JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2024, 25(11), 270–281
https://doi.org/10.12911/22998993/193130
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.08.25
Accepted: 2024.09.23
Published: 2024.10.01

Decontamination of Cadmium Pollutant Charge Using *Gracilaria gracilis* in Dakhla Bay, Morocco

Mina Dellal[1,2], Mourad Arabi[3*], Azedine Dergoun[2], Samir Benbrahim[4], Mimouna Anhichem[4], Requia Sagou[4], Samah Ait Benichou[1]

[1] Health and Environment Laboratory, Department of Biology, Ain Chock Science Faculty, Hassan II University, Casablanca, Morocco

[2] National Institute of Fisheries Research – INRH, Dakhla, Morocco

[3] Laboratory for Improvement of Agricultural Production, Biotechnology and Environment (LAPABE), Water, Environment and Health Team, Faculty of Science, Mohamed Premier University, PB 717 60000, BV M6, Oujda, Morocco

[4] National Institute of Fisheries Research – INRH, Casablanca, Morocco

* Corresponding author's e-mail: m.arabi@ump.ac.ma

ABSTRACT

Dakhla Bay is a paralic environment distinguished by various potentialities, including fishing, aquaculture, and tourism. However, the development of these human activities can lead to negative impacts on this environment, posing a threat to human health. This situation requires special attention to the environment and the implementation of a program for the protection and preservation of this ecosystem. This study aims to identify solutions to protect the marine environment from cadmium contamination by the macroalgae *Gracilaria gracilis*. The results of cadmium analyses in different compartments of Dakhla Bay, including bivalve molluscs, seawater, sediment, and macroalgae, indicate a difference in cadmium accumulation across the various studied compartments. The highest levels of cadmium are noted in macroalgae, with concentrations ranging from a minimum of 0.9 mg/kg fresh weight in the summer of 2019 to a maximum of approximately 2.55 mg/kg fresh weight recorded during the summer of 2022 at the Lassargua station. In comparison, bivalve molluscs such as *Perna perna* showed Cd levels ranging from 0.2 mg/kg to 1.4 mg/kg fresh weight at the same station. The sediment samples revealed average Cd levels ranging from 0.02 to 1.39 mg/kg dry weight in samples collected from Lassargua, while seawater concentrations were recorded at approximately 0.65 μg/L. The decontamination of cadmium by the macroalgae *Gracilaria gracilis* without impacting the quality of the algae has been well confirmed. Indeed, cadmium levels noted in macroalgae remain below the thresholds set by the regulations in force. In conclusion, the results of this study encourage the use of algocultures in Dakhla Bay to protect its ecosystem from various types of pollution.

Keywords: bivalve molluscs, pollution, cadmium, macroalgae, *Gracilaria gracilis*, algoculture, Morocco.

INTRODUCTION

Dakhla Bay is one of Morocco's most important paralic environments, representing one of the country's most fish-rich coastal regions and an important site with high aquaculture potential. Fishing and aquaculture are vital socioeconomic activities [Orbi et al., 1995]. The presence of two ports in Dakhla Bay and the construction of a new international Atlantic port in the N'tirift area will boost the realization of various types of investment related to fishing, aquaculture, trade, tourism and existing recreational activities. However, these different activities present considerable pressure on the existing paralic environment. In the context of the integrated system of sustainable environmental management set up by the government of Morocco, research projects are carried out by researchers to contribute to and support sustainable development. Indeed, within the framework of the persistent degradation of marine and forest ecosystems in Morocco, primarily ascribed to anthropogenic activities such as urbanisation, overfishing, and deforestation [Arabi et al., 2024], the national environmental strategy highlights the essential role of scientific research as a fundamental pillar. It promotes the systematic exploration of priority environmental challenges and the regular evaluation and dissemination of data concerning the quality and dynamics of the marine environment. As a result, to solve the pollution problems that could damage this environment, studies assessing the quality of these ecosystems are carried out continuously. These surveys help local operators manage the area sustainably, provide information on the quality of the environment and fishery resources, and protect consumers of fish products.

The culture of the seaweed *Gacilaria gracilis* in the Lassargua area of Dakhla Bay was launched in May 2019 to study the feasibility of culturing the seaweed in the area allocated for seaweed production, to produce agar and agar and to evaluate the capacity of the seaweed to accumulate and decontaminate Cd in shellfish production areas. Seaweeds are now considered very good bioindicators of the ecological status of water [Peltre et al., 2020].

In fact, these short-lived organisms are able to respond rapidly and gradually to variations in their environment because of their great diversity, their presence in all types of aquatic habitats and some of their physiological characteristics [Peltre et al., 2020]. Many studies have focused on demonstrating the durability of exploiting macro seaweed biomass as a raw material for wastewater treatment [Biris-Dorhoi et al., 2020]. They can reflect the ecological status and mitigate heavy metal pollution [Luo et al., 2020]. *Gracilaria* sp. can significantly remediate contaminants in mariculture ecosystems and improve the aquatic environment, and its cultivation offers a new approach for improving the coastal environment worldwide [Yang et al., 2015]. For this reason, the seaweed *Gracilaria gracilis* was selected for this project to assess Cd in shellfish production areas in Dakhla Bay for the first time.

The primary objective of this research is to evaluate the capacity of the macroalga *Gracilaria gracilis* to accumulate and remediate cadmium in shellfish production areas of Dakhla Bay, as part of a monitoring mission to conduct an integrated study of the marine environment. By analyzing cadmium levels across different compartments of the marine ecosystem, this study aims to identify solutions for protecting this ecosystem from contamination by trace elements, notably cadmium (Cd), while providing recommendations for the sustainable use of algocultures as an environmental management strategy and contributing to public health protection and the preservation of marine biodiversity.

MATERIALS AND METHODS

Study and sampling area

Dakhla Bay, located in southern Morocco, communicates with the Atlantic Ocean via a large opening on the southern side (Figure 1). It is characterized by a Saharan climate and low, uncertain pluviometry (approximately 30 mm), but the oceanic influence compensates for the region's extreme aridity. The average annual temperature is approximately 20 °C. Dakhla Bay covers an area of approximately 400 km² (37 km long 10–13 km wide) and is between 10 and 20 m deep [Orbi et al., 1995]. Eight sampling zones were selected for this study and are represented in Figure 1. These areas were used to sample marine waters, sediments, seaweeds and bivalve molluscs. Table 1 summarizes the geographical locations and sampling characteristics of the areas.

