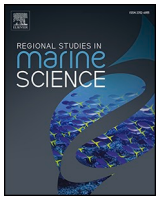
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Environmental impact of thermal power plants: Heavy metal analysis in sediments and macroalgae from Karabiga (Çanakkale), Türkiye

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ABSTRACT

The accumulation of heavy metals in ecosystems and their transfer through the food chain pose significant risks to both human health and aquatic life. In the research, the presence of toxic metals in the marine environment because of thermal power plants and industrial facilities located on the Karabiga coast was evaluated, and the bioaccumulation levels of heavy metals in algae species were determined. Heavy metal (Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn) analyses were performed using the ICP-OES device in sediment and macroalgae samples taken from 5 stations in the Karabiga coastal region in the Northwestern Anatolia of Turkey in September 2023. To assess the extent of heavy metal pollution, several indices were calculated, including the Enrichment Factor (EF), Pollution Factor (CF), Pollution Load Index (PLI), and Geoaccumulation Index (Igeo), which provide insights into the sources and levels of contamination. No significant pollution was detected based on the Pollution Indexes. All measured heavy metal concentrations in sediment samples were below the regulatory limits set by the WWQG (2021) and classified as Class A quality according to the SACS (2015) guidelines, indicating minimal pollution in the study area. Macroalgae species, particularly *Cladophora sericea* and *Gongolaria barbata*, showed elevated levels of Cu, Pb, and Zn, exceeding regulatory limits set by ANZFA (2005) and EC (2011). Potential risk calculation methods for human health were performed on 5 analyzed macroalgae samples. Considering the HI values for macroalgae, no metal was detected with a HI value greater than 1, therefore no potential health risks are expected.

1. Introduction

Since the industrial revolution, the widespread use of fossil fuels has significantly increased, leading to environmental degradation and pollution (Gümüş and Buluş, 2020). In recent years, the seas have been seriously polluted by human-induced and natural waste. Toxic elements from terrestrial sources are not biodegradable and tend to accumulate in marine sediments, posing long-term risks to aquatic ecosystems. The creatures living in the sediment suffer the most from this pollution (Kam and Yümün, 2021). Metals and trace elements, many of which are toxic and carcinogenic, are significant environmental pollutants that threaten aquatic ecosystems and human health. Many of these substances, listed as priority pollutants by the U.S. Environmental Protection Agency (USEPA), exhibit toxic and carcinogenic properties. Due to human activities, water pollution particularly from metal-containing pollutants has emerged as a critical global issue (Pant et al., 2020; Varol and Tokatlı, 2024). These heavy metals accumulate in organisms, becoming a potential source of heavy metal contamination in aquatic ecosystems (Almafrachi et al., 2024).

Among marine organisms, algae have long been used as food and have recently entered our lives as food supplements (Arulkumar et al., 2019). According to the Food and Agriculture Organization (FAO), with the growing global market demand for seaweeds (Wells et al., 2017), approximately 80 % of global seaweed production is used directly for human consumption, while 20 % is allocated to other industries such as food, cosmetics, fertilizers, animal feed additives, and medicine (Lozano

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Muñoz and Diaz, 2020; Peng et al., 2022).On the other hand, algae are used as reliable indicator organisms for monitoring pollution in aquatic environments due to their ability to recover heavy metals and retain toxic metals (Ali et al., 2021; Sinaei et al., 2018).

Numerous studies have demonstrated that sediments serve as the primary reservoir for heavy metals and can act as a potential source of both dissolved and particulate pollutants in seawater. As a result, coastal sediments are widely considered valuable indicators for monitoring heavy metal accumulation over time (Zhang et al., 2019). Sediment is a good indicator of heavy metals due to the hydrophobic properties of anthropogenic sources and their tendency to accumulate by sedimentation. Accumulation of heavy metals in marine sediments may pose a threat to human health if transported through the food web (Manahan, 2022).

The causes of metal pollution in the marine environment include natural factors such as weathering, erosion and volcanic eruptions, as well as domestic wastewater and industrial wastewater, agriculture, aquaculture, mining operations and secondary deposition of substances in polluted air (Alkan et al., 2015; Vodopivez et al., 2015). Anthropogenic inputs, especially near coastal sediments, constitute an important source of metals. Distinguishing whether metals in sediments originate from natural processes or human activities is crucial. Metal pollution in marine sediments can be evaluated using various methods (Harikumar and Nasir, 2010). For this purpose, indices such as enrichment factor (EF), Geoaccumulation Index Analysis (Igeo) and Pollution Factor (CF) are used to determine whether metals originate from natural geological structures (Alkan et al., 2015). The use of ecological risk indices provides a multidimensional environmental risk assessment, considering not only the accumulation of metals in the sediment but also the toxic potential of these metals.

Pollution from industrial areas in inland seas is high in intercontinental seas. The Dardanelles Strait, serving as a transition zone between the Marmara Sea and the Mediterranean, is influenced by both the Black Sea and the Mediterranean through its upper and lower currents (Yılmaz and Sadikoglu, 2011). The main pollutants in the Çanakkale region are; waste reaching the sea through wind and rain, waste resulting from agricultural activities, waste left during fishing activities, solid waste such as packaging, waste resulting from intense ship traffic and marina activities, and waste originating from densely populated settlements (Yenici and Turkoglu, 2023). The rapid developments in technology and industry in the coastal areas of the Marmara Sea and the coal-fired thermal power plants that have been established and put into operation in recent times have affected the Dardanelles.

There is no previously detected heavy metal study in the Karabiga region, which is located on the southern coastline of the Marmara Sea and where intensive industrial and energy production takes place. In the existing literature, heavy metal pollution in nearby regions has generally been studied either only through sediment (Kam and Önce, 2016) matrix or only through biological samples (Yümün and Önce, 2017). However, in this study, a comparative analysis of heavy metal accumulation in two different matrices was performed; thus, bioaccumulation potential and environmental risk level were evaluated together. The study area is an environmentally sensitive area under intense anthropogenic pressure due to industrial activities, agricultural practices and especially energy production facilities. There are a total of five thermal power plants on the Karabiga coast, three of which are located directly on the coastline and two of which are located approximately 50 km away. Our aim in this study is to determine the heavy metal accumulations in sediments and macroalgae taken from the Karabiga coastal region in the Northwestern Anatolia of Turkey. For this purpose, trace element values (Cu, Fe, Mn, Zn, Co, Ni, Cr and Pb) were investigated in the algae and sediment samples collected. The data obtained were evaluated with the risk indices given below for the sediment and the human health risk assessment for the algae.

2. Material and method

2.1. Study area and collection of samples

Karabiga is located in the southwest of the Marmara Region of Türkiye and falls within the borders of Biga district in Çanakkale. This region has received intense investments in thermal power plants and various industrial fields (chemistry, iron and steel, energy) established in recent years.

Sediment and macroalgae samples were collected from five strategically selected stations along the Karabiga coast in October 2023, chosen based on their proximity to industrial facilities and thermal power plants (Fig. 1). Stations 1 and 2 are two thermal power plants in this region where industrial activities and maritime transportation are intense. There is one thermal power plant near stations 3 and 4. Station 5 is the station where agricultural activities are intense and is the closest to the settlement. Collected samples are placed in sterile containers and delivered to the laboratory in the cold chain. The coordinates of the sample stations are given in Table S1.

Sampling studies were carried out by free diving between depths of 0–1 m. The underwater sampling of the materials was done by scraping them with a spatula and collected in drawstring bags made of plankton swab. The collected materials have been preserved in jars to be analyzed later in the laboratory.

Some of the collected materials were fixed in jars in a 4–6 % neutralized formaldehyde solution prepared with sea water, to be determined and identified later in the laboratory. Identification studies of the materials were carried out with Olympus brand SZX16 model stereo zoom and BX51 model binocular light microscopes. While making taxonomic definitions of the materials, decisive and distinctive anatomical and morphological features were taken into consideration.

2.2. Analysis of sediment samples

Sediment samples were taken from the designated points with the help of an Ekman bucket, which is suitable for soft soils. The samples were taken as 1 kg and placed in polypropylene containers and brought to the laboratory. The samples were placed in petri dishes and placed in an oven and left to dry at 105 ^{0}C for 24 h. The samples, completely dehumidified in the oven, were pounded with a mortar and passed through 63 μm plastic sieves (Alkan et al., 2015; Union, E. 2010) The sieved samples were weighed on a Scaltec SPB 421 brand precision balance and 0.2 g were taken. 5 mL of nitric acid (65 % HNO3), 3 mL of hydrogen peroxide and 2 mL of pure water were added and mixed and placed in a CEM Mars 6 brand (frequency 2.45 GHz, maximum power 1800 W) microwave for dissolution. After the cooled samples are centrifuged, they will be filtered through filter paper, their volume will be completed to 20 mL and filtered into falcon tubes (Islam et al., 2015).

