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Heavy metal and mineral analysis of cultivated seaweeds from Cox's Bazar Coast, Bay of Bengal, Bangladesh: a human health risk implication

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Abstract
Seaweeds are grown for their use in food and other sectors, however heavy metals (HMs) contamination raises serious issues for the environment and public health. This study focuses on seaweed samples (*Hypnea musciformes* and *Gracilaria lemaneiformis*) collected from the Rezu Khal seaweed culture site, Cox's Bazar coast, Bangladesh. HMs and minerals were determined using Atomic Absorption Spectrophotometry (AAS). Among the elements examined, *H. musciformes* displayed the highest mean concentrations of minerals and HMs, including Magnesium (Mg) (8663.00 ± 2302.06 mg/kg), Copper (Cu) (10.59 ± 1.61 mg/kg), Iron (Fe) (7566.29 ± 2842.47 mg/kg), Manganese (Mn) (9.93 ± 2.88 mg/kg), Zinc (Zn) (29.54 ± 7.51 mg/kg), and Nickel (Ni) (11.77 ± 2.63 mg/kg). Conversely, *G. lemaneiformis* exhibited the highest levels of Calcium (Ca) (798.14 ± 143.40 mg/kg), Lead (Pb) (3.91 ± 1.74 mg/kg), and Chromium (Cr) (0.59 ± 0.30 mg/kg). Specifically, Mg was prominently abundant in *H. musciformes*, while Cawas more prevalent in *G. lemaneiformis*. Both seaweed types contained Pb and Cr. None of the elements was significantly different between the species ($p < 0.05$). The consumers are not exposed to any carcinogenic or non-carcinogenic risks related to these concentrations, according to the evaluation of carcinogenic and non-carcinogenic risks.

Keywords Red seaweeds · Bay of Bengal · Trace elements · Risk assessment · Food security

1 Introduction

Seaweeds are creatures that resemble plants and grow along the shore. They use holdfasts to cling to the sea floor or any other hard substrate [1–4]. Seaweeds also have an ecological role in reducing climate change impacts [5–7]. Since the dawn of human civilization, seaweeds have played a crucial role in the diets of Korea, Japan, China, and some Southeast Asian countries, either directly or through other food groups [8, 9]. Since seaweed has high medicinal and nutritional benefits, they are currently in high demand in the international market. Seaweed contains vitamins, minerals, proteins,

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flavonoids, and soluble fiber, which are considered preventive medicines against diseases caused by a sedentary lifestyle [10]. Recent extensive cohort studies in Japan have shown that seaweed consumption reduces the risk of cardiovascular disease [10]. Therefore, seaweed aquaculture has become one of the blue economic measures around the world, and it is practiced in several countries such as China, Indonesia, Korea, the Philippines, Japan, and Malaysia [11]. Seaweed aquaculture is now a very small business in Bangladesh, mostly restricted to the southeast coastal region, particularly in certain areas of Cox's Bazar [12]. Bangladesh has about 8500 km^2 shallow (< 5 m depth) nearshore and offshore areas where 335 varied species of marine seaweeds occur naturally. Some of these seaweeds are cultured on a small scale due to socio-economic, technological, and environmental constraints [12].

Seaweed is regarded as one of the most significant marine resources for Bangladesh's achievement of its blue economy aim [13, 14]. To advance the industry, the government has added seaweed culture in the 7th Five-Year Plan and has launched seaweed farming initiatives through different organizations [12]. In Bangladesh's coastal and marine habitats, about 32 species of the 335 recorded seaweed species are abundant [12, 15]. Due to their growth ability and accessibility of wild seeds, 14 of these species (10 Rodophyta species and 4 Chlorophyta species) are suitable for cultivation [15]. Many species of the genera *Gracilaria*, *Hypnea*, and *Ulva* can grow in brackish water ecosystems such as the mouth of the Bakhkhali River and the Moheshkhali and Kutubdia canals, although most seaweeds live in marine ecosystems. Species of the genera *Gracilaria*, *Hypnea*, *Kappaphycus*, and *Porphyra*, in particular, have high commercial value because they are used as a source for the production of agar and carrageenan and as vegetables for human consumption [12].

At present days, HMs in aquatic environments has been a global concern [16–18]. Along with this, concerns regarding potential HMs pollution in seaweeds have recently been voiced [19]. The marine ecosystem eventually receives human-caused metals released from mineral extraction, petrochemicals, printing, electronic, and urban waste sources [20–22]. When harmful metals find their way into aquatic environments where seaweed grows, these plants can eventually uptake these metals, which can be transferred to the human body through the food web [23–26]. Certain biologically necessary elements may have harmful effects at higher concentrations, and some metals, like Cd, Hg, and Pb, can be hazardous even in trace amounts [27]. The human body's internal organs and fatty tissues can store HMs, which can have an impact on the central nervous system [28]. Notably, the metalloid element arsenic exhibits a variety of forms and toxicities [29]. Compared to organic arsenic, which is genotoxic, and a recognized human carcinogen particularly linked to skin, lung, bladder, and liver cancer, inorganic arsenic exhibits far greater lethality [30–33]. However, there is a concerning lack of research on the accumulation of minerals and HMs in seaweed along the Bay of Bengal (BoB), Bangladesh. To assess the suitability of seaweeds for consumption or industrial applications, understanding the levels of essential minerals and potentially harmful HMs in seaweed species is necessary. Therefore, the main objective of this study was to conduct an inclusive assessment of the minerals (Ca and Mg) and HMs (Cu, Fe, Mn, Zn, Ni, Pb, and Cr) concentrations within two specific species of red seaweed, *H. musciformes,* and *G. lemaneiformis*. These seaweeds were collected from the Rezu Khal region in the BoB in Bangladesh. The investigation focused on analyzing and quantifying the levels of essential minerals and potentially harmful HMs in these seaweed species. By addressing this objective, the research sought to provide valuable insights into the nutritional composition and potential contaminants in these seaweeds, which are crucial for understanding their ecological role and assessing their suitability for consumption or industrial applications. Additionally, the goal of this investigation was to advance understanding of the health and environmental effects of seaweed use and farming in this area.