Seawater and sediment sampling

Seawater samples were taken quarterly in 1 Litre polyethylene bottles. The samples were stored in an icebox at 4 °C and then stored at -20 °C before Cd analysis for the period of 2021–2023. Seawater samples were taken quarterly in 1 L polyethylene bottles. The samples were then kept in a cool box at 4 °C and stored at -20 °C [Belasri et al., 2024] before Cd analysis for the period of 2021–2023.

Physicochemical parameters, notably temperature, salinity, pH and dissolved oxygen in seawater, are measured in the field via a multiparameter system at monthly intervals for the period from 2019 to 2023.

Sediment samples were taken from all surface areas in 1 m² quadrants, and representative samples were taken by hand and placed in food bags. The quantity of sediment taken must be adequate for Cd analysis, equivalent to one kg of sediment for each sample. The sampling frequency adopted for the study is quarterly for the period from 2021 to 2023.

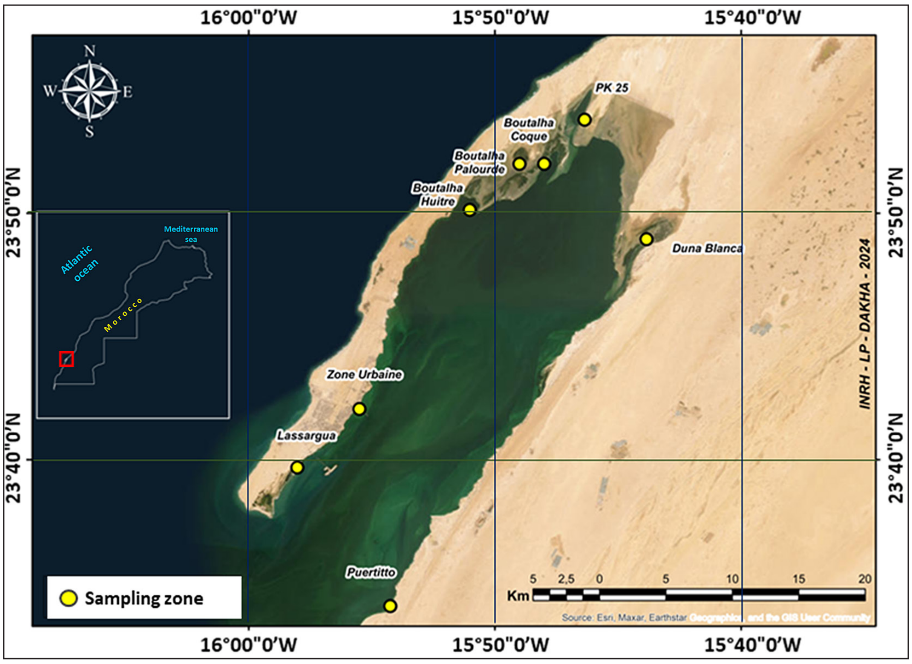

Figure 1. Locations of the sampling areas in Dakhla Bay

Table 1. Locations of the sampling areas and compartments in Dakhla Bay

Sampling area	Location Name	Geographical coordinates	Sampling compartments	Species
St1	Lassargua	23°39'40.85"N 15°58'1.55"W	Mussel	*Perna perna*
			Alga	*Gracilaria gracilis*
			Seawater	-
			Sediment	-
St2	Zone Urbaine	23°42'3.27"N 15°55'30.26"W	Seawater	-
			Sediment	-
St3	Boutalha	23°50'8.11"N 15°51'1.43"W	Oyster	*Crassostrea gigas*
		23°52'0.11"N 15°49'0.12"W	Clam	*Ruditapes decussatus*
		23°52'0.26"N 15°48'0.01"W	Common hull	*Cerastoderma edule*
			Seawater	-
			Sediment	-
St4	Pk25	23°53'47.69"N 15°46'21.42"W	Grooved razor shell	*Solen marginatus*
			Seawater	-
			Sediment	-
St5	Duna Blanca	23°48'56.70"N 15°43'50.48"W	Oyster	*Crassostrea gigas*
			Seawater	-
			Sediment	-
St6	Puertitto	23°34'3.57"N 15°54'15.07"W	Mussel	*Perna perna*
			Seawater	-
			Sediment	-

Sampling of bivalve molluscs

Samples were taken once every six months from 2018–2023, in accordance with the sampling procedures in the applicable regulations. Samples are taken only from shellfish of marketable size for human consumption. A representative sample is obtained by collecting a number of shells of similar size at different points in the sampling area. Using the square sampling method, the sampling point is sectioned into blocks, and samples are taken from at least 5 predetermined points located at equal distances from each other within each block. If necessary, the shells are cleaned of excess mud by rinsing with seawater and then drained. The containers used are bags or food-grade plastic bottles. The live shellfish were depurated as soon as possible after sampling. They are placed between 18 and 26 hours in decanted seawater from the sampling point. The samples were dripped, crushed and stored at -20°C in polyethylene bottles before analysis for Cd.

Sampling of *Gracilaria gracilis*

The Lassargua zone is located near the new port and is also one of the landing points for artisanal fishing in the Dakhla region. This area is very rich in natural shellfish beds, including mussels (*perna perna*), cockles (*Cerastoderma edule*), razor clams (*Solen marginatus*) and clams (*Ruditapes decussatus*). Since it is a port area, it is not classified, and its shellfish beds are not exploited. It is also rich in natural seaweed deposits, particularly gracilaria, which is why it was chosen as a site for seaweed farming (*Gracilaria gracilis*). The presence of the *Gracilaria gracilis* algal deposit has always been noted in the port area of Dakhla Bay, particularly in the Lassargua area, but not abundantly. With the development of port activities, this deposit has become increasingly abundant, and its presence in a well-defined habitat indicates that the environment is polluted and eutrophic. The first trials related to the cultivation of *Gracilaria gracilis* in Dakhla will be launched during the month of May 2019. The cultivation of *Gracilaria gracilis* is carried out first by collecting algae from natural deposits in the aforementioned area and then by taking cuttings from clumps of 100 g each on a specialized rope (Figure 2).

The culture of *Gracilaria gracilis* was realized following an agreement between the private companies SETEXAM and INRH in the area of Lassargua (St1). Biannual monitoring of Cd concentrations in these algae was performed from 2018–2023. The algae were purified for 18 to 24 hours, ground and stored at -20 °C in polyethylene bottles. The samples were subsequently lyophilized and stored in amber glass vials until analysis for Cd.

Cadmium dosage

Cadmium analysis in seawater, sediment, shellfish and macroalgae was conducted via inductively coupled plasma–mass spectrometry (ICP-MS) in accordance with the standards listed below:

- Moroccan Standards (Cd analysis in seawater): NM ISO 11885 V 2014
- French Standards (Cd analysis in shellfish and algae): NF EN 15763 V2010
- French Standards (Cd analysis in sediment): NF EN 16170 V 2016.

