fn} is the concentration of the specific trace element n measured in the matrix sample.

Microbiological and Nutrient Analysis of Seawater

Microbiological Indicators

Seawater samples were analyzed for fecal indicator bacteria using serial decimal dilutions (10^{-1} to 10^{-4}) prepared in sterile physiological saline solution (0.9% NaCl).

Total and Fecal Coliforms: Quantification followed the two-step presumptive/confirmative method described by Rodier et al. (2009). Initial presumptive inoculation was performed in lactose broth supplemented with bromocresol purple (BCP) and incubated at $37°C$ for 48 hours. Positive tubes showing medium acidification (yellow color) and gas production were transferred into Violet Red Bile (VRB) broth and indole-free peptone water, followed by incubation at $44°C$ for 24 hours. Indole production was tested using Kovacs' reagent; a positive red ring combined with gas production in VRB broth confirmed the presence of fecal coliforms.

Fecal Streptococci / Intestinal Enterococci: Diluted samples (1 mL) were inoculated into 9 mL of Rothe presumptive broth and incubated at $37°C$ for 48 hours. Suspected positive tubes exhibiting microbial turbidity were confirmed by inoculation into Ethyl Violet Azide (EVA) Litsky broth and incubated at $37°C$ for 24 hours. The development of a distinct blue-violet precipitate confirmed the presence of fecal streptococci.

To identify the pollution source, the ratio between fecal coliforms (FC) and fecal streptococci (FS) was evaluated according to Geldreich and Kenner (1968):

$$\text{Ratio} = \frac{\text{FC}}{\text{FS}}$$

- Ratio < 0.7: Contamination of strict animal origin.
- $0.7 \leq$ Ratio ≤ 1.0: Mixed origin with a strong predominance of animal sources.
- $1.0 <$ Ratio ≤ 2.0: Indeterminate mixed origin.
- $2.0 <$ Ratio ≤ 4.0: Mixed origin with a clear predominance of human wastewater.
- Ratio > 4.0: Contamination of strict human origin.

Dissolved Nutrients

Dissolved nutrient salts (nitrites NO_2^-, nitrates NO_3^-, ammonium NH_4^+, reactive phosphates PO_4^{3-}, and dissolved silicate $Si(OH)_4$) were determined spectrophotometrically by continuous flow colorimetry (Skalar, 1998) utilizing a San++ Automated Wet Chemistry Analyzer (Skalar Analytical, Breda, The Netherlands).

Statistical Analysis

Descriptive metrics are expressed as mean $\pm$ standard deviation (SD). Spatial variations across the three sampling areas were assessed using a one-way analysis of variance (ANOVA-1). Statistical significance for all comparative tests was strictly set at a threshold of $p < 0.05$. All statistical calculations and data modeling were executed using standard statistical software packages (Statistica).

RESULTS

In Situ Environmental Parameters and Seagrass Meadow Structure

The spatial monitoring revealed significant differences among the three coastal areas for all recorded hydrological and structural descriptors ($p < 0.01$; Table 2).

Tab 2. In situ physicochemical water parameters and structural descriptors of *Posidonia oceanica* meadows (mean ± SD) at a fixed depth of 2 ± 0.5 m.

Parameter	**Area 1 (Tipaza)**			**Area 2 (Bou Ismail)**			**Area 3 (Sidi Fredj)**			**p**
	mean	SD	N	mean	SD	N	mean	SD	N	
water temperature (°C)	14.3	0.85	15	17.2	0.21	33	16.2	1.4	21	<0.01
Salinity (PSU)	34.2	0.63	15	35.9	0.49	33	35.0	0.5	21	<0.01
Water pH	7.56	0.15	15	7.36	0.11	33	7.23	0.1	21	<0.01
***P. oceanica* density (plants/m^2) ***	581	81	25	221	41	55	269	27	35	<0.01
***P. oceanica* covering (%) ***	75	10	25	15	6	55	23	6	35	<0.01
Conservation index*	0.8	0.1	25	0.4	0.05	55	0.5	0.03	35	<0.01

*: the measures were performed at a depth of (2±0.5m).