2 Materials and methods

2.1 Study area

Rezu Khal on the coast of Cox's Bazar was selected for cultivation after a feasibility analysis (Fig. 1). This culture region was quite close to the coast, where salinity ranges from 23 to 30 ppt.

2.2 Geographical information

Rezu Khal is a topographical feature in the Bangladeshi district of Cox's Bazar. Cox's Bazar is situated in the southeastern part of the country, along the BoB. Rezu Khal is a stream or canal that flows through the region, contributing to the overall landscape and hydrology of Cox's Bazar. The location of the seaweed farm is near the sea. As a result, saline water enters the khal. There are many mangrove trees near the sites. Chemically altered or eutrophic water is frequently discharged

into the Khal from a tilapia farming facility (Niribili Monosex Tilapia Hatchery) to the west. The soil at the breeding site is mainly sandy, while the bank of the Khal is mainly muddy. As a result, there is tremendous sedimentation, and the water is not very transparent. Both at low tide and high tide, the water flows strongly. As a tidal creek, Rezu Khal experiences the ebb and flow of tides, which influences its water levels and flow patterns. During high tide, the water in Rezu Khal rises, while during low tide, the water recedes, exposing the mudflats and revealing the channel's distinct characteristics. It experiences a monsoon climate characterized by heavy rainfall. The region receives substantial precipitation during the monsoon season, typically from June to September. The heavy rains contribute to the overall water volume and flow in Rezu Khal, affecting its depth and velocity. The seasonal changes also influence Rezu Khal. In the dry season, which spans from October to May, the water levels in the creek tend to be lower, and the flow may be reduced. During this time, the stream may have slower currents and narrower channels. On the other hand, Rezu Khal experiences faster flow and higher water levels during the wet season because of increased rainfall.

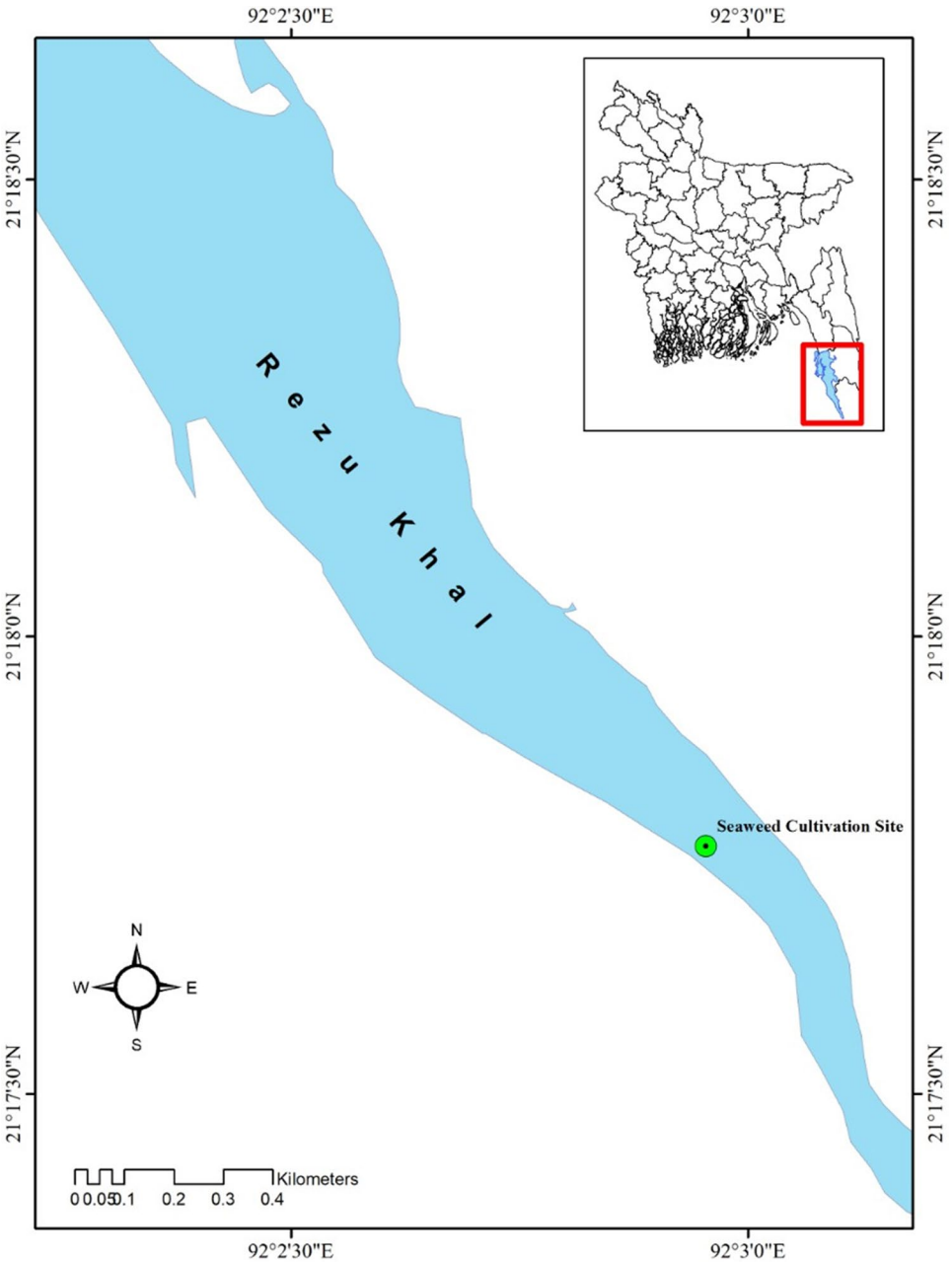


Fig. 1 Map showing the seaweed culture site in Rezu Khal, Cox's Bazar

2.3 Determination of minerals and heavy metals in seaweeds

To prevent contamination, the samples were handled with extreme caution. Glassware was thoroughly cleaned using distilled water and chromic acid. Throughout the investigation, analytical-grade materials and reagents were employed. Instrument measurements were adjusted using reagent blank determinations. Below is a brief description of the methods used for sample preparation, standard preparation, and analysis for the metal analyses.