RESULTS

Evolution of seawater physicochemical quality

Seawater is essential to the life of organisms, and its physical and chemical qualities determine their survival, progression or mortality. It is therefore important to know more about the quality of the physicochemical parameters of seawater, such as temperature, dissolved oxygen, salinity, pH, and chlorophyll a, and to qualify it via a quality grid.

Globally, environmental factors play a crucial role in the ability of macroalgae to accumulate cadmium. Specifically, temperature and salinity have been shown to significantly affect cadmium uptake.

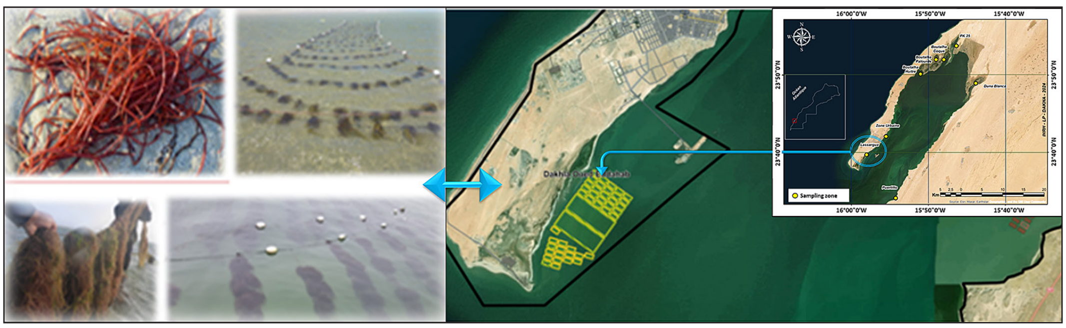

Figure 2. *Gracilaria gracilis* farm in the Lassargua area of Dakhla Bay

For instance, higher temperatures and lower salinities enhance cadmium accumulation in Gracilaria tenuistipitata [Huang et al., 2010].

Additionally, pH levels influence nutrient uptake, with optimal accumulation rates observed at a pH of 8.0 for Gracilaria tenuistipitata var. liui [Xu et al., 2001]. In another species, Ulva ohnoi, cadmium accumulation is dose-dependent and is also affected by temperature and salinity, with maximum uptake occurring at 18 °C and a salinity of 35 [Bastos et al., 2019].

Moreover, cadmium speciation varies with changes in salinity, while pH and temperature primarily affect uptake through metabolic processes in marine organisms [Pavlaki et al., 2017]. These environmental factors not only influence cadmium accumulation but can also impact algal growth rates and their physiological responses to cadmium exposure [Huang et al., 2010; Bastos et al., 2019]. Thus, understanding these factors is essential for interpreting the results of studies on cadmium accumulation in macroalgae such G. Gracilis.

Figure 3 illustrates the evolution of these physicochemical parameters namely, the temperature (T) , dissolved oxygen (O_2), salinity, and hydrogen potential (pH), in Dakhla Bay during the period 2019–2023.

Temperature

Temperature is one of the physical parameters most important to the development of the different phenomena that occur in water: dissolving salts, especially gases, and therefore also conductivity and pH determination. It is considered a limiting factor for the development of marine species [Orbi et al., 1995; Guelorget et al., 1996].

The results of seawater temperature measurements in Dakhla Bay for the period of 2019–2023 (Figure 3a) reveal that the temperature varies between a minimum of 15.5 °C and a maximum of 28.4 °C. The average annual temperature recorded is between 16.6 °C and 25.6 °C.

Historic temperature data recorded in Dakhla Bay show that the latter oscillates between a minimum of 15 °C and a maximum of 27 °C measured in the Duna Blanca area of Dakhla Bay [Anhichem et al., 2017]. In fact, the temperature is high in this area, as it is a confined zone with shallow depths, which makes it easy for these marine waters to warm. However, the maximum temperatures recorded in the marine waters of Dakhla Bay do not exceed 23.5 °C [Orbi et al., 1995]. The qualification grid qualifies the seawater temperature in the Dakhla Bay area as medium-quality water (23–28 °C).

Salinity

Salinity in the marine environment is a fairly constant parameter. It can, however, fluctuate depending on specific areas and seasons. The standard value in seawater is 35 g/kg (35 ‰). The salinity values noted in the seawater of the Dakhla Bay areas during the periods of 2019 to 2023 vary between a minimum of 36‰ and a maximum of 42‰ (Figure 3b). The average recorded salinity varies between a minimum of 37.5‰ and a maximum of 38.2‰. Historic variations in the salinity of seawater in Dakhla Bay reveal that salinity

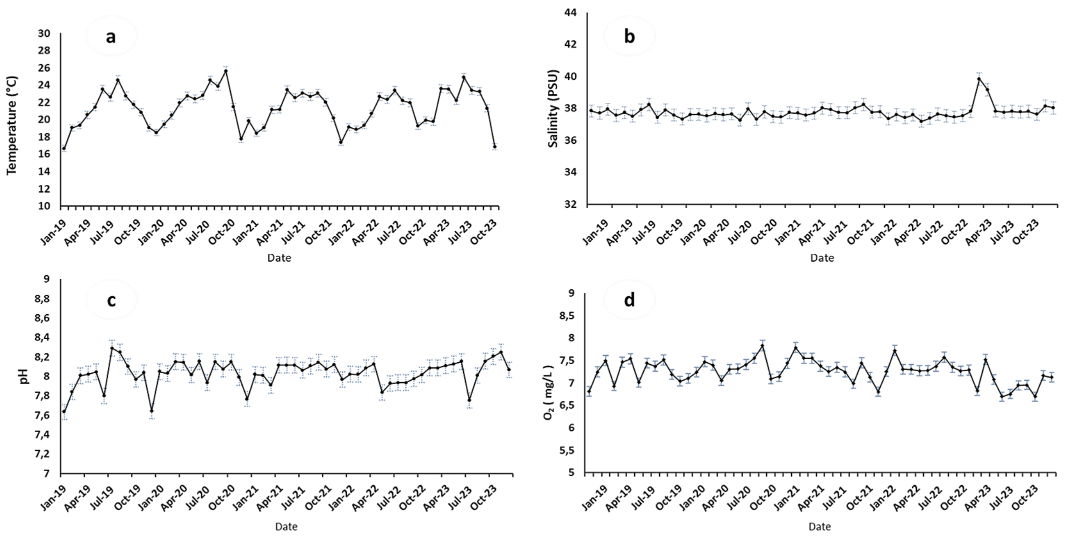

Figure 3. Variations in the average physicochemical parameters of seawater in the areas of Dakhla Bay from 2019 to 2023: (a) temperature, (b) salinity (PSU), (c) pH, (d) dissolved oxygen (mg/L)

oscillates between a minimum of 33‰, noted at the level of urban areas whose wastewater discharges cause softening of the bay's seawater, and a maximum of 41‰, noted in the most confined areas where the rate of evaporation is high (the case of Duna Blanca) [Orbi et al., 1995].

