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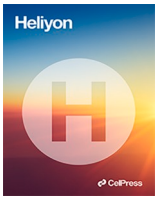

Research article

Nutritional composition and phenolic contents of *Gracilariopsis longissima*, *Padina tetrastromatica* and *Ulva intestinalis* from the Bay of Bengal, Bangladesh coast

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ABSTRACT

Seaweeds have become the focus of experts in recent years due to their biological characteristics and the variety of uses they have for both humans and animals. Biochemical composition, amino acids, fatty acids, and phenolic components were analyzed to explore the nutritive value of *Gracilariopsis longissima*, *Padina tetrastromatica*, and *Ulva intestinalis* from the Bay of Bengal, Bangladesh coast. Proximate composition and mineral content were determined according to the AOAC method. The high-performance liquid chromatography amino acid analysis system was used for the amino acid analysis and the fatty acid profile of the extracted oils was assessed as their methyl esters. The Folin–Ciocalteu technique was used to estimate the phenolic content and the aluminum chloride colorimetric technique was used to calculate the total flavonoid content. The three different species of seaweed had significantly different proximate compositions ($P < 0.05$), with *G. longissima* having the highest protein content. Except for sulfur, the mineral contents were likewise considerably higher ($P < 0.05$) in *G. longissima*. Although the amounts of the essential amino acids were greater than 50 % of the total amino acids in the three studied seaweed species, the total amino acid composition of these three species differed significantly ($P < 0.05$). The findings indicated that lipid levels were low in all the assessed species, but unsaturated fatty acid levels were high, with *G. longissima* exhibiting the highest amounts. The results showed that, compared to the other species, *G. longissima* had a substantially higher ($P < 0.05$) level of total phenolic and flavonoid content. The three studied seaweed appear to be excellent for nutrition based on their overall nutritional profiles. However, due to high protein, unsaturated fatty acid, essential amino acid, and total phenolic and flavonoid content, *G. longissima* is the most promising seaweed that will be helpful for pharmaceutical and multifunctional food applications.

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1. Introduction

Marine algae, commonly referred as seaweed, is one of the marine environment's most valuable living renewable resources. According to Lozano and Díaz [1], there are over 6000 different types of seaweed that may be found in marine environments. They are divided into three groups: Rhodophyta (red seaweed), Phaeophyta (brown seaweed), and Chlorophyta (green seaweed) based on their color, nutritional content, and chemical constituents [2]. Over 36.23 million tonnes of seaweed were produced worldwide in 2020 [3]. Seaweed is an intriguing food item used by people for many years and is relatively healthy. This varied collection of marine-adapted algae thrives and provides a variety of nutritional advantages [4]. From macronutrients to micronutrients and antioxidants, seaweed packs a powerful punch when it comes to nourishment. In addition, vegetarian dishes have become more popular among consumers in recent years. Algae may provide a beneficial alternate supply of important macro and micronutrients in this situation [5]. In fact, seaweed has been suggested as a replacement element for the creation of dietary supplements that may address a variety of dietary requirements. As a result, for future generations, seaweed is regarded as one of the most valuable resources [6,7].

According to several research [4,8], macroalgae have an intriguing nutritional and chemical constitution and are becoming more popular as meals rich in protein for human and animal consumption. According to several studies, seaweeds have a large number of proteins, minerals, vitamins, phenolic substances, polyunsaturated fats, essential amino acids, and other important compounds while having low levels of saturated fat [9–11]. Two crucial aspects of nutrition are protein and its amino acid composition. Seaweeds are reported to contain about 3–47 % protein in its dry mass [12]. Amino acids, apart from being the fundamental components of proteins and essential nutrients for human and animal growth and well-being, also hold significant regulatory roles within cells [13]. Wu [13] explains that amino acids are known to govern crucial metabolic pathways necessary for functions such as maintenance, immunity, reproduction, and development. According to conventional descriptions, seaweeds have relatively low amounts of lipids, typically between 1 and 4 percent of dry weight-but are high in unsaturated fatty acids, particularly polyunsaturated fatty acids (PUFA) [14]. When compared to other terrestrial plants, seaweeds often have a substantially greater amount of minerals due to their higher mineral content [1]. According to Tanna et al. [15], algae are also a rich source of polyphenols, which act as natural antioxidants and enable seaweed to thrive in challenging marine environments. Anticancer, anti-inflammatory, antiviral, anti-ulcer, antiallergic, and anti-hyperlipidase actions as well as their capacity to reduce cardiovascular mortality have been investigated for seaweed antioxidants [16]. Natural antioxidants derived from seaweed are highly valued due to their positive impact on health and lack of adverse effects [6]. The production of functional polymers for food, medicine, producing goods, cosmetics, fertilizer, and other applications is beginning to emerge. Seaweeds are currently harvested or grown on a commercial basis for direct consumption [17].