Mean water temperature and salinity peaked in Area 2 (17.20°C and 35.90 PSU), while the lowest values were systematically recorded in Area 1. Conversely, mean pH values significantly decreased from Area 1 (7.56) down to Area 3 (7.23).

Regarding the *P. oceanica* meadow descriptors, the seagrass was present across all studied sectors, but its structural vitality displayed severe spatial disparities. Shoot density was more than twofold higher in Area 1

(581 ± 81 shoots/m^2) compared to Area 2 (221 ± 41 shoots/m^2) and Area 3 (269 ± 27 shoots/m^2). The meadow covering capacity followed an identical regression trend, collapsing from 75% in Area 1 to a critical low of 15% in Area 2. Consequently, the Conservation Index (CI) reflected a highly degraded state in Area 2 (0.40) and Area 3 (0.50), pointing to a high proportion of dead matte, while Area 1 exhibited a healthy, well-preserved ecosystem status ($CI = 0.80$).

Trace Element Bioaccumulation and Metal Pollution Index (MPI)

In order to continue our investigations of comparative pollution study, the concentration of several trace elements (Al, Cu, Fe, Hg, Mn, Zn) was estimated from three different matrixes: the *P. oceanica* meadow sediment, the *P. oceanica* rhizome and the *P. lividus* gonads in the three areas (table 3).

Tab 3. Trace element concentrations (mg/kg dry weight, except Hg: mg/kg) and Metal Pollution Index (MPI) across environmental and biological matrices (mean ± SD).

	Al	**Cu**	**Fe**	**Hg**	**Mn**	**Zn**	**MPI**
	SD	SD	SD	SD	SD	SD	
				Tipaza			
Sediments	2.85[a]	0,006[a]	14.9[a]	0.107[a]	0.180[a]	0.027[a]	7.75
N = 6	0.77	0.002	18.9	0.01	0.07	0.007	
P. oceanica	0.015[a]	0.007[a]	0.29[b]	0.04[a]	0.006[a]	0.051[a]	3.26
rhizomes	0.0002	0.004	0.19	0.001	0.004	0.02	
N = 6							
P. lividus	0.015[b]	0.006[a]	0.05[b]	0.0029[a]	0.001b	0.07[b]	2.69
gonads	0.00015	0.002	0.05	0.0007	0.001	0.03	
N = 6							
				Bou Ismail			
Sediments	10.9[a]	0.1[a]	73.03[a]	0.18[a]	2.6a	0.5[a]	**9.73**
N = 15	2.62	0.05	39.9	0.20	0.3	0.008	
	0.13[a]	0.01[a]	0.28[b]	0.18[a]	0.005[a]	0.06[a]	3.45

P. oceanica **rhizomes** **N = 15**	0.06	0.004	0.42	0.1	0.004	0.006	
P. lividus **gonads** **N = 15**	0.015^{b}	0.004^{a}	0.1^{b}	0.15^{a}	0.001^{b}	0.1^{b}	**2.84**
	0.0002	0.003	0.02	0.12	0.002	0.05	
				Sidi Fredj			
Sediments **N = 6**	11.32^{a}	0.1^{a}	33.3^{a}	0.16^{a}	2.5^{a}	0.44^{a}	8.62
	3.62	0.0004	6.3	0.03	0.4	0.2	
P. oceanica **rhizomes** **N = 6**	0.15^{a}	0.01^{a}	0.58^{b}	0.70^{a}	0.005^{a}	0.036^{a}	**3.78**
	0.037	0.00001	0.56	0.015	0.00006	0.003	
P. lividus **Gonads** **N = 6**	0.015^{b}	0.007^{a}	0.08^{b}	0.040^{a}	0.002^{b}	0.083^{b}	2.83
	0.0001	0.00002	0.03	0.001	0.0000002	0.006	

a: significant difference ($p<0.05$), b: non-significant difference ($p\geq0.05$).