In accordance with these records, the waters of Dakhla Bay are characteristic of a mixoeuhaline sea (between 30 and 40‰), whose waters are thalassic homoiohaline, whose salinity responds to oceanic waters, which do not show significant variations over time [Orbi et al., 1995].

pH

The pH values noted in the marine waters of Dakhla Bay between 2019 and 2023 varied between a minimum of 7 and a maximum of 8.95 (Figure 3c). The average pH of the seawater in Dakhla Bay during this period varied between 7.63 and 8.29. The pH values, noted as a function of time, of seawater in Dakhla Bay varied between a minimum of 7.6 and a maximum of 9.1, values characteristic of marine water [Orbi et al., 1995; Guelorget et al., 1996]. According to the data history and the seawater qualification threshold grid, the seawater in Dakhla Bay is considered very good quality seawater.

Dissolved oxygen

From 2019 to 2023, the dissolved oxygen values recorded in seawater in the Dakhla Bay area varied between a minimum of 5.52 mg/L and a maximum of 9.95 mg/L (Figure 3d). The average dissolved oxygen level recorded during the monitoring period was 6.69 mg/L. Dissolved oxygen values, measured as a function of time in Dakhla Bay seawater, oscillate between a minimum of 4.5 mg/L recorded in 1997 [Dafir et al., 1997], and a maximum of 10.83 mg/L was recorded in 2014/2015 [Anhichem et al., 2017]. This variation illustrates that the marine waters of Dakhla Bay are well oxygenated at the surface as well as at depth, at 9 mg/L. This good oxygenation is also due to the intense currents in the southern part of the bay, where there are strong exchanges with the ocean, as well as to winds that constantly agitate the surface waters. According to the grid of thresholds for qualification of the dissolved oxygen parameter, the seawater in Dakhla Bay is of very good quality (values between 5 and 10.3 mg/L).

Evolution of the Cd concentration in the water and sediment

The results of the Cd analyses of seawater taken from the shellfish production areas of Boutalha, PK25, Duna Blanca and Puertitto in Dakhla Bay from 2021 to 2023 revealed Cd values below 0.5 µg/L. However, the Cd levels in seawater samples from two areas, the city and the port (Lassargua), slightly exceeded 0.5 µg/L. The maximum values noted in the waters of these areas are on the order of 0.60 µg/L, and 0.65 µg/L, respectively.

The results of the Cd analyses of sediment taken from the shellfish production areas of Boutalha, Pk25, Duna Blanca and Puertitto in Dakhla Bay revealed values between 0.005 mg/kg dry weight and 0.45 mg/kg dry weight (Table 2).

However, the Cd contents in the sediments collected from the urban and port areas (Lassargua) were relatively high, varying between 0.03 mg/kg dry weight and 1.4 mg/kg dry weight. The Cd concentrations decreased as a function of time in the sediments in the different areas studied (Figure 4).

Cadmium decontamination by *Gracilaria gracilis*

During the two winter and summer 2018 and before seaweed farming began in the Lassargua area, Cd analyses of the natural deposit of the seaweed *Gracilaria gracilis* were carried out to determine the zero state of Cd concentrations in

Table 2. Variation in Cd (in mg/kg dry weight) in sediment in the Dakhla Bay area (Period: 2021–2023)

Areas (zones)	Min	Max	Average ± Standard deviation
Lassargua zone	0.03	1.39	0.65 ±0.55
Urban zone	0.09	1.4	0.54± 0.44
Boutalha zone	0.01	0.05	0.03 ± 0.01
PK25 zone	0.03	0.45	0.10 ± 0.13
Duna Blanca zone	0.01	0.05	0.03 ± 0.01
Puertitto zone	0.005	0.04	0.02 ± 0.01

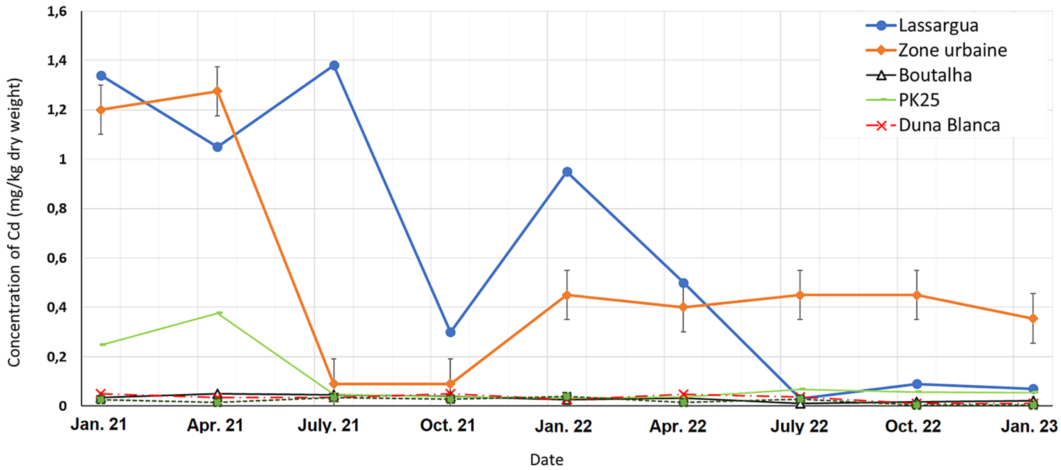

Figure 4. Variation in the average Cd concentration in the sediment of the Dakhla Bay area from 2021–2023

natural seaweed. The results of these analyses indicate concentrations on the order of 1.33 and 1.7 mg/kg dry weight (= 6.65 and 8.55 mg/kg fresh weight).

Figure 5 shows the spatiotemporal evolution of the Cd concentration in the algal and bivalve mollusc biological matrix from 2019 to 2023. The results of the Cd analyses of *Gacilaria gracilis*, which was sampled in the Lassargua port area of Dakhla Bay, revealed values ranging from a minimum of 0.9 mg/kg fresh weight recorded during the summer of 2019 to a maximum of approximately 2.55 mg/kg fresh weight. weight, recorded during the summer 2022. During the entire study period, Cd accumulation by algae was notable (Figure 5). In contrast, the Cd concentrations measured in mussels (*Perna perna*) sampled in the Lassargua area decreased as a function of time, revealing an inverse trend to that observed in *G. gracilis*. The Cd levels in the mussels ranged from a minimum of 0.2 mg/kg to a maximum of approximately 1.4 mg/kg Fresh weight. The average Cd levels in macroalgae increased as they decreased in mussels from the same sampling station (Lassargua area).