Seaweeds have a wide range of chemical compositions [18]. Divergence in the chemical components of algae may be related to species, geographic location, developmental stages, season, conditions in the environment, and processing techniques. Therefore, it is necessary to know the chemical constituents of the same species in various habitats. There are numerous research reporting the chemical or bioactive contents of different seaweed species all over the world, however, there are few studies on the Bangladeshi coast of the Bay of Bengal. As a result, this study evaluates the nutritional value of three notable seaweed species, including *Gracilariopsis longissima*, *Padina tetrastromatica*, and *Ulva intestinalis*, which are widely found along the Bay of Bengal, Bangladesh coast and the findings highlight seaweed's potential as pharmaceutical and multifunctional food applications.

2. Materials and methods

2.1. Raw materials and reagents

Seaweeds samples of *Gracilariopsis longissima* (red seaweed) and *Ulva intestinalis* (green seaweed) were collected in January 2023 from the Nuniachara coast (91°57′52.0″ E and 21°28′28.9″ N) however, *Padina tetrastromatica* (brown seaweed) was collected in February 2023 from the Saint Martin Island (92°31′62.5″ E and 20°63′13.4″ N) in Cox's Bazar, Bangladesh during low tide. The choice of collection method did not consider the size and age of the algae. Following collection, seaweed samples were rinsed with saltwater on-site before being transported to the BFRI, Riverine Sub-Station laboratory in sealed bags. Upon its arrival at the laboratory, the seaweed underwent an additional cleaning process using distilled water to remove sand, epiphytes, and other surface contaminants. Voucher specimens for *G. longissima* (GL-01), *U. intestinalis* (UI-01), and *P. tetrastromatica* (PT-01) were securely stored at BFRI, Patuakhali. All the chemical reagents used were of analytical grade.

2.2. Sample preparation

Seaweed samples were subjected to drying using a freeze dryer (Model: YJ-10A, Labocon, UK) for 48 h at −80 °C. Drying was considered complete when a consistent dry weight was achieved after a sufficient drying duration. To create a uniform powder, the dried samples were finely pulverized with a blender and sifted through a 500 μm sieve. The resulting seaweed powder was stored in glass containers at 4 °C in airtight plastic bags until it was ready for analysis.

2.3. Proximal analysis

The moisture and ash contents were determined gravimetrically following standardized procedures established by the Association of Official Analytical Chemists [19]. The protein content was estimated using the Kjeltec 2300 (N × 6.25) method, also in accordance

with AOAC [19] guidelines. To assess the lipid content of the seaweed, a Soxhlet extraction was performed. Ten (10) g of powdered seaweed sample was mixed with 150 mL n-hexane and petroleum benzine solvents at 90:60 ratio. The powdered 10 g extract was kept in the extraction thimble for 8 h and weighed again. The difference in the weight represented crude lipid content. The carbohydrate content was calculated by difference, as outlined by James [20]. This means determining the amount of carbohydrates after proximate measuring all other components. Each measurement was conducted in triplicate.

2.4. Mineral content

Exactly 0.1 g of dry sample was weighed into a glass tube, and 10 mL of nitric acid (HNO_3) was added. The mixture was allowed to stand for a few hours until the content became colorless. The digested material was then filtered through Whatman (No. 40) filter paper. The collected 2 mL filtrate was serially diluted with deionized distilled water to reach 5 mL and the minerals were detected by spectrophotometer. Sodium (Na) and potassium (K) levels were measured using a flame emission spectrophotometer (Spectrolab, UK) at 589.6 nm and 766.5 nm, respectively equipped with suitable filters. Calcium (Ca) and magnesium (Mg) were assessed using an atomic absorption spectrophotometer (Model Varian, AAS Spectra 55B, Australia) at 422.7 nm and 285.2 nm, respectively. Phosphorus (P) and sulfur (S) levels were determined with a double-beam UV-VIS spectrophotometer at 213.6 nm and 180.7 nm, respectively following the appropriate color development method as per AOAC [19] guidelines. Each analysis batch included the necessary metal standards, a blank sample, triplicate measurements, and continuous calibration verification, all following AOAC [19] procedures. The spectrometer was first calibrated, the calibration curves examined, and the correlation coefficient exceeding 0.995 was confirmed. To rectify the instrument reading, the reagent blank solution was examined. To verify the consistency of the instrument, an internal solution for quality control made from stock solutions at known concentrations was injected at the start, midpoint, and end of the study.