The results indicated that if the global metal pollution was considered through the MPI index, area 2 was the most contaminated for sediments and *P. lividus* gonads and area 3 for the *P. oceanica* rhizomes. Area 1 (Tipaza) appeared clearly as the less contaminated area. For Al, the concentration in sediments is clearly the most important by comparison with biological matrixes (*P. ocenica* and *P. lividus*). The concentration in sediments and in *P. oceanica* rhizomes is significantly lower for area 1 ($p<0.01$) than the concentration in area 2 and 3. The mean concentrations in *P. lividus* gonads are not significantly different ($p>0.05$).

For Cu, the concentration is equivalent for all matrixes in area 1 but clearly more important in sediments than in biological matrixes for area 2 and 3. The mean concentration are significantly different ($p<0.05$) for all matrixes.

For Fe, the concentration in sediments were significantly higher than the concentrations in biological matrixes. For sediments, the mean concentrations were significantly different ($p<0.05$) with a lower concentration in area 1. For *P. oceanica* and *P. lividus* the mean concentrations were not significantly different ($p>0.05$).

For Mn, the concentrations in sediments were significantly higher than the concentration in biological matrixes (*P. oceanica* and *P. lividus*). The mean concentrations in sediments and *in P. oceanica* were significantly different ($p<0.05$). In opposite the mean concentration in *P. lividus* were not significantly different ($p>0.05$) between the different areas.

For Zn, the mean concentrations in area 1 were higher in biological matrixes than in sediments but in opposite in area 2 and 3, the means concentrations were higher in sediments than in biological matrixes. The mean concentrations are significantly different ($p<0.05$) between areas for sediments and *P. oceanica* but not in *P. lividus* gonads ($p>0.05$).

Microbiological Seawater Contamination

Bacteriological monitoring pointed to acute fecal contamination gradients directly correlated with nearshore urban outfalls. The European norm 2006/7/CE indicated that in a bathing water the concentration of total coliforms cannot be upper than 500 CFUs/100 ml and the number of faecal streptococci cannot be upper than 100 CFUs/100 ml.

In area 1, total coliforms ranged from 30 to 200 CFUs/100 ml depending of the sampling site and the number of faecal streptococci was <1 CFUs/100 ml. For area 2, the number of total coliforms ranged from 10 to 14 000 CFUs/100 ml depending of the sampling site with a mean of 5000 (±6925) CFUs/ml. The number of faecal Streptococci in area 2 ranged from 2.5 to 1400 CFUs/100 mL with a mean of 340 (±600) CFUs/100 mL. In area 3, the number of total coliforms ranged from 1 to 4.4 CFUs/100 mL and the number of faecal streptococci ranged was < 1 CFUs/100 mL. According to Directive 76/160/EEC, Areas 1 and 3 complied with bathing water quality standards, whereas Area 2 exceeded the regulatory thresholds.

Dissolved Nutrients and Mineral Salts

Human activity and especially agriculture releases nutrients such as mineral salt into the water. The concentration of several mineral salts was measured into the sea water of the different areas (Table 4).

Tab 4. Dissolved nutrient salt concentrations (µM) recorded in surface seawaters across the three studied areas (mean ± SD).

Area	NH_4+	NO_2-	NO_3-	NO_3-+NO_2-	PO_4---	SiO_2
	SD	SD	SD	SD	SD	SD
Tipaza	6.8[a]	0.005[a]	0.07[a]	0.08[a]	0.01[a]	1.7[a]
N = 15	0.7	0.002	0.07	0.07	0.05	1.7
Bou- Ismail	10.3[a]	0.35[a]	0.6[a]	0.95[a]	2.4[a]	27.8[a]
N = 33	8.7	0.6	0.5	1.1	5.1	45.1
Sidi Fredj	5.3[a]	0.02[a]	0.02[a]	0.04[a]	0.03[a]	0.8[a]
N = 21	1.3	0.006	0.02	0.02	0.02	0.7

a: Significant difference ($p<0.05$)

Area 2 (Bou Ismaïl) exhibited the highest nutrient concentrations among the three study areas. Reactive phosphorus ($PO_4^{3-}: 2.40 \pm 5.10\ \mu$M) and dissolved silicate ($SiO_2: 27.8 \pm 45.1\ \mu$M) values in Bou Ismaïl were orders of magnitude higher than those in the other zones, reflecting heavy inputs from domestic laundry detergents and terrestrial runoff via local wadis. In contrast, Area 3 exhibited the lowest nutrient concentrations among the three study areas.