2.4 Sample collection and preparation

During low tide, seaweeds were collected in December, January, and February 2023–24. The winter season was chosen because there is typically less rainfall, which can help reduce the washout of metals from terrestrial sources into the coastal waters. This can result in lower concentrations of metals in seaweed samples, providing a more precise representation of the metal levels. The collected seaweeds were transported back to the laboratory in insulated containers. Upon arrival, they were thoroughly washed in multiple changes of fresh water and rinsed with distilled water to remove any epiphytes and herbivores. Subsequently, the samples were pre-frozen at − 40 °C and then freeze-dried until the moisture content reached below 10%. Three replicate samples were gathered for the analysis of the two seaweed species from the study area. In cases where there was insufficient material for three analyses during a single collection, the triplicate samples were compiled using material collected on different sampling dates. A total of 14 seaweed samples (7 *H. musciformes* and 7 *G. lemaneiformis*) were collected from the study area.

After that, organic material was likewise destroyed. It was necessary to exercise caution to prevent losses from elemental volatilization. The materials were precisely weighed (10–20 g) and placed in a tared silica dish. After that, the samples were dried in a lab oven at 120 °C. After that, the dishes were put in the muffle furnace at room temperature and gradually heated to 450 °C at a rate that would not go above 50 °C per h. The samples were burned at 450 °C in a muffle furnace for a minimum of 8 h. Trays were taken out of the furnace once the samples had cooled. After that, the sediment samples were cooked on a hot plate in the appropriate volume of 50% nitric acid. After that, the samples were filtered using Whatman No. 44 filter paper into a 100 ml volumetric flask, and the leftover material was cleaned. Distilled water was used to top off each sample solution.

2.5 Standard preparation

The metal standard solutions could degrade over time; thus, each one was produced to calibrate the instrument for each element to be determined on the same day that the analyses were conducted. Distilled water and chemicals of the highest caliber were used to create each sample. One gram each of the metals Cr, Cu, Pb, and Ni was dissolved in HNO_3 solution; 1 g each of Ca, Mg, Fe, Mn, and Zn was dissolved in HCl solution; 2.8289 g of $K_2Cr_2O_7$ (= one gram of Cr) was dissolved in water and filled a volumetric flask to one liter with distilled water to create a stock solution of 1000 mg/l of Cd, Cu, Pb, Ni, Co, Fe, Mn, Zn, Al, and Cr. Next, using micropipettes in 5 ml of 2N HNO_3, 100 ml of the working standards of every metal aside from Fe were created at concentrations of 0.1, 0.25, 0.5, 0.75, 1.0, and 2.0 mg/l. The iron stock solution was used to prepare 100 ml of the working standards for Fe (2.0, 2.5, 5.0, 10.0, and 20.0 mg/l). To prevent reagent contamination, the reagent blank was made in the same manner as the sample preparation without the sample.

2.6 Analytical measurement

Atomic Absorption Spectrophotometry (AAS, iCE 3300, Thermo Scientific, made in China) used standard analytical techniques to quantify the HMs concentrations of the collected seaweeds (Table 1). The manufacturer's recommended operational parameters and matrix modifiers were utilized during the analysis. The analyte's optimal absorption and flame conditions were achieved by setting up the atomic absorption equipment. After that, the AAS flame was aspirated with blanks (deionized water), standards, sample blanks, and samples. Plotting calibration curves for concentration vs absorbance was done. The least squares method was used to fit a straight line to the data to do statistical analysis. In addition, a blank measurement was taken, and any required adjustments were applied when determining each element's concentration. The detection limits (mg/kg), expressed in mg/kg dry weight, were as follows: Pb: 0.008, Cu: 0.2, Zn: 0.002, Mn: 0.011, Ni: 0.004, Cr: 0.072, Ca: 0.1, Mg: 0.01 and Fe: 0.01.

2.7 Assessment of human health risk from seaweed consumption

2.7.1 Estimated daily intake (EDI)

The determination of the EDI is crucial to assess the possible health risks related to the intake of aquatic food products contaminated with metals [31]. In this scenario, the EDI can be evaluated by considering the metal concentrations present in aquatic food items and their regular consumption [34]. The estimation of the EDI can be accomplished by employing the equation provided by the USEPA, as outlined in previous studies [35, 36]. This rigorous approach ensures the calculation is conducted with utmost care and attention, guaranteeing a plagiarism-free analysis.

$$EDI = \frac{CN \times IGr}{BWt}$$

The metal concentration of the metal contents (expressed in mg/kg-dry weight) is denoted as CN, while the ingestion rate is represented by IGr. The FAOSTAT database (2012 period) provides the specific ingestion rates for adults (55.5 g/day) and children (52.5 g/day) [31]. The body weight of the local consumers is indicated as BWt, with adults having a weight of 70 kg and children weighing 15 kg [37].