2.5. Amino acids profile

A high-performance liquid chromatography (HPLC) system for amino acid analysis, specifically the Shimadzu system from Japan as described in Anonymous [21], was employed. The dry seaweed sample (30 mg) was weighed into a glass tube, and 2 mL of 6 M HCl was added. Hydrolysis was carried out at 110 °C for 24 h. Each hydrolyzed extract was passed through a filter paper and then 10 mL of internal standard and 2.5 mM L-2-amino-*n*-butyric acid were added. This solution was diluted with Milli-Q water to 250 mL. An aliquot was filtered with a 0.45 μm filter. The amino acids were subjected to HPLC analysis after derivatization with 6-aminoquinolyl-nhydroxysuccinimidyl carbamate. Then, 10 μL of filtered hydrolyzed sample or standard (amino acid hydrolyzed standard), 70 μL of 200 mM borate buffer, and 20 μL of reconstituted AccQ-Fluor reagent were added into the vial followed by mixing with a vortex for several seconds. Finally, the vial was heated in a heating block at 55 °C for 10 min. Ten microliters of sample or standard solution were injected into the HPLC system. The system utilized a column filled with highly acidic cation exchange resin for amino acid separation. A binary gradient elution technique was applied to inject and separate the amino acids, followed by individual identification through a fluorescence detector. Detection was carried out using post-column derivatization at high sensitivity and under a pressure of 120 kg/cm^2. Each sample was analyzed in triplicate.

2.6. Fatty acids profile

The fatty acid profile of the extracted oils was analyzed as their methyl esters with a slight modification of the method used by Akabr et al. [22]. The oil was extracted using a soxhlet apparatus by taking 500 g of the powdered sample into a thimble with 250 cm^3 of n-hexane at 60 °C for about 8 h. The oil was recovered by evaporating off the solvent using a rotary evaporator at 40 °C and oven-dried at 75 °C for 1 h. The oil was placed in a desiccator and allowed to cool before storing in a refrigerator at 5 °C. The oil samples (20 mg) were mixed with 20 mL of methanol and acetyl chloride (20:1, v/v) solution, and to this 20 mL hexane was added. The mixture was heated at 100 °C for 30 min under continuous stirring. After cooling to room temperature, 20 mL of water was added, and using a separating funnel, the fatty acid methyl esters were extracted in the hexanoic layer. Three more extractions with hexane were made to ensure the complete removal of methyl esters. The clear supernatant (2 ml) was transferred to an autosampler vial and injected (1 μL) with auto-injector into gas chromatography (GC) for analysis. The determination of FAMEs was carried out by measuring their retention times in comparison to various standards and specific calibration curves. Using a Shimadzu GC-14B (Japan) series gas chromatograph equipped with a flame ionization detector and fused silica capillary column (FAMEWAX, Crossbond® polyethylene glycol, 15 m × 0.25 mm × 0.25 μm film thickness, Restek; Pennsylvania, USA), the fatty acid content of the seaweed was assessed. In a splitless injection system, nitrogen was employed as the carrier gas, with a constant flow rate of 20 ml/min. Initially, the set oven temperature was 150 °C for 5 min, and the injector temperature was 250 °C. After increasing the temperature by 8 °C per minute to 190 °C, it was allowed to rise by 2 °C per minute for 10 min. Fatty acid methyl ester standards (FAME mix; Sigma-Aldrich, St. Louis, Missouri, USA) were used to identify the fatty acids, and an automated GC software (Class GC-10; Shimadzu; Japan) was used to present the fatty acids as a percentage. Each sample was analyzed in triplicate.

2.7. Total phenolic and flavonoid content

The dried seaweed samples were finely powdered to enhance extraction efficiency. Specifically, 4 g of the finely powdered seaweed were immersed in 100 mL of methanol solvent. This mixture underwent agitation in a shaking incubator (KC121, Labstac, United

Kingdom) at 45 °C for 24 h, with intermittent shaking to facilitate extraction. Following incubation, the solution was filtered using Whatman No. 1 filter paper to separate the extract. Any remaining moist powder underwent a secondary extraction using the respective solvents, with intermittent shaking for 12 h and subsequent filtration to maximize yield. The methanol was then removed via rotary vacuum evaporation (SCI100-Pro, SCILOGEX, USA) at 36 °C, and the resulting samples were stored at 4 °C until further analysis. Ultimately, working solutions were prepared, each at a concentration of 5 mg/mL for every extract.

The phenolic content was determined using the Folin-Ciocalteu method as described by Martins et al. [23] with some minor adjustments. In summary, 0.1 mL of 1 M Folin-Ciocalteu (FC) reagent solution was combined with 0.5 mL of the extract solution. After 15 min, the mixture was mixed with 2.5 mL of saturated Na_2CO_3 (7.5 %) and allowed to stand for 30 min at room temperature. The absorbance at 760 nm was then measured using a spectrophotometer (Model: C7200, Peak Instrument, USA). The results are expressed as milligrams of gallic acid equivalent (mg GAE/100 g dm).