2.3. Enrichment factor (EF)

Enrichment factor (EF) is a useful index that reflects the rate of anthropogenic heavy metal pollution in sediments. In this study, Fe was used as the reference metal for normalization in the calculation of the enrichment factor.

$$\mathrm{EF}: \quad \frac{\left(\frac{M}{Y}\right) sample}{\left(\frac{M}{Y}\right) background} \tag{1}$$

Considering to Sutherland (2000), EF values are divided into 5 different categories according to the enrichment criterion; $EF < 2$, least enrichment/pollution, $2 \leq EF \leq 5$, moderate enrichment/pollution; $5 \leq EF \leq 20$, significant enrichment/pollution; $20 \leq EF \leq 40$, very high enrichment/pollution; $EF > 40$, extremely high enrichment/pollution

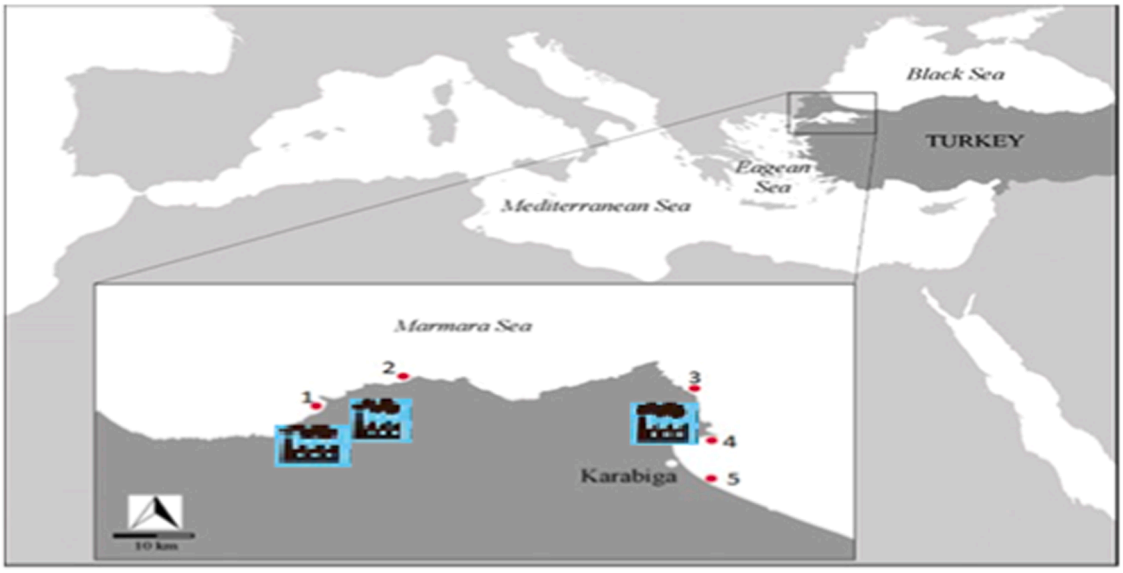


Fig. 1. Stations designated on the Çanakkale Karabiga coast.

(Alkan et al., 2020).

2.4. Contamination factor (CF)

The contamination factor (Cf) was applied to evaluate the sediment contamination of each analyzed metal concentration. It was calculated based on the following equation (Alkan et al., 2020):

$$Cf = \frac{Cm}{Cb} \quad (2)$$

Accordingly, Cm is the metal level in the sediment and Cb is the background level. The calculated Cf values are divided into four categories:

- Low pollution: $Cf < 1$;
- Moderate pollution: $1 \leq Cf < 3$;
- Significant pollution: $3 \leq Cf < 6$;
- Very high pollution: $Cf \geq 6$

2.5. Geoaccumulation index analysis (Igeo)

The geoaccumulation index proposed Muller (1981) is used to determine increasing pollution by comparing the current metal content with pre-industrialization values. The index is calculated with the following formula.

$$Igeo = \frac{\log 2Cn}{1,5xBn} \quad (3)$$

In the formula, Cn is the measured value of metal n in the sediment and Bn is the natural background concentration of metal n in the region. The background values of the elements under investigation used in the calculation of this index are the same as those used in the calculation of the pollution factors (CFs) index. The coefficient of 1.5 in the equation is used to account for possible variations in natural background values. The Igeo index includes 6 classes. Igeo ≤ 1; unpolluted: $1 <$ Igeo < 2; very slightly polluted: $2 <$ Igeo < 3; slightly polluted: $3 <$ Igeo < 4; moderately polluted: $4 <$ Igeo < 5; very polluted: $5 >$ Igeo extremely very polluted.

In this study, the background geochemical values used to calculate the Contamination Factor (CF), Enrichment Factor (EF), and Geo-accumulation Index (Igeo) were adopted from Upper Continental Crust (UCC) values as reported by Taylor and McLennan, (1985).

Recovery values for each metal concentration should be in the range of 80–110 % (AOAC, 2016). The analyzed NCS DC 74301 reference substance values were found to be close. Sensitivity levels varied between 83.7 % and 96.6 %. The highest sensitivity degree was detected in Zn, the lowest sensitivity degree was detected in Cr (Table S3). The analyzed NIST 2702 reference substance values were found to be close. Sensitivity levels varied between 81.5 % and 107.4 %. The highest sensitivity was detected in Cd, while the lowest sensitivity was detected in Pb (Table S3).

2.6. Analysis of macroalgae samples

Powdered algae samples were dried in a drying oven at 105 °C for 24 h. To 0.2 g of the dried sample, 5 mL of nitric acid (65 % HNO_3), 2 mL of hydrogen peroxide (H_2O_2), and 3 mL of pure water were added, and the mixture was left at room temperature for 24 h. The samples were then digested using a microwave digestion (Cem Mars 6) system. Heated at 180 °C for 45 min. After cooling, the digested samples were filtered through 100 mm blue-band filter paper, transferred to Falcon tubes, and diluted to a final volume of 25 mL with deionized water (Ahmad et al., 2021). The species names of the algae samples collected from the station are *Codium fragile, Gongolaria barbata, Ulva rigida, Cladophora sericea* and *Cystoseira foeniculacea*. The certified reference substance Sea lettuce (BCR 279) was used to verify the validity of the analytical method of the device. The results for the reference substance are given in Table S3. The analyzed BCR 279 reference substance values were found to be close. Sensitivity levels varied between 81.4 % and 92 %. The highest sensitivity level was determined for Zn, while the lowest sensitivity level was determined for Cu.

According to the stated study, elemental concentrations (Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn) were studied in triplicate using inductively coupled plasma optical emission spectrometry (ICP-OES, Varian Vista) (DIN EN ISO 11885:, 2009). ICP-OES stands out with its advantage of simultaneously detecting multiple elements and providing highly accurate measurements. ICP-OES operating conditions are given in Table S4.

2.7. Bioaccumulator factor (BAF)

The Bioaccumulation Factor (BAF) is defined as the ratio of the metal concentration in an aquatic organism to that in the surrounding water. The BAF was calculated using the following equation (Orosun, 2021;

Peng et al., 2022; Tao et al., 2016).

If the Bioaccumulator factor (BAF) value of a metal is less than 1, it is considered non-bioaccumulative, if the BAF value is between 1 and 5, it is bioaccumulative, and if the BAF value is greater than 5, it is considered very bioaccumulative (Costanza et al., 2012)

$$BAF = \frac{Cf}{Cw} \quad (4)$$

BAF: Bioconcentration factor
Cf: Heavy metal concentration in macroalgae (mg/kg)
Cw: Heavy metal concentration in water or sediment (mg/L)

2.8. Metal pollution index (MPI)

It is calculated by taking the geometric average of the elements detected in marine macroalgae species. The MPI value was calculated with the help of the following equation (mg/kg) (Ramteke et al., 2016).

$$MPI = (Cf1 \times Cf2 \times \ldots \times Cfn)^{1/n} \quad (5)$$

2.9. Human health risk assessment

A verified guide regarding the seaweed consumption rate in Turkey has not been reported. Therefore, the values related to human risk assessment recommended by the USEPA (2019) have been considered.

In order to calculate the human health risk assessment that may occur in consumers due to algae consumption, reference dose values were created based on Chronic Daily Intake (CDI) and Hazard Index (HI) calculations (Siddique et al., 2023; USEPA, 2019). HI was obtained from the average metal concentration in seaweeds of the current study as well as the standard guideline values of the US EPA guidelines. The sum of all hazard coefficients (HQs) for each element is called HI (USEPA, 2007). The formulas are as follows;

$$CDI = \frac{Cmetal * CR * EF * ED}{BW * AT} * 10^{-3} \quad (6)$$

CDI: Chronic Daily Intake
Cmetal: Metal level in algae (mg/kg, wet weight),
CR: Daily algae consumption rate of the consumer (gr/day),
EF: Frequency of exposure (250 days/year),
ED: Duration of exposure (70 years),
BW: Average body weight of adult consumer (70 kg).
AT: Average exposure time (365 days/year x 70),

HQ also represents the non-carcinogenic effect risks of the levels of metals taken into the body.

$$HQ = \frac{CDI}{RfD} * 10^{-3} \quad (7)$$

HQ: Hazard quotient
RfD: Oral reference dose of metals (Co: 0,03, Cr: 0005, Cu:0037, Fe: 0,7 Mn, 0047, Ni: 0,02, Pb: 0,0035, Zn:0,03)

The value expressed as HI (hazard index) is calculated by the total HQ values of the studied metals. If HI is greater than 1, it indicates that there are non-carcinogenic health risks for the consumer. If TTHQ is less than 1, non-carcinogenic health effects are not expected (Çulha et al., 2016; Tolatlı and Ustaoğlu, 2021).

$$\Sigma HI = (THQ1 \quad + THQ2 + \ldots\ldots + THQn) \quad (8)$$

2.10. Statistical analysis

After all samples ready for analysis were read 3 times and their averages were taken, the Pearson Correlation Index (PCI) test was used to determine the relationships between metals, and the one-way ANOVA Duncan multiple comparison test was used to control the significance of the difference between the variances. These tests were performed using the "SPSS 21" program.