DISCUSSION

Human activity is a major source of pollution for the environment. Since a lot of human population is located along the sea coasts, these coasts are exposed to human population (Halpern *et al.* 2008). Algeria is a relevant example with its 2,148 km of Mediterranean coastline. A lot of cities and villages are located directly close to the sea coast and tourist complexes are also located along the coast.

The baseline monitoring of physicochemical parameters highlighted strong environmental gradients across the three studied sectors. Seawater pH along the Mediterranean coast typically ranges from 7.50 to 8.40 (Chester and Jickells 2012). In our study, the significantly lower pH values recorded in Area 3 (7.23) and Area 2 (7.36) compared to the more preserved Area 1 (7.56) point to severe localized chemical disruptions rather than global ocean acidification trends. Such localized drops in pH within nearshore waters are driven by intense coastal

anthropization. Specifically, the massive loads of organic matter and untreated domestic/industrial effluents discharged directly into the shallow, confined zones of Bou Ismaïl and Sidi Fredj stimulate intense microbial respiration. The heterotrophic decomposition of this organic burden induces a high oxygen demand and local hypercapnia, releasing metabolic CO2 and shifting the carbonate equilibrium toward localized acidification. This metabolic acidification, potentially coupled with the direct input of acidic industrial compounds in Area 2, explains the critical baseline drop in pH and underscores the advanced degradation of these coastal environments.

Similarly, the spatial fluctuations in salinity and temperature emphasize the confinement and localized pressures characterizing Area 2. The elevated mean salinity (35.9 PSU) and water temperature (17.2 °C) measured in Bou Ismaïl reflect a combination of shallow bathymetry, reduced hydrodynamic flushing, and steady warm brine inputs from agricultural runoff and domestic wastewater systems. Conversely, the lower temperature and salinity baseline in Area 1 matches the natural hydrological features of an open, dynamic coastal system.

Table 5. Comparative synthesis of *P. oceanica* shoot densities across different Mediterranean regions.

Location	**Depth (m)**	**Shoot Density (shoots/m²)**	**Status / Reference**
Tipaza (Area 1)	2 ± 0.5	581±81	Intermediate / Present study
Bou Ismaïl (Area 2)	2 ± 0.5	221±41	Unsatisfactory / Present study
Sidi Fredj (Area 3)	2 ± 0.5	269±27	Unsatisfactory / Present study
Corsica (Calvi)	10	433 – 631	Preserved / Lafabrie et al., 2008
Sicily (Augusta)	5 – 8	310 – 420	Impacted / Tranchina et al., 2005

Our results demonstrate that even in the cleanest investigated sector (Area 1 - Tipaza), the meadow barely reaches an "intermediate" status (581 ± 81 shoots/m^2), indicating a generalized vulnerability along this part of the Algerian coast. More alarmingly, shoot densities collapsed below 300 shoots/m² in both Bou Ismaïl (221 ± 41 shoots/m^2) and Sidi Fredj (269 ± 27 shoots/m^2), falling into the critical "unsatisfactory" category. This clear

structural regression is further supported by the Conservation Index (CI). While Area 1 maintains a resilient architecture dominated by living seagrass ($CI = 0.80$), the index falls to 0.50 in Sidi Fredj and 0.40 in Bou Ismaïl, revealing a massive conversion of living meadows into dead matte. This ecological degradation is directly driven by high water turbidity and nutrient enrichment, which restrict light penetration and fuel the overgrowth of epiphytic competitors, ultimately triggering shoot mortality.

In marine ecosystems, persistent contaminants such as trace elements are non-degradable and cycle continuously through geochemical and biological vectors (Callender, 2003; Pan & Wang, 2012). Across our three studied areas, the overall accumulation hierarchy followed the sequence: Fe $>$ Al $>$ Mn $>$ Zn $>$ Cu $>$ Hg. For the majority of these elements, concentrations within the matte sediments heavily surpassed those measured in the biological tissues of *P. oceanica* and *Paracentrotus lividus*, corroborating the role of the organic matte as a long-term sedimentary sink (Lafabrie *et al.* 2008).