The total flavonoid concentration in the extracts was determined using the aluminum chloride colorimetric method outlined by Chia et al. [24] with slight modifications. Briefly, 3 mL of methanol, 0.2 mL of 10 % aluminum chloride, and 0.2 mL of 1 M potassium acetate were mixed with 1 mL of the extract solution. After incubating at room temperature for 30 min, the absorbance of the solution was measured at 420 nm. The total flavonoid content was expressed as milligrams of quercetin equivalent per 100 g of dry matter (mg QE/100 g dm). Each measurement was performed in triplicate.

2.8. Statistical analysis

To detect significant differences among various seaweed species, an analysis of variance (ANOVA) was carried out with Tukey's Honestly Significant Difference (HSD) test. The data were presented as mean values with corresponding standard deviations and analyzed using SPSS Inc., version 25.0, a statistical software package based in Chicago, Illinois, USA. Statistical significance was determined at a threshold of P values less than 0.05. Each analysis was replicated three times for robustness.

3. Results and discussion

3.1. Proximate composition

The proximate composition of three seaweed species collected from the Bay of Bengal, Bangladesh coast is given in Table 1. The moisture content differs significantly ($P < 0.05$) and ranges from 89.57 ± 0.64 % (*U. intestinalis*) to 92.27 ± 0.48 % (*P. tetrastromatica*) (Table 1). Seaweeds contain a large amount of moisture, and the moisture contents of the studied seaweeds were consistent with the study of Garcia et al. [25]; Jannat-Alipour et al. [26]; Premarathna et al. [27]. According to Garcia et al. [25], this information appears to be connected to the structure and morphology of the species.

The protein content of the three studied species ranged from 8.30 ± 0.37 % (*P. tetrastromatica*) to 30.63 ± 0.90 % (*G. longissima*) of DW and significantly higher ($P < 0.05$) amount of protein was found in *G. longissima* (Table 1). The current findings were similar to the findings of Jannat-Alipour et al. [26]; Rosemary et al. [18]; Palaniveloo et al. [11]. The content of protein in seaweeds are generally higher in red seaweeds than the brown and green seaweeds [8,27] which supports our current findings. Species, habitat, season, and environmental factors can all affect the protein content of seaweed [25]. Since the seaweed used in the study was gathered in the same region, during the same season, and under similar climatic circumstances, the protein content is correlated with the species used.

According to Rosemary et al. [18], lipids comprise a small portion of seaweed. In the current study, lipid content ranged from 1.36 ± 0.06 % (*U. intestinalis*) to 3.75 ± 0.08 % (*P. tetrastromatica*) of dry weight. This study has significant lipid content differences ($P < 0.05$) within the species. These findings are somewhat comparable to those of Premarathna et al. [27], although they are smaller than those attained by other authors [18,25]. Depending on the species, locality, and season, seaweed's lipid levels can vary significantly [25].

Ash content is generally abundant in seaweed [27]. Ash levels in the current research varied from 22.25 ± 1.10 to 30.50 ± 1.27 % of DW. Ash content was lowest in *G. longissima* and substantially higher ($P < 0.05$) in *U. intestinalis*. According to research by Premarathna et al. , consuming seaweed ash can prevent a variety of illnesses including arthritic conditions, gout, retention of fluids, bladder issues, and constipation. Ash is also utilized to treat children's constipation and aids in colon health maintenance [28]. The energy that carbohydrates provide for respiration and other bodily functions makes them a crucial part of metabolism. The examined seaweeds' carbohydrate levels varied from 30.45 ± 0.80 to 49.39 ± 1.62 % of DW, with *P. tetrastromatica* having a substantially higher

Table 1
Proximate composition of selected seaweed species collected from the Bay of Bengal, Bangladesh coast.

Parameters	Seaweed species		
	G. longissima	P. tetrastromatica	U. intestinalis
Moisture	90.24 ± 0.52^{b}	92.27 ± 0.48^{a}	89.57 ± 0.64^{b}
Protein (% DW)	30.63 ± 0.90^{a}	8.30 ± 0.37^{c}	17.51 ± 0.54^{b}
Lipid (% DW)	1.49 ± 0.05^{b}	3.75 ± 0.08^{a}	1.36 ± 0.06^{c}
Ash (% DW)	22.25 ± 1.10^{b}	24.58 ± 1.18^{b}	30.50 ± 1.27^{a}
Carbohydrate (% DW)	30.45 ± 0.80^{c}	49.39 ± 1.62^{a}	41.52 ± 1.36^{b}

Mean values and standard deviation of measurements for three replicates. Different superscript in a row differs significantly ($P < 0.05$).

carbohydrate content ($P < 0.05$). Syad et al. [9] and Rosemary et al. [18] reported a lower carbohydrate content than the results of the present study. According to Torres et al. [10], a variety of parameters, including species, place, and season, may have an impact on the broad variance in the carbohydrate content of different seaweed species.