3. Results and discussion

In the study, the element measurement results in the sediment samples taken during the field studies carried out in September 2023 in the Karabiga coastline are given in Table 1. The measurement results obtained from sediment samples in the study were evaluated according to the Working Water Quality Guide (WWOG, 2021) and the Guide for Screening and Evaluation of Contaminated Sediment (SACS, 2014). The values in these regulations are given in Table S2.

In the study, the Co element was determined as the lowest average in the sediment samples as 0.19 mg/kg at the 3rd station and the highest as 3.08 mg/kg at the 2rd station (Table 1). When the results obtained in this study are evaluated compared to other studies, Naik et al. (2023) in their study in the Bay of Bengal, the lowest Co value was 0.01 mg/kg and the highest was 0.092 mg/kg, El-Amier et al. (2023) in their study on the Mediterranean coast, the lowest was 0.59 mg/kg and the highest was 65.22 mg/kg, Diaz-de Alba et al. (2011) in the Bay of Gibraltar, the average Co value was 13.6 mg/kg, Ekoa Bessa et al. (2021) in the Atlantic coast, the average Co value was 104.4 mg/kg, Yuan et al. (2004) in the East China Sea, the average Co value was 2.5 mg/kg, Alkan et al. (2018) in their study in Trabzon Sürmene Gulf, the average Co value was determined as the lowest 8.89 mg/kg and the highest 32.8 mg/kg, while Kam and Önce (2016) in their study in Çanakkale Lapseki coast, the lowest Co value in the sediment was determined as 43.18 mg/kg and the highest 80.8 mg/kg and the results obtained according to this study were found to be higher. It was determined that the amount of Co detected at the second station was statistically significantly different ($p < 0.05$).

In the study, the average Cr element in sediment samples was determined as 0.72 at the 3rd station and 13.85 mg/kg at the 2nd station (Table 1). When the measurement results obtained were compared with the regulation values, it was determined to be below the limit value according to the WWOG (2021) guide and in class A quality according to the SACS (2014) guide. Ekoa Bessa et al. (2021) reported the average Cr value as 59.3 mg/kg in the Atlantic coast, Schintu et al. (2009) reported the average Cr value as 3.6 mg/kg in the Mediterranean coast, Li et al. (2013) reported the average Cr value as 57.8 in the Yellow Sea, Alkan et al. (2018) reported the average Cr value as the lowest 16.28 mg/kg and the highest 40.22 mg/kg in the Trabzon Sürmene Gulf, Kutlu et al. (2021), In their study in Iskenderun Gulf, the lowest Cr value was determined as 68.2 mg/kg and the highest as 515.8 mg/kg in the sediment; Pehlivan et al. (2021) in their study in the Marmara Sea, the lowest as 124.1 mg/kg and the highest as 137.2 mg/kg; Kam and Önce (2016) in their study in Çanakkale Lapseki coast, the lowest Cr value was determined as 27.54 mg/kg and the highest as 97.55 mg/kg in the sediment; and the average results obtained according to this study were found higher. It was determined that the amount of Cr detected at the first and second stations was statistically significantly different ($p < 0.05$).

In the study, the lowest Cu element in sediment samples was determined as 0.56 mg/kg at the 5th station and the highest as 6.73 mg/kg at the 2nd station (Table 1). When the measurement results obtained were compared with the regulation values, it was determined to be below the limit value according to the WWOG (2021) guide and in class A quality according to the SACS (2014) guide. Schintu et al. (2009) in their study on the Mediterranean coasts, the average Cu value was 0.8 mg/kg, El-Amier et al. (2023) in their study on the Mediterranean coast, the lowest was 5.98 mg/kg, the highest was 34.11 mg/kg, Alkan et al. (2018) in their study in Trabzon Sürmene Bay, the average Cu value was 29.39 mg/kg, the highest was 3107 mg/kg, Pehlivan et al., (2021) in their study in the Marmara Sea, the lowest was 25.6 mg/kg, the highest was 50.5 mg/kg, Kutlu et al. (2021) In their study in Iskenderun Bay, the lowest Cu value in the sediment was 9.66 mg/kg and the highest was 25.39 mg/kg, and Kam and Önce (2016) in their study in Çanakkale Lapseki coast, the lowest Cu value in the sediment was 13.98 mg/kg and

Table 1
Heavy metal concentrations in sediments collected from coast area of Karabiga in Çanakkale Strait (mg/kg, dry weight, mean ± SD, n = 6).

	Stations				
Metals	***1***	***2***	***3***	***4***	***5***
Co	1.74^{c}±0.53	3.08^{d}±0.31	0.19^{a}±0.03	0.89^{b}±0.19	0.34^{a}±0.12
Cr	13.13^{c}±3.25	13.85^{c}±0.78	0.72^{a}±0.11	5.06^{b}±0.34	2.51^{ab}±0.25
Cu	5.08^{c}±0.79	6.73^{d}±0.65	0.82^{ab}±0.11	1.72^{b}±0.13	0.56^{a}±0.46
Fe	6362^{c}±694.9	7172^{d}±398.4	1341^{ab}±70.38	1968^{b}±81.46	1201^{a}±72.52
Mn	184.53^{c}±24.06	176.32^{c}±19.86	45.05^{ab}±2.64	70.69^{b}±21.54	20.59^{a}±0.75
Ni	10.31^{b}±1.55	10.98^{b}±0.76	0.46^{a}±0.14	0.62^{a}±0.19	0.42^{a}±0.2
Pb	5.35^{d}±0.5	5.16^{d}±0.38	1.63^{b}±0.17	2.72^{c}±0.16	0.83^{a}±0.08
Zn	17.61^{b}±1.22	24.46^{c}±2.58	0.84^{a}±0.11	1.83^{a}±0.13	0.70^{a}±0.23

the highest was 33.34 mg/kg, and the average results obtained according to this study were found to be higher. It was determined that the amount of Cu detected at the second station was statistically significantly different ($p < 0.05$).

In the study, the lowest average Fe element in sediment samples was determined as 1201 mg/kg at the 5th station and the highest as 7172 mg/kg dry mass at the 2nd station (Table 1). When the measurement results obtained were compared with the regulation values, they were determined below the limit value according to the WWOG (2021) guide. El-Amier et al. (2023) in their study on the Mediterranean coast, the lowest was 2735 mg/kg and the highest was 29908 mg/kg, Schintu et al. (2009) in their study on the Mediterranean coast, the average Fe value was 4500 mg/kg, Diaz-de Alba et al. (2011) in the Gulf of Gibraltar, the average Fe value was 25457 mg/kg, Ekoa Bessa et al., (2021) in the Atlantic coast, the average Fe value was 18095 mg/kg, El-Sikaily et al. (2004) in their study on the Mediterranean coast, the average Fe value was 142.7 mg/kg, Kutlu et al. (2021) In their study in Iskenderun Bay, the lowest Fe value in the sediment was 19900 mg/kg and the highest was 38800 mg/kg. Kam and Önce (2016) in their study in Çanakkale Lapseki coast, the lowest Fe value in the sediment was 24879 mg/kg and the highest was 42559 mg/kg, and the average results obtained according to this study were found to be higher. It was determined that the amount of Fe detected in the second station was statistically significantly different ($p < 0.05$).

In the study, the lowest average Mn element in sediment samples was determined as 20.59 mg/kg at the 5th station and the highest as 184.53 mg/kg at the 1st station (Table 1). When the measurement results obtained were compared with the regulation values, they were determined below the limit value according to the WWOG (2021) guide. Yuan et al. (2004) reported the average Mn value in the East China Sea as 106.7 mg/kg, Schintu et al. (2009) reported the average Mn value as 106.7 mg/kg in their study on the Mediterranean coast, Alkan et al. (2018) reported the average Mn value as the lowest 204.41 mg/kg and the highest 446.87 mg/kg in their study in Trabzon Sürmene Bay, Pehlivan et al. (2021) reported the lowest 503.4 mg/kg and the highest 642.1 mg/kg in their study in the Marmara Sea, Kutlu et al. (2021) In their study in Iskenderun Bay, the lowest Mn value in the sediment was 494 mg/kg and the highest was 750 mg/kg, Kam and Önce (2016) in their study in Çanakkale Lapseki coast, the lowest Mn value in the sediment was 283.7 mg/kg and the highest was 1874 mg/kg, and the average results obtained according to this study were found to be higher. It was determined that the amount of Mn detected in the first and second stations was statistically significantly different ($p < 0.05$).