2.7.2 Non-carcinogenic risk assessment

The Target Hazard Quotient (THQ) estimation is conducted to estimate the probable risks linked with exposure to metal contaminants resulting from consuming contaminated food items [38]. In this context, the THQ can be determined by calculating the ratio between the EDI and the oral reference dose (RfD). The RfDs for specific metal contaminants, namely Cu, Fe, Mn, Zn, Ni, Pb, Cr, and Ca, are 4.0E−02, 7.0E−01, 1.4E−01, 3.0E−01, 1.1E−02, 2.00E−03, 3.0E−03 and 1.0E−03, respectively [37]. RfD of Mg is not available; hence, health risk was assessed excluding Mg concentration. The calculation of the THQ adheres to the equation established by Heshmati et al. [39] and Ahmed et al. [32]:

$$THQ = \frac{EDI \times Ed \times Ep}{At \times RfD} \times 10^{-3}$$

The variable Ed represents the duration of exposure to the metal contents, which is set at 65 years based on the information provided by USEPA [37]. Ep denotes the frequency of exposure, assumed to be 365 days per year, according to Ahmed et al. [40]. The mean time for the non-carcinogenic elements, At, is determined by multiplying Ed by Ep. If At yields value less than 1, it indicates that there are no non-carcinogenic effects on the local consumers, as established by Abtahi et al. [41].

2.7.3 Hazard index (HI) evaluation

The HI assessment is crucial in determining the possible risks connected with humans' consumption of various contaminated food items. It is essential to consider that exposure to multiple contaminants can lead to additive and interactive effects on human health, as Saha et al. [42] highlighted. The HI for these multiple contaminants can be evaluated following the equation provided by Ahmed et al. [31, 32] and Zhao et al. [43].

$$HI = \sum_{i=k}^{n} THQ$$

In this context, THQ represents the risk assessment value associated with the presence of multiple metal contents in the samples. If the THQ value exceeds 1, it indicates the presence of significant non-carcinogenic impacts on human health, as stated by Hossain et al. [44]. These rigorous measurements and references ensure a better understanding of THQ and its implications in evaluating the potential health effects resulting from exposure to multiple metal contaminants [25].

Table 1 Heavy metals and minerals content (mg/kg) of *Hypnea musciformes* and *Gracilaria lemaneiformis* collected from the Rezu Khal seaweed culture site (samples were collected in the winter of December, January, and February)

Sampling date	Species	Ca	Mg	Cu	Fe	Mn	Zn	Ni	Pb	Cr
01.12.2021	*Hypnea musciformes*	870	9800	8.44	6200	14.6	23.1	12.33	2.71	0.4
	Gracilaria lemaneiformis	953	9580	9.66	5940	16.5	34.2	13.35	3.75	0.5
15.12.2021	*Hypnea musciformes*	1000	9721	9.11	6324	11.1	31.0	9.0	2.22	0.01
	Gracilaria lemaneiformis	808	9301	10.0	6100	12.5	28.1	7.23	2.31	0.2
30.12.2021	*Hypnea musciformes*	540	9200	10.89	10,200	6.0	43.1	11.1	4.5	0.4
	Gracilaria lemaneiformis	602	9001	8.79	9800	7.9	32.1	12.3	3.9	0.7
15.01.2022	*Hypnea musciformes*	677	9840	10.81	6840	8.2	22.1	15.75	4.3	0.35
	Gracilaria lemaneiformis	698	8500	9.89	4590	6.0	20.1	12.15	4.65	0.86
30.01.2022	*Hypnea musciformes*	535	3600	10.0	4200	12.0	32.2	8.25	3.21	0.65
	Gracilaria lemaneiformis	1012	5400	9.97	3600	8.0	24.5	11.5	2.31	0.83
15.02.2022	*Hypnea musciformes*	847	8400	13.27	6600	9.6	23.1	13.95	3.45	0.68
	Gracilaria lemaneiformis	786	6362	10.49	3750	7.0	28.9	7.2	3.1	0.87
30.02.2022	*Hypnea musciformes*	901	10,080	11.59	12,600	8.0	32.2	12	4.5	0.34
	Gracilaria lemaneiformis	728	9600	12.22	8490	10.1	37.2	18	7.35	0.18
Average (mean ± SD)	*Hypnea musciformes*	767.14 ± 183.81	8663.00 ± 2302.06	10.59 ± 1.61	7566.29 ± 2842.47	9.93 ± 2.88	29.54 ± 7.51	11.77 ± 2.63	3.56 ± 0.91	0.40 ± 0.22
	Gracilaria lemaneiformis	798.14 ± 143.40	8249.14 ± 1683.72	10.15 ± 1.05	6038.57 ± 2361.28	9.71 ± 3.68	29.30 ± 5.82	11.68 ± 3.72	3.91 ± 1.74	0.59 ± 0.30
Range	*Hypnea musciformes*	535.00–1000.00	3600.00–10080.00	8.44–13.27	4200.00–12600.00	6.00–14.60	22.10–43.10	8.25–15.75	2.22–4.50	0.01–0.68
	Gracilaria lemaneiformis	602.00–1012.00	5400.00–9600.00	8.79–12.22	3600.00–9800.00	6.00–16.50	20.10–37.20	7.20–18.00	2.31–7.35	0.18–0.87

2.8 Statistical analysis

The mean and standard deviation of metal concentrations were calculated, and statistical tests were conducted using SPSS V.22 software. The Kolmogorov–Smirnov and Shapiro–Wilk tests were utilized to assess the normality test of the data [45]. To identify significant variations in the targeted elements among the specimens in the studied area, the ANOVA test was employed for each species with a significance level set at $p < 0.05$ (indicating a 95% confidence level). Additionally, Levene's test was applied to determine the homogeneity of variances for ANOVA tests, with a significance level of $p < 0.05$ [32, 45]. Experimental results were expressed using the mean ± SD of triplicate samples.