3.2. Mineral content

Table 2 lists the mineral content (%) of three studied seaweed species gathered from the Bay of Bengal, Bangladesh coast. With the exception of sulfur, every mineral content in *G. longissima* was considerably higher ($P < 0.05$). In *U. intestinalis*, the sulfur content was substantially higher ($P < 0.05$). Compared to terrestrial plants or meals produced from animals, seaweed has more minerals.[29] The present results indicate that these seaweeds are rich in potassium, calcium, and sulfur content which supports the findings of Lahaye [30] and Kumar et al. [31]. According to Premarathna et al. calcium is the most important mineral for the development of strong teeth and bones. In all three studied seaweeds, the Na/K ratios ranged from 0.18 to 0.34, which is below 1 (Table 2). As per the dietary guidelines provided by the World Health Organization (WHO), these seaweeds can be incorporated into meals for humans experiencing high blood pressure symptoms. This is because the ratio of sodium (Na) to potassium (K) in this product is less than 1, which aligns with the recommended dietary choices for individuals with high blood pressure [32]. Additionally, seaweeds with low Na/K ratios are good for replacing sodium chloride [11]. According to seaweed species, location, wave, season, environment, physiological parameters, processing type, and mineralization technique, mineral concentrations might differ [33]. According to the findings, the seaweed under this study has an appropriate concentration of minerals, which implies that they might serve as significant sources of dietary supplements for minerals that are crucial for human and animal nutrition.

3.3. Amino acids

The studied species of seaweed's amino acid profiles are displayed in Table 3. The amount of total amino acids (TAAs) was substantially higher ($P < 0.05$) in *G. longissima* and significantly lower in *P. tetrastromatica*. Among essential amino acids, a higher concentration of tyrosine was found in *G. longissima*, and leucine in *P. tetrastromatica*, and *U. intestinalis*. All seaweed species have high concentrations of aspartic acid and glutamic acid in the case of non-essential amino acids, which validates earlier research by Tabarsa et al. [34] and Magdugo et al. [35]. Due to their role in giving seaweed its characteristic flavor and taste, aspartic acid and glutamic acid have been detected in various seaweed species [35].

Among the three seaweed species, *G. longissima* had considerably higher amounts of essential amino acids (EAAs) and non-essential amino acids (NEAAs) (Table 3). The findings of the EAAs/NEAAs ratio show that the three seaweeds in this study have a healthy balance of essential amino acids and non-essential amino acids. The EAAs/NEAAs ratios of the three seaweeds were more than 1, indicating suitable for human consumption of these seaweeds are a balanced source of amino acid intake [36]. More than 50 % of the total amino acids in these three seaweeds have been identified as EAAs based on the EAAs/TAAs ratio.

All of the seaweeds that were gathered for this study were analyzed for essential amino acids, and significantly high levels of amino acids were identified in *G. longissima*, followed by *U. intestinalis*, and *P. tetrastromatica* (Table 3). This finding indicates that these seaweeds may be useful as dietary sources. The majority of the essential amino acids are found in seaweed, which is why it is regarded as a rich source of protein [11]. In the current investigation, the amino acid profiles of the seaweed samples revealed that they had greater amounts of several essential amino acids than the egg and milk protein that is eaten globally [15]. In contrast to brown and green seaweed, red seaweed has higher concentrations of essential amino acids for the human body [36], which is consistent with our findings. The amino acid content of seaweed fluctuated depending on the species, environment, and time of harvest [15].

3.4. Fatty acids

The information on the fatty acid profile of the three types of seaweed that were investigated is displayed in Table 4. According to Premarathna et al. [27], fatty acids were found to have positive benefits including cardio-protective, great antioxidants, antimitotic, strengthening the cell membrane, resisting cancer, antiviral, anti-mutagenic activity, and healing damaged cells and tissues.

The three species differ significantly ($P < 0.05$) in terms of their amount of saturated fatty acids (SFA) and unsaturated fatty acids

Table 2
The mineral content (%) of selected seaweed species collected from the Bay of Bengal, Bangladesh coast.