Iron (Fe) and Aluminum (Al)

Sedimentary Fe concentrations reached unprecedented values in Area 2 ($73{,}03 \pm 39{,}900$ mg/kg dw) and Area 3 ($33{,}300 \pm 6{,}300$ mg/kg dw), heavily overshooting standard baselines described in Spain (13 to 200 mg/kg; Cesar *et al.* 2009), Egypt ($1{,}690$ to $8{,}060$ mg/kg; El Nemr *et al.* 2013), and Greece ($2{,}000$ to $29{,}000$ mg/kg; Kalantzi *et al.* 2013). This extreme accumulation is tightly linked to domestic sewage and active industrial discharges within Bou Ismaïl Bay. Fe concentrations within *P. oceanica* rhizomes (280 to 580 mg/kg dw) and *P. lividus* gonads (50 to 100 mg/kg dw) were also higher than reference values from Corsica (35 to 89 mg/kg; Bonanno and Orlando-Bonaca 2017) and Italy (23 to 36 mg/kg; Pinsino *et al.* 2008), demonstrating a high bioavailability of iron in these coastal waters.

Aluminium trends mirrored this pattern, with sediment values peaking at $11{,}320$ mg/kg in Area 3 and $10{,}900$ mg/kg in Area 2, which are orders of magnitude higher than Spanish baselines (0.6 to 13.6 mg/kg; Cesar *et al.* 2009) but align with raw sediment ranges in Greece ($3{,}000$ to $45{,}000$ mg/kg; Kalantzi *et al.* 2013). The accumulation of Al in *P. oceanica* rhizomes (15 to 150 mg/kg dw) exceeded Corsican baseline measurements (8 to 85 mg/kg; Bonanno and Orlando-Bonaca 2017), highlighting the presence of heavy terrestrial runoff.

Manganese (Mn) and Zinc (Zn)

Sedimentary Mn peaked at $2{,}600$ mg/kg in Bou Ismaïl, outperforming Egyptian baseline ranges (880 to $3{,}270$ mg/kg; El Nemr *et al.* 2013). This matrix-bound Mn represents an ecotoxicological risk: under

localized hypoxic conditions triggered by organic enrichment, sedimentary Mn is reduced and released as bioavailable Mn^{2+} ions into the water column (Pinsino et al., 2009), which can induce severe developmental abnormalities in *P. lividus* embryos (Pinsino *et al.* 2011; Migliaccio *et al.* 2014).

Zinc patterns revealed an interesting inversion. In the pristine Area 1, Zn concentrations were higher in the biological matrices than in the surrounding sediment, reflecting natural physiological uptake. However, in Areas 2 and 3, sediment Zn concentrations surged to 500 mg/kg and 440 mg/kg respectively, severely exceeding levels found in Spain (0.01 to 3.1 mg/kg; Cesar *et al.* 2009) and the Adriatic Sea (123 mg/kg; Frascari *et al.* 1988). While Zn values in *P. lividus* gonads (70 to 100 mg/kg dw) remained below the contamination thresholds reported in Italy (117 to 368 mg/kg; Pinsino *et al.* 2008), the elevated ambient Zn poses a cryptic threat, as high zinc exposures are known to compromise the immune response of sea urchins against marine pathogens (Pagliara and Stabili 2012).

Copper (Cu) and Mercury (Hg)

Sedimentary Cu in Bou Ismaïl and Sidi Fredj (100 mg/kg) was significantly higher than in Spain (< 0.01 mg/kg; Cesar *et al.* 2009) and the Adriatic Sea (38 mg/kg; Frascari *et al.* 1988), directly pointing to industrial effluent footprints. Conversely, Cu concentrations in *P. oceanica* rhizomes (7 to 10 mg/kg dw) and *P. lividus* gonads (4 to 7 mg/kg dw) remained stable and tightly matched standard Mediterranean baselines (Lafabrie *et al.* 2008; Tranchina et al., 2005; Bonanno and Orlando-Bonaca 2017).