3 Results and discussion

In the present study, the concentrations of two minerals and seven HMs were analyzed. The concentrations of available minerals and HMs in *H. musciformes* and *G. lemaneiformis* seaweeds are shown in Table 1, where no noteworthy difference ($p > 0.05$) was found between the two species. The highest mean amount of minerals and HMs, i.e., Mg (8663.00 ± 2302.06 mg/kg), Cu (10.59 ± 1.61 mg/kg), Fe (7566.29 ± 2842.47 mg/kg), Mn (9.93 ± 2.88 mg/kg), Zn (29.54 ± 7.51 mg/kg) and Ni (11.77 ± 2.63 mg/kg) was detected in *H. musciformes*. On the other hand, the highest volume of Ca (798.14 ± 143.40 mg/kg), Pb (3.91 ± 1.74 mg/kg), and Cr (0.59 ± 0.30 mg/kg) was reported in *G. lemaneiformis*. The statistical test revealed that the species' element concentrations significantly differed ($p \leq 0.05$). Moreover, the calculated Kolmogorov–Smirnov and Shapiro–Wilk tests indicated that element concentration was non-normal distributed in the species. Furthermore, the calculated Levene's test determined evidence of significant heterogeneity in variances ($p < 0.05$).

3.1 Minerals

3.1.1 Calcium (Ca)

Calcium (Ca) is an essential mineral that is naturally present in seaweed and offers numerous health benefits to humans. Seaweed consumption can provide a valuable source of dietary Ca, which plays a crucial role in maintaining strong bones and teeth, promoting proper muscle function, and aiding in nerve transmission. Ca is linked to healthy bones and teeth, but it is also essential for blood coagulation, contraction of muscles, brain activity regulation, and normal heartbeat. The bones contain 99% of the Ca that the human body has; the remaining 1% is found in the blood, muscles, and other tissues. Adequate Ca intake from seaweed can help prevent osteoporosis and contribute to overall bone health. However, it is important to note that excessive intake of Ca can lead to toxicity and adverse health effects. When Ca levels exceed the recommended limits, it can cause constipation, and kidney stones, and interfere with the absorption of other minerals, such as Fe and Zn. In this study, the highest mean Ca amount was recorded in *G. lemaneiformis* (798.14 ± 143.40 mg/kg) and the lowermost in *H. musciformes* (767.14 ± 183.81 mg/kg) (Table 1). Siddique et al. [8] studied seaweeds at Saint Martin's Island (SMI) in the BoB, Bangladesh, and found 496.26 ± 2.45 mg/kg and 484.18 ± 4.68 mg/kg Ca in *H. pannosa* and *H. musciformis*, respectively (Table 2).

3.1.2 Magnesium (Mg)

Magnesium (Mg) is an essential mineral found in seaweed that offers numerous health benefits to humans. Seaweed consumption can provide a valuable source of dietary Mg, which is involved in various physiological processes. Mg plays a vital role in maintaining proper nerve and muscle function, regulating blood pressure, supporting a healthy immune system, and promoting bone health. Adequate Mg intake from seaweed can also help alleviate symptoms of migraines, reduce the risk of cardiovascular diseases, and improve mood and mental well-being. Moreover, Mg aids in the creation of energy and other essential bodily processes, including the health of muscles and neurons. However, it is important to note that excessive intake of Mg can lead to toxicity and adverse health effects. When Mg levels exceed the recommended limits, it can cause gastrointestinal issues, diarrhea, and interfere with the absorption of other minerals, such as calcium and zinc. As shown in the data, Mg is the most abundant element in both seaweeds and the amounts

Table 2 Comparison of minerals and heavy metals of *Hypnea musciformes* and *Gracilaria lemaneiformis* with other national and international studies (mean value or range) (Unit: mg/kg)

Species	Ca	Mg	Cu	Fe	Mn	Zn	Ni	Pb	Cr	Regions	References
Hypnea musciformes	767.14 ± 183.81	8663.00 ± 2302.06	10.59 ± 1.61	7566.29 ± 2842.47	9.93 ± 2.88	29.54 ± 7.51	11.77 ± 2.63	3.56 ± 0.91	0.40 ± 0.22	Rezu Khal, Bangladesh	Present study
Gracilaria lemaneiformis	798.14 ± 143.40	8249.14 ± 1683.72	10.15 ± 1.05	6038.57 ± 2361.28	9.71 ± 3.68	29.30 ± 5.82	11.68 ± 3.72	3.91 ± 1.74	0.59 ± 0.30	Rezu Khal, Bangladesh	Present study
Gracilaria sp.			4.13–5.78		119.10–82.35	4.80–7.50	4.05–8.10	1.05–1.20	12.0	Sudanese coast of the Red Sea	[22]
Hypnea sp.			4.13–10.80		88.20–191.18	7.43–14.18	5.40–8.10	1.10–2.33	10.95–13.95	Sudanese coast of the Red Sea	[22]
Gracilaria sp.			3.29		163.3	94.73	2.19	5.13	2.77	Gulf of Thessaloniki, Aegean	[48]
Hypnea sp.			7.22		61.78	95.10	7.88	4.07	8.88	Gulf of Thessaloniki, Aegean	[48]
Gracilaria edulis			2.84			4.32		5.31		Gulf of Mannar, India	[55]
Gracilaria folifera			4.07			6.74		8.02		Gulf of Mannar, India	[55]
Hypnea musciformes			2.95			8.04		8.91		Gulf of Mannar, India	[55]
Hypnea musciformes			1.99			14.32		4.05		Abu Qir Bay, Egypt	[56]
Hypnea pannosa	496.26 ± 2.45	3278.12 ± 28.04	5.58 ± 0.04	621.66 ± 3.52	116.72 ± 0.60	7.55 ± 0.07	6.23 ± 0.09	2.68 ± 0.02	7.77 ± 0.08	Saint Martin's Island, Bay of Bengal, Bangladesh	[8]
Hypnea musciformis	484.18 ± 4.68	2112.70 ± 17.80	7.06 ± 0.01	659.32 ± 11.17	75.96 ± 0.26	16.60 ± 0.28	6.13 ± 0.11	2.97 ± 0.06	8.66 ± 0.05	Saint Martin's Island, Bay of Bengal, Bangladesh	[8]

ranged from 3600.00–10080.00 mg/kg and 5400.00–9600.00 mg/kg in *H. musciformes* and *G. lemaneiformis*, respectively (Table 1). Siddique et al. [8] found 3278.12 ± 28.04 mg/kg and 2112.70 ± 17.80 mg/kg Mg in *H. pannosa* and *H. musciformis*, respectively (Table 2).