The results of the ANOVA statistical analysis test, which was carried out with the average Cd concentrations accumulated by seaweed and mussels, revealed a highly significant difference between the Cd accumulation capacity of the seaweed *Gracilaria gracilis* and the mussel (*perna perna*) in the Lassargua area of Dakhla Bay (p <

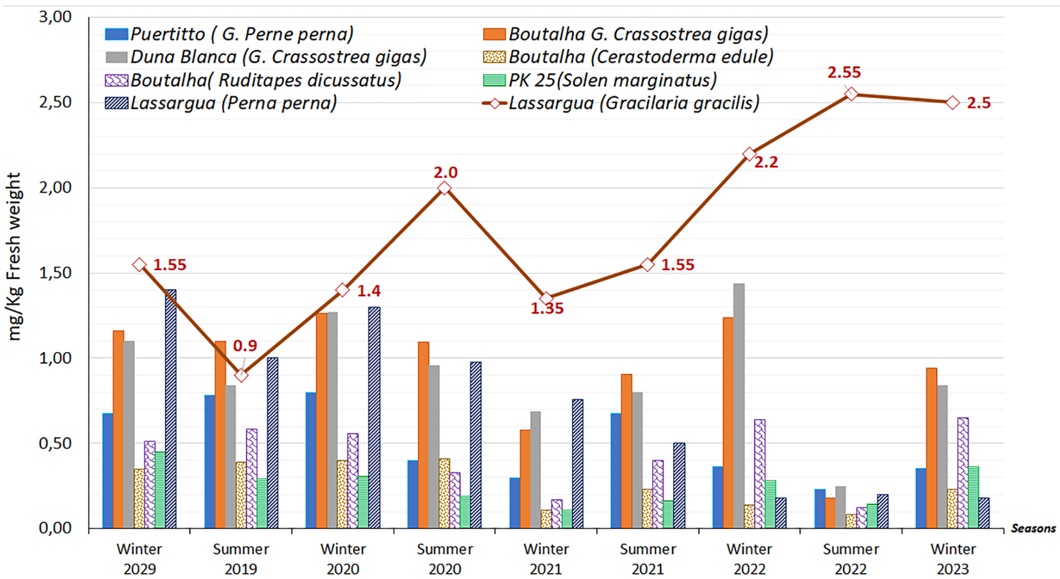

Figure 5. Evolution of average Cd concentrations in alga *Gracilaria gracilis* seaweed and bivalve molluscs in Dakhla Bay from 2019 to 2023

0.05 = 0.000575). The results of the PCA (Figure 6) are consistent with the statistical results of the ANOVA test, which highlighted the highly significant difference in Cd accumulation by algae and mussels. The PCA therefore confirmed that the physicochemical parameters measured indeed facilitated Cd accumulation in the biological matrix (algae and mussels) in the Lassargua area.

The results of Cd evolution in bivalve molluscs from shellfish production areas in Dakhla Bay from the winter 2019 to the winter 2023 (Figure 5) revealed that the decrease in Cd in burrowing species occurred beyond the winter 2019, particularly from the start of rearing of *Gracilaria gracilis* in Dakhla Bay. However, a decrease in Cd levels in filter-feeding bivalve molluscs was observed only beginning in 2020. However, an increase in Cd levels in bivalve molluscs from production areas in Dakhla Bay was recorded beginning in the summer of 2021, in the winter 2022 and in the winter 2023. This increase is likely due to accidental Cd contamination in areas of Dakhla Bay, but the results suggest that the impact of Cd decontamination in bivalve molluscs from other shellfish production areas in Dakhla Bay, notably Boutalha, Pk25, Duna Blanca and Puertitto by the alga *Gracilaria gracilis*, is negligible.

The results of the ANOVA statistical analysis, which was carried out with the averages of the Cd levels accumulated by the algae and filter-feeding bivalve molluscs, revealed that the difference in Cd accumulation capacity was not significant between the algae *Gracilaria gracilis* and the two filter-feeding bivalve mollusc species, notably, the oysters (*Crassostrea gigas*) collected from both the Boutalha and Duna Blanca areas and the mussel species (*Perna perna*) collected from the Puertitto area ($p > 0.05 = 1.0134$).

The results of the ANOVA statistical analysis, which was carried out with the averages of the Cd levels accumulated by the algae and burrowing bivalve molluscs, revealed that the difference in Cd accumulation capacity was not significant between *Gracilaria gracilis* and the burrowing bivalve mollusc species, notably the common cockle (*Cerastoderam edule*), clam (*Ruditapes decussatus*) taken from the Boutalha area and the razor clam (*Solen marginatus*) taken from the Pk25 area ($p > 0.05= 3.3025$) (Figure 7).

A statistical PCA was carried out to highlight the relationships that may exist between the environmental factors studied, particularly the physicochemical parameters and the concentration of Cd accumulated in algae and mussels in the Lassargua area of Dakhla Bay (Figure 8). The variation in the totality of the parameters studied is expressed by the two factorial axes Dim1 and Dim 2 of the principal component analysis (PCA), with 24.27% for the Dim 1 axis and 25.47% for the Dim 2 axis.

The analysis of the individuals in the PCA clearly revealed that the percentage of Cd accumulated by the algae was greater than that accumulated by the mussels in the Lassargua Zone of Dakhla Bay (Figure 6).

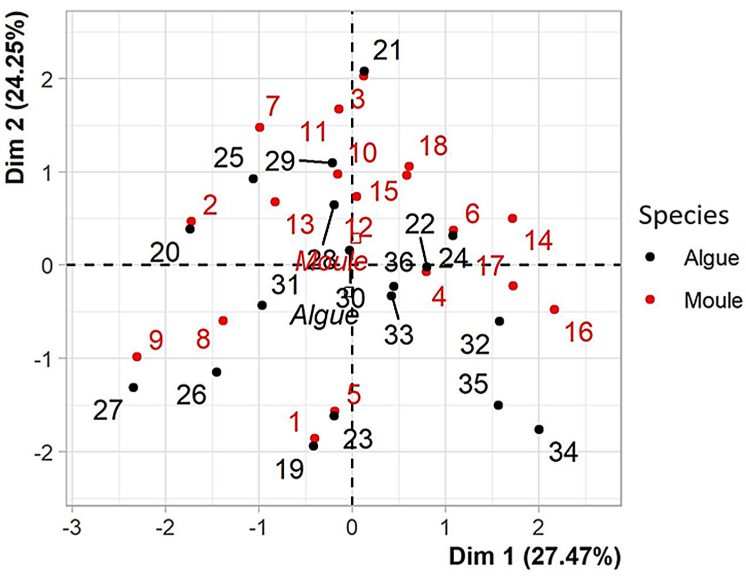

Figure 6. PCA results produced by the individuals studied in mussels and the alga *Gracilaria gracilis* from the Lassargua area