In the study, the lowest average Ni element in sediment samples was determined as 0.42 mg/kg at the 5th station and the highest as 10.98 mg/kg at the 2nd station (Table 1). When the measurement results obtained were compared with the regulation values, it was determined to be below the limit value according to the WWOG (2021) guide and in class A quality according to the SACS (2014) guide. El-Sikaily et al. (2004) reported the average Fe value as 3.3 mg/kg in their study on the Mediterranean coast, Diaz-de Alba et al. (2011) reported the average Ni value as 106.2 mg/kg in the Gulf of Gibraltar, Ekoa Bessa et al. (2021) reported the average Co value as 104.4 mg/kg in the Atlantic coast, Alkan et al. (2018) In their study in Trabzon Sürmene Gulf, the average Ni value was determined as the lowest 10.82 mg/kg and the highest 23.463 mg/kg. Pehlivan et al. (2021) in the Marmara Sea, the lowest 119 mg/kg and the highest 277.4 mg/kg. Kam and Önce (2016) in the study on Çanakkale Lapseki coast, the lowest Ni value in the sediment was determined as 43.25 mg/kg and the highest 246.52 mg/kg, and the average results obtained according to this study were found to be higher. It was determined that the amount of Ni detected in the first and second stations was statistically significantly different ($p < 0.05$).

In the study, the lowest Pb element in sediment samples was determined as 0.83 mg/kg at the 5th station and the highest as 5.35 mg/kg at the 1st station (Table 1). When the measurement results obtained were compared with the regulation values, it was determined to be below the limit value according to the WWOG (2021) guide and in class A quality according to the SACS (2014) guide. Yuan et al. (2004) In the East China Sea, the average Pb value was 8.6 mg/kg, Schintu et al. (2009) in their study on the Mediterranean coasts, the average Ni value was 11.4 mg/kg, Alkan et al. (2018) in their study in Trabzon Sürmene Bay, the average Pb value was determined as the lowest 17.26 mg/kg and the highest 208.19 mg/kg, Kutlu et al. (2021) in the study in İskenderun Bay, the Pb value in the sediment was determined as the lowest 2.73 mg/kg and the highest 12.93 mg/kg, and the average results obtained according to this study were found to be higher. It was determined that the amount of Pb detected in the first and second stations was statistically significantly different ($p < 0.05$).

In the study, the lowest average Zn element in sediment samples was determined as 0.70 mg/kg at the 5th station and the highest as 24.46 mg/kg at the 2nd station (Table 1). When the measurement results obtained were compared with the regulation values, it was determined to be below the limit value according to the WWOG (2021) guide and in class A quality according to the SACS (2014) guide. Diaz-de Alba et al. (2011) reported the average Zn value in the Gulf of Gibraltar as 60.8 mg/kg, Ekoa Bessa et al. (2021) reported the average Zn value in the Atlantic coast as 102.7 mg/kg, Yuan et al. (2004) reported the average Co value in the East China Sea as 35.9 mg/kg, Alkan et al. (2018) reported the average Zn value as the lowest 17.26 mg/kg and the highest 208.19 mg/kg in the study conducted in Sürmene Bay, Trabzon, Turkey, Pehlivan et al. (2021) reported the lowest 81.7 mg/kg and the highest 116.2 mg/kg in the study conducted in the Marmara Sea, Kutlu et al. (2021) In their study in Iskenderun Bay, the lowest Zn value in the sediment was 23.9 mg/kg and the highest was 70.6 mg/kg, Kam and Önce (2016) in their study in Çanakkale Lapseki coast, the lowest Zn value in the sediment was 62.9 mg/kg and the highest was 265.4 mg/kg, and the average results obtained according to this study were found to be higher. It was determined that the amount of Zn detected in the second station was statistically significantly different ($p < 0.05$).

In the one-way analysis of variance (ANOVA) conducted on sediment samples, it was found that the concentrations of Co, Cu, Fe, and Zn at the second station differed significantly from those at the other stations. Additionally, statistically significant differences were observed in the levels of Cr, Mn, Ni, and Pb between the first and second stations. These findings indicate that anthropogenic activities in the vicinity of the second station have a more pronounced impact on sediment quality. The

pronounced accumulation of metals observed at the second station indicates that the nearby thermal power plant and other industrial facilities exert a dominant influence on sediment quality. This suggests that thermal power plants contribute to the environmental burden of heavy metals not only through atmospheric emissions but also via wastewater discharge and particulate deposition.

Enrichment factor values of sediment samples are given in Table 2. Calculating the enrichment factor is one of the most commonly used methods to assess anthropogenic effects on sediments (Gałuszka et al., 2014). The average order of EF values of metals is Zn> Ni> Mn> Pb> Cr> Fe> Cu> Co. EF values indicate minimal enrichment as EF < 2 is found for all stations and metals. On the other hand, previous studies indicate that EF < 2 indicates the natural or lithogenic origin of the elements, while EF > 2 indicates the anthropogenic origin of the elements (Varol and Tokatlı, 2024). Similar results were found in the Nile Delta (Abdelaal et al., 2022), Red Sea (Lasheen et al., 2024).

Geoaccumulation values of sediment samples are given in Table 2. Geoaccumulation index (IGEO) is a measure of metal accumulation in sediment compared to the contextual concentration of the specific metal (Naik et al., 2023). Zn, Mn, Cr, Fe, Cu, Pb and Co metals Igeo values in all sediment samples are less than zero or close to zero. While the Igeo values of the 1st and 2nd stations were slightly above zero, they were below zero at the 3rd, 4th and 5th stations. These results indicate that the stations are not contaminated with metals. Similar results were found in the Suez Canal (Nour et al., 2022), Red Sea (Lasheen et al., 2024).

Pollution factor values of sediment samples are given in Table 2. The contamination factor is a frequently used method to describe the current situation in studies investigating the origin of heavy metal concentrations in sediments (Kam and Yümün, 2021). The pollution factor values of the sampled sediments are as follows from highest to lowest: Zn> Mn> Cr> Fe> Cu> Pb> Co. In this study, pollution factor values were determined as low level pollution (Cf<1) for all metals. Similar results were found in the Suez Canal, Red Sea (Lasheen et al., 2024).

The relationship between heavy metal parameters of sediment samples collected from the Karabiga coast was determined by Pearson Correlation Index (PCI) analysis and is given in Table S5. Relationships between heavy metals in sediment samples are at 0.01 significance level ($p < 0.01$) Co metal is positively correlated with Cr, Cu and Zn metals, Cr metal is positively correlated with Cu, Fe, Mn, Ni, Pb and Zn metals, Cu metal is positively correlated with Fe, Mn, Ni and Zn metals, Fe metal is positively correlated with Mn, Ni, Pb and Zn metals, Mn metal is positively correlated with Ni and Pb, Ni metal is positively correlated with Zn. Relationships between heavy metals are at 0.05 significance level ($p < 0.05$) Co metal is positively correlated with Fe, Mn, Ni and Pb metals, Cu metal is positively correlated with Pb metal, Mn metal is positively correlated with Zn, Ni metal is positively correlated with Pb, Pb metal is positively correlated with Zn.

In the study, the average elemental measurement results in macroalgae samples taken during field studies conducted in Karabiga in September 2023 are given in Table 3. In this study, the bioaccumulation level of heavy metals in seaweed collected from the Marmara Sea was compared with the standard regulatory limits of heavy metals of different countries (Table S6).

In this study, the highest Co concentration was found in *G. barbata* (0.85 mg/kg; Table 3) and the lowest Co concentration was found in *C. fragile* (0.48 mg/kg; Table 3). Aşıkkutlu (2021a),b) found the Co concentration in *G. barbata* as 0.847 mg/kg. Arıcı et al. (2019) found the Co concentration in *C. barbata* as 0.5 mg/kg. Shams El-Din et al. (2014) found the Co concentration in *U. intestinalis* as 1.45 mg/kg. No significant difference was found among the studied algae species in terms of Co metal ($p > 0.05$).

In this study, the highest Cr concentration was found in the *C. sericea* species (5.96 mg/kg; Table 3) and the lowest Cr concentration was found in the *G. barbata* species (2.82 mg/kg; Table 3). Aşıkkutlu (2021a) A found the Cr concentration as 8.09 mg/kg in *C. glomerata* species. Akcali and Kucuksezgin (2011) found the Cr concentration as 2.13 mg/kg in *Cystoseira* sp. in Çanakkale province. Squadrone et al. (2018) found the Cr concentration in *H. scoparia* species as 7.4 mg/kg in their study. Aşıkkutlu and Okudan (2021) found the Cr concentration as 1.99 mg/kg in *G. barbata* species. It was determined that the amount of Cr detected in the *C. sericea* species was statistically significantly different ($p < 0.05$).

In this study, the highest Cu concentration was found in *G. barbata* species (13.74 mg/kg; Table 3) and the lowest Cu concentration was found in *U. rigida* species (6.35 mg/kg; Table 3). ANZFA (2005) set the upper intake level for Cu in seaweeds (10 mg/kg). Except for *C. sericea* and *G. barbata*, Cu level was found to be 10 mg/kg lower. Aşıkkutlu and Okudan (2021) found the Cu concentration as 16.09 mg/kg in *G. barbata* species. Alp et al. (2012) found the highest copper concentration of 12.76 mg/kg in *Ulva* sp. on the Mersin coast. Arıcı et al. (2019) found the Cu concentration as 10.2 mg/kg in *C. barbata* species. It was determined that the amount of Cu detected in the *G. barbata* species was statistically significantly different ($p < 0.05$).