Parameters	Seaweed species		
	G. longissima	P. tetrastromatica	U. intestinalis
Sodium (%)	0.82 ± 0.02^{a}	0.83 ± 0.02^{a}	0.60 ± 0.02^{b}
Potassium (%)	4.47 ± 0.05^{a}	2.41 ± 0.03^{b}	2.20 ± 0.04^{c}
Calcium (%)	2.54 ± 0.04^{a}	1.11 ± 0.02^{b}	0.67 ± 0.02^{c}
Magnesium (%)	0.58 ± 0.02^{a}	0.34 ± 0.01^{b}	0.59 ± 0.01^{a}
Phosphorus (%)	0.31 ± 0.03^{a}	0.07 ± 0.00^{c}	0.18 ± 0.01^{b}
Sulfur (%)	1.56 ± 0.05^{b}	0.95 ± 0.03^{c}	3.90 ± 0.06^{a}
Na/K	0.18 ± 0.01^{c}	0.34 ± 0.01^{a}	0.27 ± 0.01^{b}

Mean values and standard deviation of measurements for three replicates. Different superscript in a row differs significantly ($P < 0.05$).

Table 3
Amino acids composition (% dry weight) of selected seaweed species collected from the Bay of Bengal, Bangladesh coast.

Amino acids (% dry wt.)	Seaweed species		
	G. longissima	P. tetrastromatica	U. intestinalis
Aspartic acid	1.94 ± 0.03^{a}	0.59 ± 0.01^{c}	1.27 ± 0.03^{b}
Glutamic acid	2.36 ± 0.02^{a}	0.91 ± 0.02^{c}	2.16 ± 0.03^{b}
Serine	1.80 ± 0.01^{a}	0.39 ± 0.01^{c}	0.87 ± 0.01^{b}
Glycine	1.96 ± 0.02^{a}	0.43 ± 0.01^{c}	0.79 ± 0.02^{b}
Histidine	2.01 ± 0.01^{a}	0.26 ± 0.01^{c}	0.51 ± 0.01^{b}
Arginine	1.95 ± 0.01^{a}	0.40 ± 0.01^{c}	0.62 ± 0.02^{b}
Threonine	2.75 ± 0.01^{a}	0.29 ± 0.01^{c}	0.72 ± 0.02^{b}
Alanine	1.55 ± 0.02^{a}	0.51 ± 0.01^{c}	1.31 ± 0.01^{b}
Proline	Nd	Nd	Nd
Tyrosine	3.48 ± 0.03^{a}	0.27 ± 0.02^{c}	0.83 ± 0.01^{b}
Valine	2.08 ± 0.01^{a}	0.46 ± 0.02^{c}	0.91 ± 0.02^{b}
Methionine	1.75 ± 0.01^{a}	0.31 ± 0.01^{c}	0.58 ± 0.01^{b}
Cysteine	Nd	Nd	Nd
Isoleucine	2.89 ± 0.02^{a}	0.70 ± 0.03^{c}	0.79 ± 0.02^{b}
Leucine	1.80 ± 0.03^{a}	0.92 ± 0.03^{c}	1.59 ± 0.03^{b}
Phenylalanine	Nd	Nd	Nd
Lysine	2.16 ± 0.02^{a}	0.89 ± 0.02^{c}	1.43 ± 0.03^{b}
EAAs	18.92 ± 0.04^{a}	4.10 ± 0.02^{c}	7.36 ± 0.03^{b}
NEAAs	11.56 ± 0.02^{a}	3.23 ± 0.01^{b}	7.02 ± 0.02^{c}
TAAs	30.48 ± 0.06^{a}	7.33 ± 0.04^{c}	14.38 ± 0.05^{b}
EAAs/NEAAs	1.64 ± 0.01^{a}	1.27 ± 0.02^{b}	1.05 ± 0.01^{c}
EAAs/TAAs (%)	62.07 ± 0.02^{a}	55.93 ± 0.01^{b}	51.18 ± 0.01^{c}
NEAAs/TAAs (%)	37.93 ± 0.01^{c}	44.07 ± 0.01^{b}	48.82 ± 0.02^{a}

Mean values and standard deviation of measurements for three replicates. Different superscript in a row differs significantly ($P < 0.05$).

(UFA) (Table 4). The most prevalent saturated fatty acid in the studied seaweed species was palmitic acid. Palmitic acid concentrations were substantially higher ($P < 0.05$) in *G. longissima* and lower in *P. tetrastromatica*. The overall amounts of unsaturated fatty acids in all of the macroalgae under study were higher than those of saturated fatty acids, with UFA/SFA ratios ranging from 1.10 ± 0.01 % (*U. intestinalis*) to 1.18 ± 0.02 % (*G. longissima*). According to Ortiz et al. [37], the ratio of saturated and unsaturated fatty acids fluctuates depending on the species, season, region, and genetic diversity.