Analysis of variance: One factor

DETAILED REPORT

Groups	*Number of samples*	*Sum*	*Average*	*Variance*
Lassargua *(Gracilaria gracilis)*	9	16	1.777777778	0.318194444
Boutalha *(Cerastoderma edule)*	9	2.34	0.26	0.017275
Boutalha *(Ruditapes decussatus)*	9	3.96	0.44	0.038775
PK25 *(Solen marginatus)*	9	2.3	0.255555556	0.012490278

ANALYSIS OF VARIANCE

Source of Variations	*Sum of squares*	*Degree of freedom*	*Average of squares*	*F*	*Probability*	*Critical value for F*
Between groups	14.57302222	3	4.857674074	50.24295772	3.302583872	2.901119584
Within groups	3.093877778	32	0.096683681			
Total	17.6669	35				

Figure 7. Comparison of Cd accumulation in three burrowing bivalve molluscs and the alga *Gracilaria gracilis* (ANOVA test)

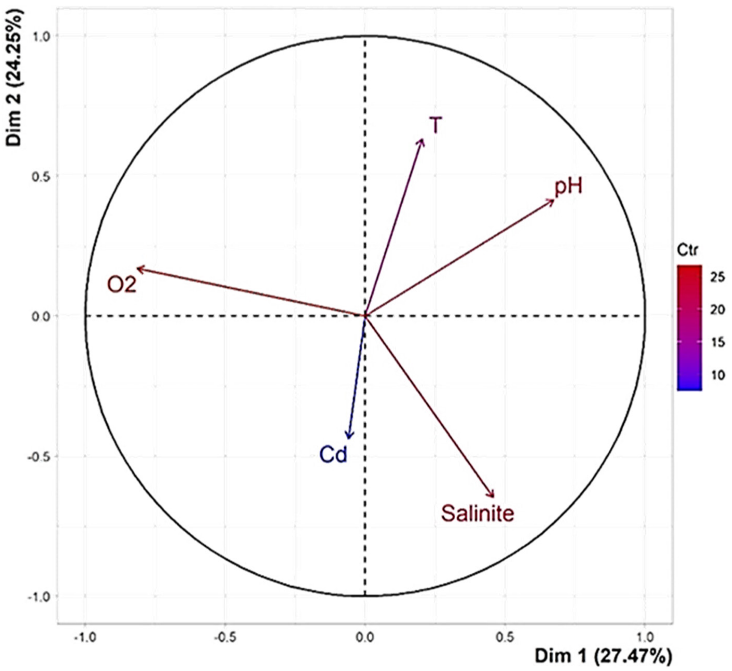

Figure 8. PCA results produced by the variables studied in water, seaweed and mussels from the Lassargua area

DISCUSSIONS

The results of the Cd assessment of the farmed alga *Gracilaria gracilis* from the Lassargua area of Dakhla Bay revealed good accumulation of Cd in the alga throughout the study period (2019–2023). The concentration of Cd in *Gracilaria gracilis* varies over time [Astorga-España et al., 2015; De Souza et al., 2012]. However, there was a large difference between the Cd accumulation capacity of the alga *Gracilaria gracilis* from the natural deposit and that of the farmed alga from the Lassargua zone of Dakhla Bay. In fact, metabolic stages such as the algal growth rate and exposure time affect Cd accumulation by algae [Duinker et al., 2016].

As the Gracilaria species have previously shown significant capacity for Cd accumulation, with the microalga "Gracilaria tikvahiae" demonstrating high accumulation of multiple heavy metals [Burdin and Bird, 1994]. The alga microalga "Gracilaria tenuistipitata" exhibited biphasic Cd uptake kinetics, accumulating 223–496 mg/kg dry weight within 6 days, with over 50% retention after 10 days in Cd-free seawater [Hu et al., 1996]. This species also showed the ability to bioaccumulate about 9% of Cd from the environment [Tonon et al., 2011]. Comparatively, other macroalgae like "Blindigia marginata" have also demonstrated effectiveness as biomonitors for Cd and other metals [Chakraborty and Owens, 2013]. Factors influencing Cd accumulation in Gracilaria include light availability, with reduced uptake in darkness, suggesting an energy-dependent process [Hu et al., 1996].

Seaweed from natural deposits is exposed for long periods and therefore represents a fairly mature seaweed, whereas farmed seaweed is exposed for short periods in large areas of the zone, but its growth stages are not sufficiently advanced. Indeed, the variations in metal concentrations appear to be zone specific, linked to algal growth rates and differ from one part of the alga to another. In addition, the presence of a large surface area of algae in contact with water facilitates the absorption of contaminants [Duinker et al., 2016]. Studies in vitro confirmed the rapid accumulation and bioconcentration of Cd by marine algae, with some species recording Cd concentrations between 0 and 6 minutes of exposure [Boily, 2004].

Since the start of seaweed (*Gracilaria gracilis*) farming and throughout the monitoring period, Cd accumulation by farmed seaweed has become increasingly significant. However, a decrease in Cd levels in mussels (*perna perna*) was observed. Mussels are very good bioindicators because of their ability to accumulate metals present in the environment, with a concentration factor of approximately 10^3 to 10^5 in relation to the water in the environment [Casas, 2005]. We note that the highest levels accumulated by the mussel are on the order of 1.4 mg/kg Fresh weight was recorded during the winter 2019, while the lowest levels were on the order of 0.2 mg/kg Fresh weight recorded during the winter 2022 (Figure 5).

As average Cd levels increase in macroalgae, they decrease in mussels. These results suggest that the exposure of mussels and algae in identical marine environments may favour the decontamination of mussels from Cd, given that algae rapidly concentrate high levels of Cd present in seawater compared with the Cd levels concentrated by mussels (*perna perna*). Additionally, the results of the ANOVA revealed a highly significant difference between the Cd accumulation capacity of the alga *Gracilaria gracilis* and that of the mussel (*Perna perna*) in the Lassargua area. Statistical analysis of the individuals in the PCA confirmed that the percentage of Cd accumulated by the algae was greater than that accumulated by the mussel in the Lassargua Zone of Dakhla Bay.