In this study, the highest Fe concentration was found in the *C. sericea* species (900.56 mg/kg) and the lowest Fe concentration was found in the *C. foeniculacea* species (205.38 mg/kg; Table 3). Aşıkkutlu and Okudan (2021) found the Fe concentration as 383.2 mg/kg in *C. foeniculacea* species Arıcı et al. (2019) found the Fe concentration as

Table 2
Enrichment factor (EF), Geoaccumulation Index Analysis (Igeo), Pollution factor values (Cf) of the stations.

Enrichment factor								
Station	**Co**	**Cr**	**Cu**	**Fe**	**Mn**	**Ni**	**Pb**	**Zn**
1	0.026	0.146	0.102	0.135	0.190	0.768	0.132	1.020
2	0.045	0.154	0.135	0.152	0.298	0.516	0.261	0.583
3	0.003	0.008	0.016	0.028	0.098	0.081	0.202	0.141
4	0.013	0.056	0.034	0.042	0.314	0.179	0.192	0.217
5	0.005	0.028	0.011	0.025	0.197	0.142	0.079	0.322
Geoaccumulation Index Analysis (Igeo)								
1	0.008	0.028	0.031	0.0002	0.0059	0.0236	0.0230	0.2122
2	0.016	0.028	0.037	0.0002	0.0059	0.0243	0.0225	0.2365
3	−0.023	−0.004	−0.004	0.0001	0.0043	−0.007	0.0067	−0.012
4	−0.002	0.017	0.010	0.0002	0.0048	−0.004	0.0137	0.0447
5	−0.015	0.010	−0.011	0.0001	0.0034	−0.008	−0.002	−0.026
Pollution factor values								
1	0.026	0.146	0.102	0.135	0.217	0.109	0.076	1.355
2	0.045	0.154	0.135	0.152	0.207	0.116	0.074	1.882
3	0.003	0.008	0.016	0.028	0.053	0.005	0.023	0.065
4	0.013	0.056	0.034	0.042	0.083	0.007	0.039	0.141
5	0.005	0.028	0.011	0.025	0.024	0.004	0.012	0.054

Table 3
Heavy metal concentrations in seaweed species coast area of Karabiga in Çanakkale Strait (mg/kg, dry weight, mean ± SD, n = 6).

	Chlorophyta			Rhodophyta	
Metals	***C. fragile***	***Ulva rigida***	***C. sericea***	***G. barbata***	***C. foeniculacea***
Co	0.48^{a}±0.44	0.57^{a}±0.5	0.63^{a}±0.32	0.85^{a}±0.58	0.79^{a}±0.12
Cr	4.21^{ab}±2.52	3.68^{ab}±1.35	5.96^{b}±1.49	2.82^{a}±1.47	3.03^{ab}±1.49
Cu	7.13^{a}±2.31	6.35^{a}±2.74	12.6^{ab}±2.34	13.74^{b}±6.63	6.86^{a}±0.5
Fe	478.2^{ab}±427.8	692.33^{ab}±586.4	900.56^{b}±176.7	635.83^{ab}±441.5	205.38^{a}±176.4
Mn	25.36^{ab}±2.81	29.45^{bc}±11.73	44.59^{c}±2.23	32.49^{bc}±16.48	10.51^{a}±0.77
Ni	3.70^{ab}±1.6	1.69^{a}±0.86	4.26^{ab}±1.8	4.25^{b}±2.52	2.47^{ab}±0.79
Pb	1.69^{ab}±1.46	1.42^{a}±0.52	3.48^{bc}±0.44	3.41^{c}±1.64	1.54^{a}±0.26
Zn	6.86^{a}±3.52	7.96^{a}±4.51	17.06^{a}±3.39	29.13^{a}±25.29	50.79^{a}±28.48

481.4 mg/kg in *C. barbata* species. Aşıkkutlu (2021a) found the Fe concentration as 6702.3 mg/kg in *C. glomerata* species. It was determined that the amount of Fe detected in the *C. sericea* species was statistically significantly different ($p < 0.05$).

In this study, the highest Mn concentration was found in *C. sericea* species (44.59 mg/kg; Table 3), and the lowest Mn concentration was found in *C. foeniculacea* species (10.51 mg/kg; Table 3). Aşıkkutlu and Okudan (2021) found the Manganese concentration in *C. foeniculacea* species as 18.1 mg/kg. Aşıkkutlu (2021a) found the Mn concentration as 37.7 mg/kg in *C. glomerata* species. Arıcı et al. (2019) found Mn concentration as 21.3 mg/kg in *C. barbata* species. It was determined that the amount of Mn detected in the *C. sericea* species was statistically significantly different ($p < 0.05$).

In this study, the highest Ni concentration was found in the *C. sericea* species (4.26 mg/kg; Table 3) and the lowest Ni concentration was found in the *U. rigida* species (1.69 mg/kg;). Aşıkkutlu and Okudan, (2021) found the Ni concentration as 18.63 mg/kg in *G. montagnei* species. Aşıkkutlu (2021a) found the Ni concentration as 4.44 mg/kg in *U. compressa* species. Arıcı et al. (2019) found the Ni concentration as 21.3 mg/kg in *C. barbata* species. In their study, Koçbaş et al. (2023) found the Ni concentration as 8.19 mg/kg in *U. intestinalis* species. It was determined that the amount of Ni detected in the *G. barbata* species was statistically significantly different ($p < 0.05$).

In this study, the highest Pb concentration was found in the *C. sericea* species (3.48 mg/kg; Table 3) and the lowest Pb concentration was found in the U. *rigida* species (1.42 mg/kg; Table 3). CEVA (2014) 5 mg/kg and EC (2011) 3 mg/kg, set limit values or Pb in seaweed. Pb levels were found below 3 mg/kg except for *C. sericea* (3.48 mg/kg) and *G. barbata* (3.41 mg/kg). Aşıkkutlu and Okudan, (2021) found the Pb concentration as 2.63 mg/kg in *C. foeniculacea* species. Aşıkkutlu (2021a) found the Pb concentration as 1.77 mg/kg in *U. compressa* species Arıcı et al. (2019).Arıcı et al. (2019) found the lead concentration as 1.44 mg/kg in *C. barbata* species. Akcali and Kucuksezgin (2011) found the Pb concentration as 0.06 mg/kg in *Cystoseira* sp. in Çanakkale province. It was determined that the amount of Pb detected in the *G. barbata* species was statistically significantly different ($p < 0.05$).

In this study, the highest Zn concentration was found in the *C. foeniculacea* species (67.35 mg/kg; Table 3) and the lowest Zn concentration was found in the *C. fragile* species (6.86 mg/kg; Table 3). ANZFA (2005) set the upper intake level for Cu in seaweeds (10 mg/kg). Except for *U. rigida* and *C. fragile*, Zn levels were found to be above 14 mg/kg. Aşıkkutlu and Okudan, (2021) found the Zn concentration as 26.7 mg/kg in *C. foeniculacea* species. Aşıkkutlu (2021a) found the Zn concentration in *U. compressa* species as 0.06 mg/kg. Arıcı et al. (2019) found the Zn concentration as 59.5 mg/kg in *C. barbata* species. Akcali and Kucuksezgin, (2011) found the Zn concentration as 75.5 mg/kg in *Cystoseira* sp. in Çanakkale province. No significant difference was found among the studied algae species in terms of Zn metal ($p > 0.05$).

An ANOVA analysis was performed to examine the heavy metal concentrations in different macroalgae species and evaluated the differences in metal accumulation among species. Significant differences were observed in the concentrations of Cr, Fe and Mn in C. sericea and in the concentrations of Cu, Ni and Pb in G. barbata ($p < 0.05$). These findings indicate that different algal species have varying capacities for heavy metal bioconcentration, and these differences may arise from species-specific physiological and biochemical characteristics.

The relationship between the heavy metal parameters of macroalgae samples collected from the Karabiga coast was determined by Pearson Correlation Index (PCI) analysis and is given in Table S7. Relationships between heavy metals in macroalgae are positively correlated with Co metal, Mn and Zn metals, positively correlated with Cr metal, positively correlated with Cu, Fe, Ni and Pb metals, positively correlated with Fe metal, positively correlated with Ni and Pb, and positively correlated with Ni metal, at 0.01 significance level ($p < 0.01$).

BAF values in macroalgae are shown in Fig. 2. Among the metals, the highest BAF value was found in Zn metal with 5.59, and the lowest BAF value was found in Mn with 0.11. BAF values were less than 1 in all species of Co, Cr, Fe, Mn and Ni metals. In Cu metal, BAF values in all species were between 1 and 5 (Fig. 2).

MPI values of seaweeds are given in Fig. 3. If the MPI value is > 1, it indicates contamination. Metal Pollution Index (MPI) is an index that expresses the degree of heavy metal pollution in biological samples. In the current study, the highest MPI value was determined in *C. sericea* (0.044) and the lowest MPI value was determined in *C. foeniculacea* (0.0001).