When compared to the other two seaweed species, *U. intestinalis* showed a substantially higher ($P < 0.05$) percentage of MUFA content (Table 4). The most prevalent MUFA in the three studied seaweeds was oleic acid. The levels of MUFA in the current investigation were greater than those observed by Palaniveloo et al. [11] and Premarathna et al. [27] but lower than those of Magdugo et al. [35]. The significantly highest ($P < 0.05$) PUFA levels were found in *G. longissima* and lowest in *U. intestinalis* (Table 4). Linoleic acid was the most predominant PUFA in the three seaweeds. The PUFA levels in the current research were greater than those observed by Palaniveloo et al. [11] and Premarathna et al. [27], but more or less similar to Ortiz et al. [37]. In accordance with the findings of Chan and Matanjun [38], increasing the consumption of foods rich in polyunsaturated fatty acids (PUFA) while reducing the intake of saturated fat can effectively lower the risk of heart disease.

Table 4
Fatty acids composition (relative percentage, %) of selected seaweed species collected from the Bay of Bengal, Bangladesh coast.

Fatty acids (relative percentage, %)	Seaweed species		
	G. longissima	P. tetrastromatica	U. intestinalis
Myristic acid (C14:0)	4.76 ± 0.00^{b}	10.48 ± 0.03^{a}	4.52 ± 0.01^{c}
Palmitic acid (C16:0)	39.64 ± 0.03^{a}	30.71 ± 0.03^{c}	36.28 ± 0.05^{b}
Palmitoleic acid (C16:1)	7.12 ± 0.02^{b}	5.17 ± 0.02^{c}	12.83 ± 0.03^{a}
Stearic acid (C18:0)	1.52 ± 0.00^{c}	5.54 ± 0.01^{b}	6.92 ± 0.02^{a}
Oleic acid (C18:1)	13.50 ± 0.02^{a}	10.65 ± 0.04^{b}	9.51 ± 0.03^{c}
Linoleic acid (C18:2)	7.52 ± 0.01^{b}	9.31 ± 0.03^{a}	7.53 ± 0.02^{b}
Linolenic acid (C18:3)	16.12 ± 0.02^{a}	13.56 ± 0.03^{c}	15.71 ± 0.05^{b}
Eicosenoic acid (C20:1)	2.57 ± 0.01^{b}	7.01 ± 0.02^{a}	1.28 ± 0.01^{c}
Arachidonic acid (C20:4)	4.20 ± 0.02^{b}	5.63 ± 0.02^{a}	3.85 ± 0.01^{c}
Docosahexaenoic acid (C22:6)	3.05 ± 0.01^{a}	1.94 ± 0.01^{b}	1.57 ± 0.01^{c}
SFA	45.92 ± 0.04^{c}	46.73 ± 0.05^{b}	47.72 ± 0.05^{a}
UFA	54.08 ± 0.04^{a}	53.27 ± 0.03^{b}	52.40 ± 0.03^{c}
MUFA	23.22 ± 0.03^{b}	22.82 ± 0.02^{c}	23.61 ± 0.03^{a}
PUFA	30.87 ± 0.04^{a}	30.46 ± 0.03^{b}	28.68 ± 0.03^{c}
UFA/SFA	1.18 ± 0.02^{a}	1.13 ± 0.02^{b}	1.10 ± 0.01^{b}
ω3/ω6	1.63 ± 0.01^{a}	1.04 ± 0.01^{c}	1.52 ± 0.02^{b}
ω6/ω3	0.61 ± 0.01^{c}	0.96 ± 0.01^{a}	0.66 ± 0.01^{b}

Mean values and standard deviation of measurements for three replicates. Different superscript in a row differs significantly ($P < 0.05$).

According to Hamid et al. [39], the ω3/ω6 ratio in prehistoric human diets was around 1:1. The seaweed species studied in the current study were significantly different ω3/ω6 ratio. According to Goodstine et al. [40], the ratio of ω3/ω6 being larger than 1 generally denotes improved nutritional quality and lowers the risk of cancer of the breast, particularly in pre-menopausal women, however, all seaweeds had a more than 1 ω3/ω6 ratio. Prior reports by Ortiz et al. [37] and Uribe et al. [41] revealed a similar ω3/ω6 ratio. Due to a favorable ω3/ω6 ratio and greater PUFA content, the fatty acid profile of these seaweeds suggests that they have promise as a functional food. On the contrary, the lower ω6/ω3 ratio is highly preferable, and the UK Department of Health advises a value of less than 4, and exceeding the limit is harmful to human health and may exacerbate cardiovascular disease [42]. In our investigation, the ω6/ω3 ratio value was less than 1 (0.61–0.96) and recommended for consumption. However, differences in the fatty acid content of marine seaweed depend upon the species, harvesting sites, seasons, and environmental conditions [27].