3.2 Heavy metals

The mean values of the seven HMs amount for two algal species, namely *H. musciformes* and *G. lemaneiformis*, followed the same order Fe > Zn > Ni > Cu > Mn > Pb > Cr, and no substantial variation ($p > 0.05$) was detected between the two species. In contrast to *G. lemaneiformis*, significantly higher amounts of all HMs studied were found in *H. musciformes*, which can be seen in Table 1.

3.2.1 Copper (Cu)

The biochemistry of all living things requires the trace element Cu, which is essential for life [46]. Cu is a vital element as it plays a crucial role in the synthesis of hemoglobin and is present in several enzymes. Nonetheless, it is worth mentioning that excessive levels of copper can result in acute toxicity. However, in Bangladesh, there is no adopted legislation specifying the highest permissible amount of HMs in various edible seaweeds. The Australian and New Zealand Food Authority (2005) recommended a Cu content of 10 ppm in 240 fresh seaweeds as the maximum allowable limit [47]. The highest mean Cu concentration was found in *H. musciformes* (10.59 ± 1.61 mg/kg) and the lowermost in *G. lemaneiformis* (10.15 ± 1.05 mg/kg) (Table 1). Malea and Kevrekidis [48] recorded 3.29 mg/kg Cu in *Gracilaria* and 7.22 mg/kg in *Hypnea* from the Gulf of Thessaloniki, Aegean. Ali et al. [21] recorded a lower amount of Cu in *Gracilaria* and *Hypnea* from the Sudanese coast of the Red Sea (Table 2). Here, both seaweeds exceeded the permissible limits (10 mg/kg) for Cu concentrations in plant tissue [49].

3.2.2 *Iron* (Fe)

Iron (Fe) deficiency is a global problem, although it is one of the most abundant HMs in the Earth's crust [50]. Fe is an essential mineral that is found naturally in seaweed and offers numerous health benefits to humans. Seaweed, being a rich source of Fe, can contribute to maintaining healthy blood and preventing Fe deficiency anemia. Fe is a key component of hemoglobin, the protein responsible for transporting oxygen throughout the body. Consuming seaweed can help increase Fe levels, supporting optimal oxygen delivery, energy production, and overall cellular function. Furthermore, Fe plays a vital role in immune function, cognitive development, and maintaining healthy skin, hair, and nails. As shown in Table 1, Fe was the most abundant HM in the two red seaweeds studied (7566.29 ± 2842.47 mg/kg and 6038.57 ± 2361.28 mg/kg in *H. musciformes* and *G. lemaneiformis*, respectively). Red seaweeds are reported to contain more Fe than brown and green seaweeds [51]. Siddique et al. [8] recorded 621.66 mg/kg and 659.32 mg/kg Fe in *H. pannosa* and *H. musciformis* (Table 2).

3.2.3 Manganese (Mn)

Manganese (Mn) is a trace mineral that is naturally present in seaweed and offers several health benefits to humans. Seaweed consumption can provide a dietary source of Mn, which plays a crucial role in various enzymatic reactions and the production of antioxidant enzymes. Mn is involved in bone development, wound healing, and the metabolism of carbohydrates, proteins, and cholesterol. However, it is important to be aware that excessive intake of Mn can be toxic to human health. When Mn levels exceed the recommended limits, it can accumulate in the body and lead to neurological issues, such as Parkinson's-like symptoms, cognitive impairment, and behavioral changes. It is therefore essential to maintain a balanced intake of Mn from seaweed and other dietary sources, ensuring it remains within safe levels to prevent any potential toxicity. A high requirement for Mn was found in every species studied [52]. *H. musciformes* and *G. lemaneiformis* contained 9.93 ± 2.88 and 9.71 ± 3.68 mg/kg Mn, respectively. Siddique et al. [8] found a much higher Mn concentration in seaweeds at SMI in the BoB, Bangladesh. Malea and Kevrekidis [48] recorded 163.3 mg/kg in *Gracilaria* sp. and 61.78 mg/kg of *Hypnea* sp. from the Gulf of Thessaloniki, Aegean (Table 2).

3.2.4 Zinc (Zn)

Zinc (Zn) is a naturally produced HM that is found in all plants and animals. Zn is an essential mineral found in seaweed that offers numerous health benefits to humans. Seaweed consumption can provide a valuable source of Zn, which plays a vital role in various physiological processes, including immune function, wound healing, and DNA synthesis. It is supportive of normal development in humans, particularly in the early stages of life [53, 54]. Zn also maintains healthy skin, promotes proper growth and development, and supports reproductive health. However, maintaining an appropriate Zn intake balance is crucial, as excessive levels can lead to toxicity. When Zn levels exceed the recommended limits, it can interfere with the absorption of other essential minerals, such as Cu and Fe, and cause adverse effects on human health. Zn levels in fresh 264 seaweed should not exceed 14 ppm, according to the Australian and New Zealand Food Authority (2005). In the present study, the mean Zn concentrations in *H. musciformes* and *G. lemaneiformis* were 29.54 ± 7.51 and 29.30 ± 5.82 mg/kg, respectively. The recorded amount is higher than the amount recorded by Anbazhagan et al. [55], Abdallah [56], and Siddique et al. [8] (Table 2).