This study used data from eight metals (Pb, Co, Zn, Cu, Ni, Mn, Cr, Fe) to assess potential health risks to adults. No metal was detected with HI value > 1 in 6 macroalgae species. Therefore, no potential health risks are expected. The order of macroalgae according to HI values is *C. sericea*> *G. barbata*> *C. foeniculacea*> *U. rigida*> *C. fragilea*. HI values of macroalgae species *Codium fragile* (0.1616), *G. barbata* (0.2406), *U. rigida* (0.1681), *C. foeniculacea* (0.183) and *C. sericea* (0.2836) were also found below 1, indicating that consumption is safe as there is no carcinogenic health risk for adults (Table 4). In Bangladesh; Siddique et al. (2023) found the HI value for seaweeds as 0.414. Chen et al. (2018) calculated the HI from dry seaweed consumption in southeastern China as 0.22, considering the elements Al, Cd, Cr, Cu, Hg, Ni, and Pb. The HI calculated for Malaysian seaweeds significantly exceeds the health hazard limit (HI = 4.38) (Khandaker et al., 2021). In this study, high levels of heavy metal accumulation detected in *C. sericea* and *G. barbata* species indicate potential negative effects on the structure and function of the marine ecosystem. Especially high concentrations of toxic metals such as Cu, Pb and Ni may negatively affect the photosynthetic activity, growth rates and enzymatic processes of macroalgae. This may lead to disruptions in the physiological functions of macroalgae, which are primary producers, and threaten the health of the organisms that form the basis of the food web.

4. Conclusion

The study identified toxic metal bioaccumulation in sediments and macroalgae from the Karabiga coast of Çanakkale. The simultaneous analysis of abiotic and biotic matrices conducted in sediment and biotic samples has enabled the joint assessment of pollutant dispersion in the environment and their bioaccumulation potential. In this respect, the study presents a comprehensive approach that integrates chemical

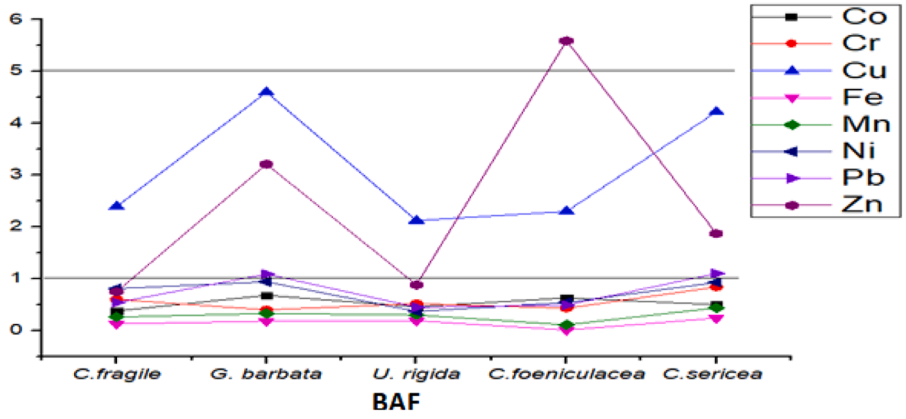


Fig. 2. $BAF_{sediment}$ results of metals belonging to macroalgae.

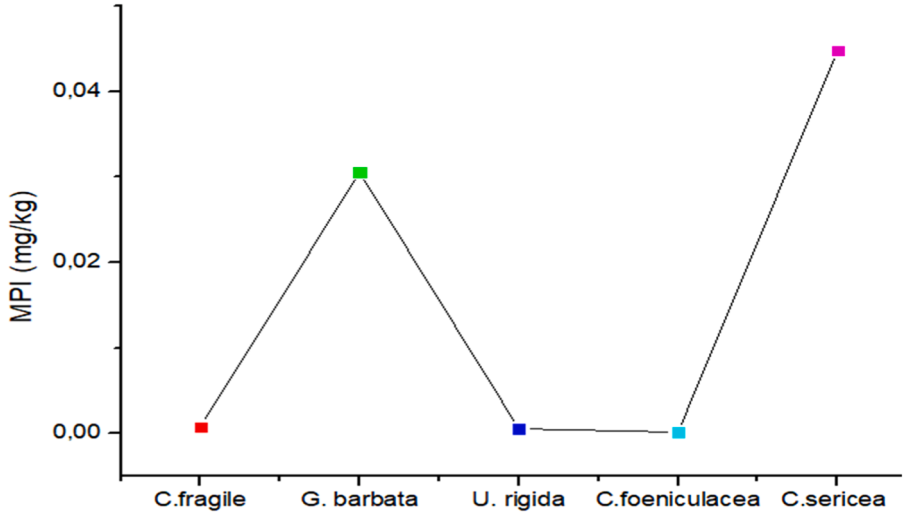


Fig. 3. MPI results of metals from macroalgae.

Table 4
Health risk calculation values of macroalgae.

Algae		Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
C. fragile	CDI	2.45E−05	2.15E−04	3.63E−04	2.44E−02	1.29E−03	1.89E−04	8.62E−05	3.50E−04
	HQ	8.16E−04	4.29E−02	9.82E−03	3.48E−02	2.75E−02	9.43E−03	2.46E−02	1.17E−02
	HI	1.62E−01							
G. barbata	CDI	4.33E−05	1.44E−04	7.00E−04	3.24E−02	1.66E−03	2.17E−04	1.74E−04	1.49E−03
	HQ	1.44E−03	2.88E−02	1.89E−02	4.63E−02	3.52E−02	1.08E−02	4.97E−02	4.95E−02
	HI	2.41E−01							
U. rigida	CDI	2.91E−05	1.88E−04	3.24E−04	3.53E−02	1.50E−03	8.62E−05	7.24E−05	4.06E−04
	HQ	9.69E−04	3.75E−02	8.75E−03	5.04E−02	3.19E−02	4.31E−03	2.07E−02	1.35E−02
	HI	1.68E−01							
C. foeniculacea	CDI	4.03E−05	1.54E−04	3.50E−04	1.05E−02	5.36E−04	1.26E−04	7.85E−05	2.59E−03
	HQ	1.34E−03	3.09E−02	9.45E−03	1.50E−02	1.14E−02	6.30E−03	2.24E−02	8.63E−02
	HI	1.83E−01							
C. sericea	CDI	3.21E−05	3.04E−04	6.42E−04	4.59E−02	2.27E−03	2.17E−04	1.77E−04	8.70E−04
	HQ	1.07E−03	6.08E−02	1.74E−02	6.56E−02	4.84E−02	1.09E−02	5.07E−02	2.90E−02
	HI	2.84E−01							

monitoring data with ecotoxicological risk assessment. This approach stands out as one of the few examples in the literature focusing on the monitoring of thermal power plant impacts and provides a contribution to the development of regional environmental policies.

Appropriate preventive measures need to be taken by management bodies to protect edible seaweed and the marine environment from chemical pollution. This study also reveals that seaweed, which is consumed less in our country, does not pose a significant risk to human health even in Karabiga, a region with heavy sea traffic and thermal power plants. Policies should be implemented to encourage the consumption of seaweed, an alternative food in our country.

Trace elements in the seas, biotic and abiotic factors, pose numerous health risks to aquatic life. The increase in maritime traffic, tourism and most importantly industrial pollution increases the amount of trace elements day by day. There is a need for further studies on this subject, focusing on larger areas and longer time periods, especially in the region

where we conducted our research. Similarly, experts and authorities need to monitor seawater quality periodically.

In addition to these factors, large cargo ships arriving at Bosphorus are a vital transit point for maritime transportation discharge their bilge and ballast water into the strait near the port. Depending on their density, these wastes can settle on the seabed, remain suspended in the water, or become benthic. Driven by water movements such as waves and currents, they can disperse throughout the strait, causing harm to marine organisms.

High metal concentrations in the Dardanelles can adversely impact water quality and threaten aquatic life. Therefore, it is crucial to implement serious measures to reduce the continuous input of metals into this region, which holds significant maritime and tourism potential. To protect edible seaweed and the marine ecosystem from chemical contamination, management units should conduct periodic environmental monitoring programs, identify and control the sources of heavy metals and other toxic components, and develop an effective wastewater treatment and control mechanism.

CRediT authorship contribution statement

Baran Aşikkutlu: Software, Writing – original draft, Data curation. **Cengiz Akköz:** Supervision, Investigation. **Emine Şükran Okudan:** Writing – original draft, Data curation, Formal analysis. **Merve Koçak:** Methodology, Formal analysis. **Gümüş Numan Emre:** Validation, Methodology, Writing – review & editing, Software, Conceptualization, Supervision. **Hatice Banu Keskinkaya:** Methodology, Software, Writing – review & editing, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104314.

Data availability

Data will be made available on request.

References

Abdelaal, A., Abdelkader, A.I., Alshehri, F., Elatiar, A., Almadani, S.A., 2022. Assessment and spatiotemporal variability of heavy metals pollution in water and sediments of a coastal landscape at the Nile Delta. Water 14, 3981. https://doi.org/10.3390/w14233981.

Ahmad, H., Zhao, L., Liu, C., Cai, C., Ma, F., 2021. Ultrasound assisted dispersive solid phase microextraction of inorganic arsenic from food and water samples using CdS nanoflowers combined with ICP-OES determination. Food Chem. 338, 128028. https://doi.org/10.1016/j.foodchem.2020.128028.

Akcali, I., Kucuksezgin, F., 2011. A biomonitoring study: heavy metals in macroalgae from eastern Aegean coastal areas. Mar. Pollut. Bull. 62, 637–645. https://doi.org/10.1016/j.marpolbul.2010.12.021.