The results obtained clearly demonstrate the important role of the alga *Gracilaria gracilis* in the dynamics of Cd accumulation in mussels, which effectively reflects changes in water quality in the area [Biris-Dorhoi et al., 2020]. Indeed, the Cd concentrations in the water of the Lassargua area were negligible and did not exceed 0.65 µg/L. Some studies have shown that the use of algae-based adsorbents has produced satisfactory and very significant results, with very high yields in water purification achieved by decontaminating wastewater containing heavy metals, particularly Cd [Znad et al., 2022].

The results of the Cd analyses of the sediments collected from areas in Dakhla Bay revealed negligible average Cd levels, which decreased with time. The maximum Cd levels are noted in the two most polluted areas of Dakhla Bay, notably the urban area, where the maximum is approximately 1.4 mg/kg dry weight, and the Lassargua area, where the maximum is approximately 1.39 mg/kg dry weight [Anhichem et al., 2017].

The average Cd levels adsorbed by sediment in the Lassargua area are increasingly low throughout the study period, which may be due to Cd absorption by benthic species and low levels of Cd in seawater. Sediments in the marine environment are recognized as the main reservoir of heavy metals and are essential for metal release and transport [Ustaoğlu et al., 2024]. Additionally, the dynamics of Cd in sediment are very complex since the presence of Cd in sediment is managed by physical, chemical and biological processes [Gonzalez and Foan, 2015]. Consequently, algae, burrowing bivalve molluscs and other benthic species can absorb Cd from adjacent waters and sediments. We can conclude that algae have the potential to bioremediate heavy metals, particularly in sediments [Luo et al., 2020].

During this study, the results of Cd monitoring in mussels, seaweed, seawater and sediment in the Lassargua area confirmed the decontamination of Cd in mussels, seawater and sediment by the seaweed *Gracilaria gracilis.*

The average Cd levels recorded in burrowing and filter-feeding bivalve mollusc species from shellfish production areas in Dakhla Bay, notably Boutalha, PK 25, Duna Blanca and Puertitto, suggest that algae farming is responsible for the decline in Cd levels recorded. However, very high levels of Cd were noted in filter-feeding burrowing species during the summer of 2021, the winter 2022 and the winter 2023. This increase may be caused by a period of accidental Cd contamination affecting the entire area, but these results invalidate the hypothesis that the alga *Gracilaria gracilis* decontaminates Cd in bivalve molluscs in these areas of Dakhla Bay.

The results of the ANOVA statistical analyses indicate that the difference in the Cd accumulation capacity between algae and burrowing, filter-feeding bivalve molluscs is not very significant. Indeed, the location of the algal bed is known to be one of the environmental factors that can influence the level of Cd contamination in algae [Duinker et al., 2016; Roleda et al., 2019], reflecting the negligible impact of Cd decontamination in bivalve molluscs from these areas by farmed algae. Indeed, although the surface area of *Gracilaria gracilis* algae under cultivation is very large in the Lassargua area, its impact on Cd decontamination in the shellfish production areas of Dakhla Bay has not been proven. The average Cd levels recorded in the two groups of filter-feeding and burrowing bivalve molluscs and in the alga *Gracilaria gracilis* clearly demonstrate that the geographical origin of the alga in relation to the shellfish beds studied are variables that affect the accumulation of trace elements by macroalgae [Duinker et al., 2016; Roleda et al., 2019].

Consequently, the decontamination of Cd in mussels from the Lassargua area by the alga *Gracilaria gracils* grown in the same area has been confirmed. However, the decontamination of Cd in the two groups of bivalve molluscs located in the Boutalha, Duna Blanca and PK25 areas, more than 35 km north of the Lassargua area, and in the Puertitto area, 12 km west of the Lassargua area, by the alga *Gracilaria gracilis* in culture has not been well demonstrated and remains to be confirmed. For this reason, a study of the decontamination of Cd in the aforementioned areas by the same alga, *Gracilaria gracilis*, in culture in these areas or in vitro may yield very satisfactory results [Gonzalez and Foan, 2015].

CONCLUSION

On the basis of the results expected from this study, Cd accumulation by the farmed alga *Gracilaria gracilis* was confirmed throughout the study period (2019–2023). A correlation between various environmental factors, notably temperature, pH, salinity and dissolved oxygen, as well as the location and area of algal rearing, is well noted and has facilitated Cd accumulation by the alga Gracilaria gracilis, which in turn has facilitated Cd decontamination in the Lassargua area. This decontamination was evidenced by the decrease in Cd concentrations in mussels (*perna perna*), which showed a reverse trend in Cd levels compared with those measured in farmed algae.

The results of the PCA and ANOVA revealed a highly significant difference between the Cd accumulation capacity of *Gracilaria gracilis* algae and mussels in the Lassargua area, demonstrating the important role of *Gracilaria gracilis* algae in the dynamics of Cd accumulation in mussels, which effectively reflects changes in seawater quality in this area.

REFERENCES

1. Anhichem, M., Dellal, M., Chfiri, R., Yahyaoui, A., Benbrahim, S., 2017. Étude de la qualité des eaux et des sédiments de la Baie de Dakhla au Maroc. Qualité physico-chimique et contamination métallique. Bulletin de la Societe Zoologique de France, 142(4).
2. Arabi, M., Mechkirrou, L., El Malki, M., Alaoui, K., Chaieb, A., Maaroufi, F., Karmich, S., 2024. Overview of Ecological Dynamics in Morocco–Biodiversity, Water Scarcity, Climate Change, Anthropogenic Pressures, and Energy Resources–Navigating Towards Ecosolutions and Sustainable Development. In E3S Web of Conferences - EDP Sciences, 527, 01001. https://doi.org/10.1051/e3sconf/202452701001
3. Astorga-España, M.S., Galdón, B.R., Rodríguez, E.R., Romero, C.D., 2015. Mineral and trace element concentrations in seaweeds from the sub-Antarctic ecoregion of Magallanes (Chile). Journal of Food Composition and Analysis, 39, 69–76. https://doi.org/10.1016/j.jfca.2014.11.010
4. Bastos, E., Schneider, M., de Quadros, D.P., Welz, B., Batista, M.B., Horta, P.A., Rörig, L.R., Barufi, J.B., 2019. Phytoremediation potential of Ulva ohnoi (Chlorophyta): Influence of temperature and salinity on the uptake efficiency and toxicity of cadmium. Ecotoxicology and environmental safety, 174, 334–343. https://doi.org/10.1016/j.ecoenv.2019.01.130
5. Belasri, L., Arabi, M., Sabri, S., Hmimid, F., Ait Benichou, S., 2024. Transfer of metals from the soil to medicago sativa irrigated with municipal landfill leachate. Journal of Ecological Engineering, 25(8), 336–346. https://doi.org/10.12911/22998993/190349
6. Biris-Dorhoi, E.S., Michiu, D., Pop, C.R., Rotar, A.M., Tofana, M., Pop, O.L., Socaci, S.A., Farcas, A.C., 2020. Macroalgae—A sustainable source of chemical compounds with biological activities. Nutrients, 12(10),