Total Mercury (Hg) levels in the sediments (0.11 to 0.18 mg/kg) remained low, falling near or below the 25th percentile of general Mediterranean sediment distributions (0.15 mg/kg). However, *P. oceanica* rhizomes in Area 3 (Sidi Fredj) displayed a sharp, localized accumulation peak (0.700 ± 0.015 mg/kg), which stands out against reference data from Italy (0.06 to 0.20 mg/kg; Lafabrie *et al.* 2009), Corsica (0.05 mg/kg; Lafabrie *et al.* 2008), and the Ionian Sea (0.12 mg/kg; Pennesi *et al.* 2013). This anomaly in Sidi Fredj points to a localized source of mercury, likely originating from historical coastal infrastructure or antifouling paints leaching from the adjacent recreational marina.

Coastal nutrient enrichment from domestic, agricultural, and industrial sources triggers severe imbalances in marine systems. High levels of nitrate and phosphate fuel the rapid growth of opportunistic macroalgae and

phytoplankton blooms, reducing water transparency and causing anoxia in the benthos. In our study, dissolved nutrient concentrations followed the clear hierarchy: $NH_4^+ > SiO_2 > PO_4^{3-} > NO_3^- > NO_2^-$

The massive nutrient enrichment recorded in Area 2 (Bou Ismaïl) confirms its advanced eutrophic state. Ammonium levels (10.30 ± 8.70 μM) greatly exceeded values from heavily anthropized basins like Izmir Bay in Turkey (0.22 to 0.32 μM; Kucuksezgin *et al.* 2006) and the Po River estuary in Italy (0.71 to 1.47 μM; Berto et al., 2010), though they remained slightly below raw Atlantic coastal outfalls in Portugal (13.20 μM; Santos et al., 2011).

This severe nutrient enrichment is further corroborated by the reactive phosphate (PO_4^{3-}: 2.40 ± 5.10 μM) and dissolved silicate (SiO_2: 27.80 ± 45.10 μM) peaks in Bou Ismaïl. These values are significantly higher than those reported for the Adriatic Sea (PO_4^{3-}: 0.03 to 0.05 μM; SiO_2: 7 to 14 μM; Degobbis *et al.* 2000) and Egyptian coastal lagoons (PO_4^{3-}: 0.04 μM; El-Rayis et al., 2012). This heavy nutrient signature in Bou Ismaïl is directly related to the massive discharge of untreated domestic detergents, urban sewage, and agricultural fertilizers into the bay. These high nutrient loads fuel a persistent state of eutrophication, explaining the low shoot density and highly degraded state of the *local P. oceanica* meadows.

Although the field surveys were conducted in 2010, the present dataset represents one of the few integrated historical assessments available for the central Algerian coast. Such baseline information is particularly valuable for evaluating long-term changes in coastal ecosystem health and for supporting future monitoring and restoration programs.

CONCLUSIONS

This study demonstrates the high efficiency of a multi-compartment biomonitoring approach to assess coastal environmental degradation. The severe depletion of *Posidonia oceanica* structural descriptors, characterized by a collapse in shoot density and a critical drop in the Conservation Index ($CI = 0.40$), provides clear biological evidence of the ecological regression occurring within Bou Ismaïl Bay. This seagrass degradation is directly correlated with acute anthropogenic gradients, driven by heavy urban and agricultural nutrient enrichment (NH_4^+ ; PO_4^{3-}) and substantial geochemical accumulation of industrial trace elements (Fe; Al; Zn; Cu) within the sedimentary matte sink. Furthermore, the high localized mercury (Hg) bioaccumulation detected in Sidi Fredj highlights the presence of persistent, localized chemical footprints. Overall, these findings underline the urgent

need to establish sustainable wastewater treatment infrastructures and stricter regulatory frameworks along the Algerian coast to mitigate land-based pollution and safeguard the remaining ecological niches of this key Mediterranean ecosystem. Beyond documenting the environmental conditions observed in 2010, this study establishes a historical reference that can support future evaluations of ecological trajectories and the effectiveness of coastal management measures in Bou Ismaïl Bay.

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