Ali, A.Y.A., Idris, A.M., Eltayeb, M.A.H., El-Zahhar, A.A., Ashraf, I.M., 2021. Bioaccumulation and health risk assessment of toxic metals in red algae in Sudanese Red Sea coast. Toxin Rev. 40, 1327–1337. https://doi.org/10.1080/15569543.2019.1697886.

Alkan, N., Alkan, A., Akbas, U., Fisher, A., 2015. Metal pollution assessment in sediments of the southeastern Black Sea Coast of Turkey. Soil Sediment Contam. Int. J. 24, 290–305. https://doi.org/10.1080/15320383.2015.950723.

Alkan, N., Alkan, A., Erüz, C., 2018. Determination of metals in water and sediment samples of the Sürmene River, Turkey. In: Exergy for A Better Environment and Improved Sustainability 2: Applications. Springer, pp. 175–181. https://doi.org/10.1007/978-3-319-62575-1_13.

Alkan, N., Alkan, A., Demirak, A., Bahloul, M., 2020. Metals/metalloid in marine sediments, bioaccumulating in macroalgae and a mussel. Soil Sediment Contam. Int. J. 29, 569–594. https://doi.org/10.1080/15320383.2020.1751061.

Almafrachi, H.A.A., Gümüş, N.E., Çorak Öcal, İ., 2024. Heavy metal bioaccumulation in fish: ımplications for human health risk assessment in ten commercial fish species from Konya, Türkiye. Int. J. Environ. Sci. Technol. 1–10. https://doi.org/10.1007/s13762-024-05875-3.

Alp, M.T., Ozbay, O., Sungur, M.A., 2012. Determination of heavy metal levels in sediment and macroalgae (Ulva sp. and Enteromorpha sp.) on the Mersin Coast. Ekoloji 21, 47–55. https://doi.org/10.5053/ekoloji.2011.827.

ANZFA, 2005. Authority, Australian and NewZealand Food.

AOAC, 2016. Requirements, official methods of analysis. Append. F Guidel. Stand. Method Perform.

Arıcı, E., Bat, L., Yıldız, G., 2019. Comparison of metal uptake capacities of the brown algae Cystoseira barbata and Cystoseira crinita (Phaeophyceae) collected in Sinop. Turk. Pak. J. Mar. Sci. 28, 5–17.

Arulkumar, A., Nigariga, P., Paramasivam, S., Rajaram, R., 2019. Metals accumulation in edible marine algae collected from Thondi coast of Palk Bay, Southeastern India. Chemosphere 221, 856–862. https://doi.org/10.1016/j.chemosphere.2019.01.007.

Aşıkkutlu, B., 2021a. Elemental composition of macroalgae species and water samples taken from aquatic ecosystems in different regions from Turkey. Fresenius Environ. Bull. 30, 11449–11456.

Aşıkkutlu, B., Okudan, E.Ş., 2021b. Macro and trace element levels of macroalgae cystoseira foeniculacea ve gongolaria montagnei species from mediterranean region (Antalya/ Turkey). J. Anatol. Environ. Anim. Sci. 6, 757–764. https://doi.org/10.35229/jaes.950591.

CEVA, 2014. Reglementation Algues Alimentaires. Ceva Synthese Regle.

Chen, Q., Pan, X.-D., Huang, B.-F., Han, J.-L., 2018. Distribution of metals and metalloids in dried seaweeds and health risk to population in southeastern China. Sci. Rep. 8, 3578. https://doi.org/10.1038/s41598-018-21732-z.

Costanza, J., Lynch, D.G., Boethling, R.S., Arnot, J.A., 2012. Use of the bioaccumulation factor to screen chemicals for bioaccumulation potential. Environ. Toxicol. Chem. 31, 2261–2268. https://doi.org/10.1002/etc.1944.

Çulha, S.T., Yabanli, M., Baki, B., Yozukmaz, A., 2016. Heavy metals in tissues of scorpionfish (Scorpaena porcus) caught from Black Sea (Turkey) and potential risks to human health. Environ. Sci. Pollut. Res. 23, 20882–20892. https://doi.org/10.1007/s11356-016-7337-2.

Diaz-de Alba, M., Galindo-Riano, M.D., Casanueva-Marenco, M.J., Garcia-Vargas, M., Kosore, C.M., 2011. Assessment of the metal pollution, potential toxicity and speciation of sediment from Algeciras Bay (South of Spain) using chemometric tools. J. Hazard. Mater. 190, 177–187. https://doi.org/10.1016/j.jhazmat.2011.03.020.

DIN EN ISO 11885, 2009. Water quality Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES)(ISO 11885: 2007); German version EN ISO, 2009, 11885.

EC, 2011. European Commission), Setting maximum levels for certain contaminants in foodstuffs. Commission Regulation (EC) No. 420/2011. Amending Regulation.

Ekoa Bessa, A.Z., Ngueutchoua, G., Kwewouo Janpou, A., El-Amier, Y.A., Njike Njome Mbella Nguetnga, O.-A., Kankeu Kayou, U.R., Bisse, S.B., Ngo Mapuna, E.C., Armstrong-Altrin, J.S., 2021. Heavy metal contamination and its ecological risks in the beach sediments along the Atlantic Ocean (Limbe coastal fringes, Cameroon). Earth Syst. Environ. 5, 433–444. https://doi.org/10.1007/s41748-020-00167-5.

El-Amier, Y.A., Bonanomi, G., Abd-ElGawad, A.M., 2023. Assessment of heavy metals contamination and ecological risks in coastal sediments of the Mediterranean seashore. Reg. Stud. Mar. Sci. 63, 103017. https://doi.org/10.1016/j.rsma.2023.103017.

El-Sikaily, A., Khaled, A., Nemr, A.El, 2004. Heavy metals monitoring using bivalves from Mediterranean Sea and Red Sea. Environ. Monit. Assess. 98, 41–58. https://doi.org/10.1023/B:EMAS.0000038178.98985.5d.

Gałuszka, A., Migaszewski, Z.M., Zalasiewicz, J., 2014. Assessing the anthropocene with geochemical methods. Geol. Soc. Lond. Spec. Publ. 395, 221–238. https://doi.org/10.1144/SP395.5.

Gümüş, B., Buluş, A., 2020. Uluslararası çevre sorunlar ve William Nordhaus' un çevre ekonomisine katkıları. Alanya Akad. Bak. ış 4, 1015–1031. https://doi.org/10.29023/alanyaakademik.686110.

Harikumar, P.S., Nasir, U.P., 2010. Ecotoxicological impact assessment of heavy metals in core sediments of a tropical estuary. Ecotoxicol. Environ. Saf. 73, 1742–1747. https://doi.org/10.1016/j.ecoenv.2010.08.022.

Islam, M.S., Ahmed, M.K., Raknuzzaman, M., Habibullah-Al-Mamun, M., Islam, M.K., 2015. Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. Ecol. Indic. 48, 282–291. https://doi.org/10.1016/j.ecolind. 2020.106237.

Kam, E., Önce, M., 2016. Pollution potential of heavy metals in the current sea sediments between Bandirma (Balikesir) and Lapseki (Çanakkale) in the Marmara Sea. J. Eng. Technol. Appl. Sci. 1, 141–148. https://doi.org/10.30931/jetas.297619.

Kam, E., Yümün, Z., 2021. Geographical distribution of toxic elements in Northeast Marmara Sea sediments and analysis of toxic element pollution by various pollution index methods (Istanbul/Turkey). Appl. Ecol. Environ. Res. 19, 1869–1893. https://doi.org/10.15666/aeer/1903_18691893.

Khandaker, M.U., Chijioke, N.O., Heffny, N.B., Bradley, D.A., Alsubaie, A., Sulieman, A., Faruque, M.R.I., Sayyed, M.I., Al-Mugren, K.S., 2021. Elevated concentrations of metal (loids) in seaweed and the concomitant exposure to humans. Foods 10, 381. https://doi.org/10.3390/foods10020381.