3.5. Total phenolic and flavonoid content

As displayed in Table 5, the total phenolic content of the three studied seaweeds differs significantly ($P < 0.05$) and ranged from 12.59 ± 2.27 in *U. intestinalis* to 88.70 ± 2.19 mg GAE/g dry weight in *G. longissima* for the methanol extracts. Methanol was selected as the extraction solvent for this study due to its superior performance in previous experiments [43,44]. These findings are in line with those of Tanna et al. [15], who found that red seaweed had a greater total phenolic content than green and brown seaweed.

Due to their extensive spectrum of biological and chemical activities, including their antioxidant and free radical scavenging characteristics, flavonoids are the most important natural phenolic [16]. In addition to protecting against cardiovascular mortality, flavonoids also exhibit antihepatotoxic, reducing, and antiulcer properties [45]. Table 5 also includes the three studied seaweed's total flavonoid content. For the methanol extracts, the total flavonoid quantity varied substantially ($P < 0.05$), ranging from 7.92 ± 1.97 mg QE/g dry weight in *U. intestinalis* to 71.46 ± 2.17 mg QE/g dry weight in *G. longissima*. These findings are in line with those of Tanna et al. [15], who claimed that red seaweed had a greater flavonoid concentration than green and brown seaweed. The risk of chronic diseases, such as diabetes, heart disease, and obesity, may be prevented or decreased by regularly consuming phenolic substances [16]. The origin, growing season, extraction methods, conditions of storage, and presence of interfering components in extracts such as fatty acids or pigments are all factors that impact the variation in phenolic compounds [46].

The study has not considered the potential impact of environmental factors such as water temperature, salinity, and nutrient availability on the nutritional composition and phenolic contents of seaweeds which can influence biochemical composition and phenolic contents. Further research could explore the potential health benefits and nutritional implications of consuming seaweeds from the Bay of Bengal, Bangladesh. This could involve in vitro and in vivo studies to evaluate the bioactivity and physiological effects of bioactive compounds present in these seaweeds. Moreover, research on sustainable harvesting practices, cultivation techniques, and resource management strategies for seaweeds along the Bangladesh coast could contribute to the development of sustainable seaweed industries while preserving marine ecosystems.

4. Conclusion

In the current study, three widely available seaweeds (*G. longissima*, *P. tetrastromatica*, and *U. intestinalis*) collected from the Bay of Bengal coast of Bangladesh were examined for their chemical composition, total phenolic and flavonoid content. Based on their nutritional value, each of these kinds of seaweed may potentially be transformed into human and animal foods. However, *G. longissima* is the most potential for incorporation into food because of its high levels of protein, essential amino acids, unsaturated fatty acids, and overall phenolic and flavonoid content. Moreover, due to their nutritional value total phenolic and flavonoid content, these seaweeds might be employed in the pharmaceutical and food industries to create nutritious food to support diseases like diabetes, though seaweed intake is uncommon in Bangladesh. More study is needed to properly examine the health benefits of this and other available seaweed species and to maximize their economic value.

Data availability

Data will be made available on request.

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Table 5
Total phenolic and flavonoid content of selected seaweed species collected from the Bay of Bengal, Bangladesh coast.

Seaweed species	Total phenolic content (mg GAE/g dry weight)	Total flavonoid content (mg QE/g dry weight)
G. longissima	88.70 ± 2.19^{a}	71.46 ± 2.17^{a}
P. tetrastromatica	68.74 ± 1.95^{b}	58.15 ± 2.05^{b}
U. intestinalis	12.59 ± 2.27^{c}	7.92 ± 1.97^{c}

Mean values and standard deviation of measurements for three replicates. Different superscript in a column differs significantly ($P < 0.05$).

CRediT authorship contribution statement

Md Rahamat Ullah: Writing – original draft, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Mousumi Akhter:** Methodology, Data curation, Conceptualization. **Abu Bakker Siddique Khan:** Methodology, Data curation, Conceptualization. **Farhana Yasmin:** Methodology, Data curation, Conceptualization. **Md Monjurul Hasan:** Writing – review & editing, Supervision, Methodology. **Aovijite Bosu:** Visualization, Validation, Supervision. **Mohammed Ashraful Haque:** Supervision, Project administration, Funding acquisition. **Md Shoebul Islam:** Methodology, Formal analysis, Data curation. **Md Amirul Islam:** Writing – review & editing, Validation, Supervision. **Yahia Mahmud:** Writing – review & editing, Project administration, Funding acquisition.

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.

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