3.2.5 Nickel (Ni)

Nickel (Ni) is a trace element found in seaweed and has potential health benefits and toxicity concerns for humans. Seaweed consumption can provide a source of Ni, which is involved in various metabolic processes and enzyme functions. Ni is essential in the body for proper cell growth, immune function, and DNA repair. However, it is important to note that excessive intake of Ni can lead to toxicity and adverse health effects. When Ni levels exceed the recommended limits, it can cause some individuals allergic reactions, skin irritation, and respiratory issues. Long-term exposure to high levels of Ni has also been associated with an increased risk of certain cancers. In general, Ni can potentially affect the general population by ingesting contaminated food and water [57]. The mean Ni concentrations in *H. musciformes* and *G. lemaneiformis* were 11.77 ± 2.63 and 11.68 ± 3.72 mg/kg, respectively. The present study shows that Ni concentration in seaweeds in Rezu Khal is higher than in seaweeds from SMI, the Gulf of Thessaloniki, and the Sudanese Red Sea coast [8, 22, 48] (Table 2).

3.2.6 Lead (Pb)

Lead (Pb) is a HM that can be found in seaweed and poses significant health risks to humans. While seaweed is beneficial in many ways, it is important to note that Pb can accumulate in seaweed through environmental contamination. Consumption of seaweed contaminated with Pb can lead to severe health issues. Excessive intake of Pb can cause neurological problems, developmental delays in children, impaired cognitive function, and damage to vital organs like the kidneys and liver [58, 59]. Furthermore, Pb exposure has been linked to an increased risk of hypertension, cardiovascular disease, and reproductive disorders. It is crucial to ensure that seaweed and all food sources are regularly tested for lead contamination to protect human health and prevent any potential toxicity. Pb is a typical HM that poses a major risk to human health, especially in developing countries [60]. However, there is no information on regulatory restrictions on the amount of Pb in edible seaweeds [61]. The European Commission (EC, 2011) has recommended a Pb level of 3 ppm, and the maximum level recommended by France for seaweed is also 5 mg/kg dry weight [62]. Human body systems and organs are affected by Pb poisoning [63, 64]. Pb exposure, even at modest doses (3.0 g/kg/day), can negatively affect a person's IQ, learning ability, and attention span [63, 64]. Seaweed intake is generally thought to pose a low risk of Pb exposure to humans [65]. In the present study, Pb concentrations in the seaweed ranged from 2.22 mg/kg to 7.35 mg/kg (Table 1). The average concentration of Pb in *H. musciformes* is 3.56 mg/kg, while in *G. lemaneiformis* the concentration was recorded 3.91 mg/kg (Table 2).

3.2.7 Chromium (Cr)

Chromium (Cr) can occur in a variation of oxidation states from 0 to 6+. Trivalent Cr (III) is much less soluble in plants than hexavalent Cr (VI). Chromium poisoning in humans is mainly caused by ingestion of Cr (VI) in the gastrointestinal tract and lungs [66] and, to a lesser extent, through intact skin [67]. Notably, several biotoxic effects, including on the liver, kidneys, and hematologic system, may be caused by high exposure to Cr (VI) [64, 68]. Prolonged exposure to high levels of chromium has also been associated with an increased risk of certain cancers [25, 45]. To ensure overall well-being, it is crucial to maintain a balanced intake of chromium from seaweed and other dietary sources, avoiding excessive

consumption to prevent potential toxicity and adverse health outcomes. The higher mean Cr concentration was found in *G. lemaneiformis* (0.59 ± 0.30 mg/kg) than in *H. musciformes* (0.40 ± 0.22 mg/kg). The present study shows a lower concentration of Cr than Siddique et al. [8], Ali et al. [22], and Malea and Kevrekidis [48] (Table 2).

3.3 Estimated daily intake (EDI)

The calculation of the EDI was conducted to assess both the significant non-carcinogenic risk effect and the carcinogenic health impact associated with the consumption of contaminated aquatic foods, as outlined by Liu et al. [69]. The EDI calculation follows the guidelines of the oral reference dose (Rfd) specific to each metal content, which determines the threshold for toxic metal element response and ensures the protection of public health, according to Baki et al. [70]. Table 3 presents the EDIs for adults and children, corresponding to the consumption of the investigated species. The observed EDIs followed the descending order: Fe > Ca > Zn > Cu > Mn > Ni > Pb > Cr and were compared against the Recommended Daily Allowance (RDA) proposed by WHO [71]. When the EDIs were lesser than the respective RDA for specific metal elements, it indicated a negligible threat to human health through ingestion, as indicated by Ahmed et al. [31]. However, it is important to note that considering it solely as an "acceptable range" or "unacceptable range" based on being lower than the RDA/RfD would not be wise, as cautioned by Baki et al. [70].

3.4 Non-carcinogenic risk assessment

The results of the calculated THQ for the consumption of the investigated fish species have been depicted in Table 3. The THQ values for both adults and children were observed in the following descending order: Fe > Pb > Ni > Cu > Zn > Mn > Ca > Cr. In adults, the range of THQ values ranged from 1.57E−06 to 8.49E−03, while in children, it ranged from 3.50E−05 to 3.78E−02. On average, children had nearly four times higher THQ values compared to adults. However, all THQ values were lower than the threshold limit of 1. THQ values below 1 indicate that the exposure levels are also below the reference limit. Therefore, the lifetime consumption of such fish species would not harm human health, as stated by Yi et al. [72]. Nevertheless, assessing the HI is essential as it indicates the alarming condition of the non-carcinogenic effects on public health, as suggested by Liu et al. [69].