Koçbaş, F., Çulha, S.T., Gündoğdu, A., Türkçü, N., 2023. Comparison of heavy metal concentrations in marine macroalgae of the Northern Aegean Sea. Türkiye. Eurasia J. Med. Biol. Sci. 3, 23–33.
Kutlu, B., Özcan, T., Özcan, G., 2021. Analysis of heavy metal contamination in surface sediments of Iskenderun Bay, Turkey. Oceanol. Hydrobiol. Stud. 50, 411–420. https://doi.org/10.2478/oandhs-2021-0035.
Lasheen, ElsR., Mansour, A.M., Mohamed, A.W., Osman, M.R., Khaleal, F.M., Tahoon, M. A., Alarifi, N., Jordan, G., Abdelaal, A., 2024. Assessing the heavy metals in surface sediments of Wadi El-Gemal Island, Red Sea, Egypt: Pollution Levels, Sources, and Associated Risks. Water Air \ Soil Pollut. 235, 461. https://doi.org/10.1007/s11270-024-07273-4.
Li, G., Hu, B., Bi, J., Leng, Q., Xiao, C., Yang, Z., 2013. Heavy metals distribution and contamination in surface sediments of the coastal Shandong Peninsula (Yellow Sea). Mar. Pollut. Bull. 76, 420–426. https://doi.org/10.1016/j.marpolbul.2013.08.032.
Lozano Muñoz, I., Diaz, 2020. Minerals in edible seaweed: Health benefits and food safety issues. Crit. Rev. Food Sci. Nutr. 62, 1592–1607. https://doi.org/10.1080/10408398.2020. 1844637.
Manahan, S.E., 2022. Environmental chemistry. CRC press. https://doi.org/10.1201/9781003096238.
Muller, G., 1981. Schwermetallbelstung der sedimente des neckars und seiner nebenflusse: eine estandsaufnahme. Chem. Ztg. 105, 157–164.
Naik, S., Pradhan, U., Karthikeyan, P., Bandyopadhyay, D., Sahoo, R.K., Panda, U.S., Mishra, P., Murthy, M.V.R., 2023. Ecological risk assessment of heavy metals in the coastal sediment in the South-western Bay of Bengal. Front. Mar. Sci. 10, 1255466. https://doi.org/10.3389/fmars.2023.1255466.
Nour, H.E., Alshehri, F., Sahour, H., El-Sorogy, A.S., Tawfik, M., 2022. Assessment of heavy metal contamination and health risk in the coastal sediments of Suez Bay, Gulf of Suez, Egypt. J. Afr. Earth Sci. 195, 104663. https://doi.org/10.1016/j.Jafrearsci.2022.104663.
Orosun, M.M., 2021. Assessment of arsenic and its associated health risks due to mining activities in parts of North-central Nigeria: probabilistic approach using Monte Carlo. J. Hazard. Mater. 412, 125262. https://doi.org/10.1016/j.jhazmat.2021.125262.
Pant, R.R., Zhang, F., Rehman, F.U., Koirala, M., Rijal, K., Maskey, R., 2020. Spatiotemporal characterization of dissolved trace elements in the gandaki river, central himalaya Nepal. J. Hazard Mater. 389, 121913. https://doi.org/10.1016/j.jhazmat.2019.121913.
Pehlivan, H., Akbulut, Aydın, Muratçay, E.V., 2021. Investigation of heavy metal pollution in sediments of southern Marmara Sea (The Kocasu Delta). Gazi Üniversitesi MüHend.. Mimar. Fak. Derg. 36, 1271–1288. https://doi.org/10.17341/gazimmfd.722544.
Peng, Z., Guo, Z., Wang, Z., Zhang, R., Wu, Q., Gao, H., Wang, Y., Shen, Z., Lek, S., Xiao, J., 2022. Species-specific bioaccumulation and health risk assessment of heavy metal in seaweeds in tropic coasts of South China Sea. Sci. Total Environ. 832, 155031. https://doi.org/10.1016/j.scitotenv.2022.155031.
Ramteke, S., Sahu, B.L., Dahariya, N.S., Patel, K.S., Blazhev, B., Matini, L., 2016. Heavy metal contamination of vegetables. J. Environ. Prot. (Irvine. Calif.). 7, 996–1004. https://doi.org/10.4236/jep.2016.77088.
SACS, 2014. Screening and Assessment of Contaminated Sediment. New York State Department of Environmental Conservation, Division of Fish, Wildlife and Marine Resources.Screening and Assessment of Contaminated Sediment. New York State Department of Environmental Conse.
Schintu, M., Marras, B., Maccioni, A., Puddu, D., Meloni, P., Contu, A., 2009. Monitoring of trace metals in coastal sediments from sites around Sardinia, Western Mediterranean. Mar. Pollut. Bull. 58, 1577–1583. https://doi.org/10.1016/j.marpolbul.2009.07.015.
Shams El-Din, N.G., Mohamedein, L.I., El-Moselhy, K.M., 2014. Seaweeds as bioindicators of heavy metals off a hot spot area on the Egyptian Mediterranean Coast during 2008-2010. Environ. Monit. Assess. 186, 5865–5881. https://doi.org/10.1007/s10661-014-3825-3.
Siddique, M.A.M., Hossain, M.S., Chakma, B., Islam, M.M., Hossain, M.M., Shazada, N.E., Walker, T.R., 2023. Metal and metalloid bioaccumulation in dried red seaweed Hypnea musciformis and health risk assessment for consumers. Mar. Pollut. Bull. 194, 115302. https://doi.org/10.1016/j.marpolbul.2023.115302.
Sinaei, M., Loghmani, M., Bolouki, M., 2018. Application of biomarkers in brown algae (Cystoseria indica) to assess heavy metals (Cd, Cu, Zn, Pb, Hg, Ni, Cr) pollution in the northern coasts of the Gulf of Oman. Ecotoxicol. Environ. Saf. 164, 675–680. https://doi.org/10.1016/j.ecoenv.2018.08.074.
Squadrone, S., Brizio, P., Battuello, M., Nurra, N., Sartor, R.M., Riva, A., Staiti, M., Benedetto, A., Pessani, D., Abete, M.C., 2018. Trace metal occurrence in Mediterranean seaweeds. Environ. Sci. Pollut. Res. 25, 9708–9721. https://doi.org/10.1007/s11356-018-1280-3.
Sutherland, B.R., 2000. Internal wave reflection in uniform shear. Q. J. R. Meteorol. Soc. 126, 3255–3286. https://doi.org/10.1002/qj.49712657013.
Tao, C., Peng, T., Feng, C., Chen, N., Hu, Q., Hao, C., 2016. The feasibility of an up-flow partially aerated biological filter (U-PABF) for nitrogen and COD removal from domestic wastewater. Bioresour. Technol. 218, 307–317. https://doi.org/10.1016/j.biortech.2016.06.098.
Taylor, S.R., McLennan, S.M., 1985. The Continental Crust: Its Composition and Evolution. Blackwell Scientific Publications, Oxford.
Tolatlı, C., Ustaoğlu, F., 2021. Meriç Delta Balıklarında Toksik Metal Birikimlerinin Değerlendirmesi: Muhtemel İnsan Sağlığı Riskleri. Acta Aquat. Turc 17, 136–145.
Union, E, 2010. Common Implementation Strategy for the Water Framework Directive (2000/60/EC), Guidance on Chemical Monitoring of Sediment and Biota under the Water Framework Directive.
USEPA, 2007. Concepts, Methods, and Data Sources For Cumulative Health Risk Assessment of Multiple Chemicals, Exposures and Effects: A Resource Document (Final Report, 2008).
USEPA, 2019. U.S. Environmental Protection Agency. Regional Screening Levels (RSLs)–Equations. USEPA.
Varol, M., Tokatlı, C., 2024. Metals and phosphorus in the sediments of streams emptying into the Çanakkale strait (Dardanelles): Spatial distribution, pollution status, risk assessment and source identification. Environ. Res. 252, 118795. https://doi.org/10.1016/j.envres.2024.118795.
Vodopivez, C., Curtosi, A., Villaamil, E., Smichowski, P., Pelletier, E., Mac Cormack, W. P., 2015. Heavy metals in sediments and soft tissues of the Antarctic clam Laternula elliptica: more evidence as a? possible biomonitor of coastal marine pollution at high latitudes? Sci. Total Environ. 502, 375–384. https://doi.org/10.1016/j.scitotenv.2014.09.031.
Wells, M.L., Potin, P., Craigie, J.S., Raven, J.A., Merchant, S.S., Helliwell, K.E., Smith, A. G., Camire, M.E., Brawley, S.H., 2017. Algae as nutritional and functional food sources: revisiting our understanding. J. Appl. Phycol. 29, 949–982. https://doi.org/10.1007/s10811-016-0974-5.
WWOG, 2021. Working Water Quality Guidelines: Aquatic Life, Wildlife Agriculture. B. C. Ministry of Environment and Climate Change Strategy. Water Quality Guideline Series. WQG-08. Prov. B.C, Victoria B.C.
Yenici, E., Turkoglu, M., 2023. Abundance and composition of marine litter on the coasts of the Dardanelles (Canakkale Strait, Turkey). Environ. Monit. Assess. 195, 4. https://doi.org/10.1007/s10661-022-10511-z.
Yılmaz, S., Sadikoglu, M., 2011. Study of heavy metal pollution in seawater of Kepez harbor of Çanakkale (Turkey). Environ. Monit. Assess. 173, 899–904.
Yuan, C., Shi, J., He, B., Liu, J., Liang, L., Jiang, G., 2004. Speciation of heavy metals in marine sediments from the East China Sea by ICP-MS with sequential extraction. Environ. Int. 30, 769–783. https://doi.org/10.1016/j.envint.2004.01.001.
Yümün, Z.Ü., Önce, M., 2017. Monitoring heavy metal pollution in foraminifera from the Gulf of Edremit (northeastern Aegean Sea) between Izmir, Balıkesir and Çanakkale (Turkey). J. Afr. Earth Sci. 130, 110–124. https://doi.org/10.1016/j.jafrearsci.2017.03.015.
Zhang, M., He, P., Qiao, G., Huang, J., Yuan, X., Li, Q., 2019. Heavy metal contamination assessment of surface sediments of the Subei Shoal, China: spatial distribution, source apportionment and ecological risk. Chemosphere 223, 211–222. https://doi.org/10.1016/j.chemosphere.2019.02.058.