3085. https://doi.org/10.3390/nu12103085

7. Boily, F., 2004. Mécanismes de prise en charge et toxicité du cadmium en présence de thiosulfate chez une algue verte, Chlamydomonas reinhardtii. Rapport de l'Institut National de la Recherche Scientifique (Canada).
8. Burdin, K.S., Bird, K.T., 1994. Heavy metal accumulation by carrageenan and agar producing algae. https://doi.org/10.1515/botm.1994.37.5.467
9. Casas, S., 2005. Modélisation de la bioaccumulation de métaux traces (Hg, Cd, Pb, Cu et Zn) chez la moule, Mytilus galloprovincialis, en milieu méditerranéen (Doctoral dissertation, Université du Sud Toulon Var).
10. Chakraborty, S., and Owens, G., 2013. Metal distributions in seawater, sediment and marine benthic macroalgae from the South Australian coastline. International Journal of Environmental Science and Technology, 11, 1259–1270. https://doi.org/10.1007/s13762-013-0310-4
11. Dafir, J.E., 1997. Application de la dynamique du phosphore à l'étude de l'organisation et du fonctionnement de certains écosystèmes aquatiques (lagune Nador, baie Dakhla, barrage Al Massira)(gestion et préservation). Doctorat d'état, Université Hassan II, Faculté des Sciences Ain Chock, Casablanca, Maroc.
12. De Souza, L.C., Rodrigues, J.C., Campos, M.L., de Almeida, J.A., da Silveira, C.B., Machado, F.C., Spada, G., 2012. Capacidade de remoção do Cd por zeólita natural. Revista de Ciências Agroveterinárias, 11(2), 138–145.
13. Duinker, A., Roiha, I.S., Amlund, H., Dahl, L., Lock, E.J., Kögel, T., Maage, A., Lunestad, B. T., 2016. Potential risks posed by macroalgae for application as feed and food–a Norwegian perspective. National Institute of Nutrition and Seafood Research (NIFES), 23. https://doi.org/10.13140/RG.2.2.27781.55524
14. Gonzalez, J-L., Foan L., 2015. Evaluation de la contamination des eaux: Comparaison des mesures par échantillonnage passif (DGT, POCIS, SBSE) et des mesures dans le Biote. Action n° IIB01-4 Développement et optimisation des technologies innovantes de prélèvement et d'analyse, IFREMER - Institut Français de Recherche pour l'Exploitation de la Mer. AQUAREF, Fevrier 2015.
15. Guelorget, O., Orbi, A., Lefebvre, A., 1996. La baie de Dakhla, Organisation biologique et fonctionnement. Institut National de Recherche Halieutique, Maroc.
16. Hu, S., Tang, C.H., Wu, M.C., 1996. Cadmium accumulation by several seaweeds. Science of The Total Environment, 187, 65–71. https://doi.org/10.1016/0048-9697(96)05143-1
17. Huang, X., Ke, C., Wang, W.X., 2010. Cadmium and copper accumulation and toxicity in the macroalga Gracilaria tenuistipitata. Aquatic Biology, 11, 17–26. https://doi.org/10.3354/ab00288
18. Luo, H., Wang, Q., Liu, Z., Wang, S., Long, A., Yang, Y., 2020. Potential bioremediation effects of seaweed Gracilaria lemaneiformis on heavy metals in coastal sediment from a typical mariculture zone. Chemosphere, 245, 125636. https://doi.org/10.1016/j.chemosphere.2019.125636
19. Orbi, A., Dafir, J. M., Berraho, A., Sarf, F., 1995. Étude pluridisciplinaire de la baie de Dakhla. Rapport interne, Institut Scientifique des Pêches Maritimes, Royaume du Maroc, 86, 26.
20. Pavlaki, M.D., Morgado, R.G., van Gestel, C.A., Calado, R., Soares, A.M., Loureiro, S., 2017. Influence of environmental conditions on the toxicokinetics of cadmium in the marine copepod Acartia tonsa. Ecotoxicology and environmental safety, 145, 142–149. https://doi.org/10.1016/j.ecoenv.2017.07.008
21. Peltre, M.C., Rodriguez, S., Vergon, J.P., Chauvin, C., 2014. Guide pratique de détermination des algues macroscopiques d'eau douce et de quelques organismes hétérotrophes. Irstea, pp.204, 2014.
22. Roleda, M.Y., Marfaing, H., Desnica, N., Jónsdóttir, R., Skjermo, J., Rebours, C., Nitschke, U., 2019. Variations in polyphenol and heavy metal contents of wild-harvested and cultivated seaweed bulk biomass: Health risk assessment and implication for food applications. Food Control, 95, 121–134. https://doi.org/10.1016/j.foodcont.2018.07.031
23. Tonon, A.P., Oliveira, M.C., Soriano, E.M., Colepicolo, P., 2011. Absorption of metals and characterization of chemical elements present in three species of Gracilaria (Gracilariaceae) Greville: a genus of economical importance. Revista Brasileira De Farmacognosia-brazilian Journal of Pharmacognosy, 21, 355–360. https://doi.org/10.1590/S0102-695X2011005000058
24. Ustaoğlu, F., Yüksel, B., Tepe, Y., Aydın, H., Topaldemir, H., 2024. Metal pollution assessment in the surface sediments of a river system in Türkiye: Integrating toxicological risk assessment and source identification. Marine Pollution Bulletin, 203, 116514. https://doi.org/10.1016/j.marpolbul.2024.116514
25. Xu, Z., Lin, X., Ji, X., Wang, Z., Huang, C., 2001. Effect of environmental factors on N and P uptake by Gracilaria tenuistipitata var. liui Zhang et Xia. Ying yong sheng tai xue bao. The journal of applied ecology, 12(3), 417–21.
26. Yang, Y., Chai, Z., Wang, Q., Chen, W., He, Z., Jiang, S., 2015. Cultivation of seaweed Gracilaria in Chinese coastal waters and its contribution to environmental improvements. Algal research, 9, 236–244. https://doi.org/10.1016/j.algal.2015.03.017
27. Znad, H., Awual, M.R., Martini, S., 2022. The utilization of algae and seaweed biomass for bioremediation of heavy metal-contaminated wastewater. Molecules, 27(4), 1275. https://doi.org/10.3390/molecules27041275