The estimated HI, representing the total THQ, was 1.93E−02 for adults and 8.61E−02 for children. The HI values were also below 1, indicating that the local consumers were protected from non-carcinogenic impacts. These findings align with a study by Khalil et al. [73] where THQ and HI values were within safe conditions, below 1. However, it is essential to note that while THQ and HI are useful tools for risk assessment, they do not directly measure the actual combined

Table 3 EDI, THQ, HI, and CR for the investigated minerals and metals from the species

		EDI		THQ		HI		CR	
Elements	Species	Adult	Children	Adult	Children	Adult	Children	Adult	Children
Pb	HM	2.80E−03	1.25E−02	7.99E−04	3.56E−03			2.38E−08	1.06E−07
	GL	3.07E−03	3.55E−02	8.78E−04	3.91E−03			2.61E−08	1.16E−07
Cu	HM	8.32E−03	3.71E−02	2.08E−04	9.27E−04				
	GL	7.98E−03	3.55E−02	1.99E−04	8.88E−04				
Ca	HM	6.03E−01	2.68E+00	1.23E−05	5.48E−05				
	GL	7.98E−03	2.79E+00	1.28E−05	5.70E−05				
Cr	HM	3.14E−04	1.40E−03	1.57E−06	3.50E−05	1.93E−02	8.61E−02		
	GL	4.64E−04	2.07E−03	2.32E−06	5.16E−05				
Zn	HM	2.32E−02	1.03E−01	7.74E−05	3.45E−04				
	GL	2.30E−02	1.03E−01	7.67E−05	3.42E−04				
Ni	HM	9.25E−03	4.12E−02	8.41E−04	3.75E−03				
	GL	9.18E−03	4.09E−02	8.34E−04	3.72E−03				
Fe	HM	5.94E+00	2.65E+01	8.49E−03	3.78E−02				
	GL	4.74E+00	2.11E+01	6.78E−03	3.02E−02				
Mn	HM	7.80E−03	3.48E−02	5.57E−05	2.48E−04				
	GL	7.63E−03	3.40E−02	5.45E−05	2.43E−04				

impacts of multiple contaminants on human health, as cautioned by Li et al. [74]. Our result was in line with the findings from Chen et al. where local people are risk-free for some metal contents (Al, Mn, As, Ni, Cr, Cu, Hg, Cd, Pb, and Se) due to seaweed consumption. Similar findings were reported by Roleda et al. [75].

3.5 Carcinogenic risk (CR) assessment

Carcinogenic Risk (CR) was evaluated specifically for Pb only, as the oral carcinogenic slope factor is available for Pb among the other investigated substances. The range of CR values in adults ranged from 2.38E−08 to 2.61E−08, while in children, it ranged from 1.06E−07 to 1.16E−07, as shown in Table 3. Among all the species, *Gracilaria lemaneiformis* exhibited the highest CR value in the children group, indicating that children are relatively more susceptible to carcinogenic risk effects, particularly from the consumption of this species. However, the cumulative CR values did not exceed the threshold range of 10^{-6} to 10^{-4}. Therefore, our CR findings do not generate any significant carcinogenic risk to the local consumers. These findings are consistent with the findings of Arisekar et al. [76] and Ali et al. [22], who stated that their CR values were within an acceptable range near the Thamirabarani River and Sudanese Red Sea Coast, respectively. In another study, Peng et al. [23] reported that As and Cr in carcinogenic risk assessment exceeded the acceptable levels. These elements were identified as the limiting factors, meaning they could pose the most significant risk regarding potential carcinogenic effects associated with consuming seaweeds. It is important to note that spontaneous climate change, rapid industrialization, and economic activities can increase the amount of metal content in the study area, posing a potential threat to carcinogenic risk issues.

The results of this study have significant ramifications for Bangladesh's and other countries' control of seaweed consumption and cultivation. The presence of HMs in seaweed samples highlights the need for regular monitoring and assessment of seaweed farming sites to ensure that they are not contaminated with harmful substances. During farming, measures should be implemented to prevent the accumulation of HMs in seaweed tissues. This may involve monitoring water quality, site selection, and implementing sustainable farming practices to reduce the risk of HM contamination. Additionally, there is a need for further research on the sources of HM contamination in seaweed culture sites to mitigate the risks associated with HM exposure effectively. Regulatory agencies should implement measures to ensure that seaweed products meet safety standards and are free from harmful contaminants. Studies focusing on the bioaccumulation and transfer of HMs from seaweeds to higher trophic levels could provide valuable insights into the environmental implications of HM contamination in seaweed farms. Additionally, research on the potential health effects of consuming seaweed products with varying levels of HM contamination could help to develop guidelines for safe consumption. Stakeholders may contribute to the seaweed industry's sustainable growth while preserving consumer and environmental safety by addressing these issues.

4 Conclusion

Seaweeds have a long history of being used for a wide range of purposes, including the manufacture of agar, alginates, carrageenan, and furcellaran as well as soil manure and energy production in agriculture. Furthermore, they serve as key ingredients in beauty products and medicines. Seaweeds have a long-standing tradition of being harnessed for their multitude of benefits. With their high demand on the global market, many countries are now actively engaged in seaweed cultivation. In Bangladesh, extensive research is ongoing to establish successful seaweed cultivation practices.

The specific focus of this research was the cultivation of *H. musciformes* and *G. lemaneiformis* in the Rezu Khal region. The aim was to evaluate their growth rates and the potential for cultivation in this area. Analysis revealed the presence of various minerals such as Ca, Mg, and Fe within these seaweed species. Notably, certain HMs were also detected in the cultivated seaweed samples. The estimated THQ and CR revealed that the study area was free from non-carcinogenic and carcinogenic risks due to the consumption of aquatic food items.

The findings underscore the importance of understanding the impact of pollution and the seaweed's capacity to absorb HMs, both in natural and cultivated settings. This understanding is essential to guarantee the goods' quality and safety as well as to handle any possible environmental effects, particularly as seaweed farming grows.

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Data availability All data supporting the findings of this study are available within the paper.

Declarations

Ethics approval and consent to participate We do not need any ethical permission for this study. All authors approved the final manuscript and agreed to participate.

Consent for publications All authors approved the final manuscript and the submission to this journal.

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