Journal of Applied Phycology (2026) 38:2293–2305
https://doi.org/10.1007/s10811-026-03846-4

RESEARCH

Investigating the effect of post-harvest treatment on nutritional and antioxidant activities of *Ulva lactuca* originating from Bangladesh

Suman Mojumder[1] · Mita Nur Akter[1] · Oishee Barua[1] · Rahul Sharma[1] · Dwaipayan Sikdar[1] · Sajal Roy[2] · Rajib Banik[3] · Uttam Kumer Roy[4]

Received: 23 November 2025 / Revised: 5 March 2026 / Accepted: 11 March 2026 / Published online: 8 April 2026
© The Author(s) 2026

Abstract

To utilise seaweed commercially, post-harvest processing is typically essential, serving to prevent decay, extend shelf life, and facilitate the extraction of specific chemical components. In this study, the presence of a variety of nutritionally important compounds in *Ulva lactuca* was investigated following different treatments: washing with fresh water (fresh), followed by drying under freeze dryer, open air, direct sun and conventional oven. The analysis encompassed the determination of proximate composition (carbohydrates, proteins, lipids, ash, and moisture), elements (C, H, N, S and P) and metal contents, bioactive compounds (phenolics and flavonoids), and *in vitro* antioxidant activities. The findings indicate that *U. lactuca* is rich in essential minerals, and total carbohydrate content is not significantly influenced by post-harvest drying treatments. Sun-dried *U. lactuca* exhibited the highest lipid (5.71 ± 0.41 % DW), phenolic content (52.9 ± 0.33 mg GAE g^{-1} DW), and total antioxidant capacity (16.19 ± 1.09 mg AAE g^{-1} DW), while air-dried only preserved the highest FRAP activity (0.38 ± 0.04 mg $Fe^{2+}E$ g^{-1} DW) and DPPH scavenging (0.25 ± 0.03 mg AAE g^{-1} DW). Freeze-dried samples retained the highest protein content (9.69 ± 0.27 % DW) and reducing power (1.59 ± 0.05 mg AAE g^{-1} DW), whereas total flavonoids were greatest in the fresh sample (9.58 ± 0.08 mg QCE g^{-1} DW). Overall, sun or air drying are indicated as effective, low-cost methods for preserving the nutritional and bioactive qualities of *U. lactuca* compared to freeze or oven drying.

Keywords Antioxidant · Chlorophyceae · Minerals · Nutritional analysis · Drying · *Ulva*

Introduction

Seaweeds are eukaryotic, multicellular, benthic organisms, found growing throughout the coastal areas from tropical to polar regions (García-Poza et al. 2020). They are regarded as living reservoirs of a wide range of compounds (polysaccharides, lipids, proteins, pigments, minerals, vitamins, and enzymes) and are acting as a natural filter by absorbing oceanic pollutants and toxins and are maintaining a clean environment for the aquatic ecosystems (Morais et al. 2021; Choudhary et al. 2023; Honey et al. 2024; Sobuj et al. 2024) . Seaweeds have been utilized as food, feed and fertilizer in various cultures for centuries, particularly in East Asian countries. Seaweed-derived compounds are commercially used as raw materials in food, cosmetic, nutraceutical, and pharmaceutical industries worldwide. The extract (mainly containing phenols and flavonoids) derived from seaweed has also been reported to show antibacterial, antifungal, anti-aging and preferable antioxidant properties (Khan et al. 2016; Thawabteh et al. 2023). The global commercial seaweeds market is gradually expanding and estimated value was US$40 billion in 2020 and is projected to reach US$95 billion by 2027 at a CAGR (compound annual growth rate) of 9.6 % from the period 2020 to 2027 (Sobuj et al. 2024).

Ulva is one of the rapidly and abundantly grown green seaweeds found in coastal communities around the world (Mohamed et al. 2023). About 1500 t of *Ulva* biomass (dried) was produced globally in land based, open-sea farming including photo bioreactor (Mantri et al. 2020). *Ulva* is

✉ Uttam Kumer Roy
u.k.roy@lboro.ac.uk

[1] Department of Biochemistry and Molecular Biology, University of Chittagong, Chattogram, Bangladesh

[2] Department of Soil Science, University of Chittagong, Chattogram, Bangladesh

[3] Bangladesh Council of Scientific and Industrial Research (BCSIR), Dhaka 1205, Bangladesh

[4] School of Architecture, Building and Civil Engineering, Loughborough University, Leicestershire LE11 3TU, UK

consumed as aonori in Japan or in soup and salad in Europe (Lawton et al. 2021). High nutrients and fiber content have made *Ulva* an attractive feed for aquaculture, livestock and poultry (Simon et al. 2022). Its biomass can also be used as feedstock to produce biofuel due to presence of high carbohydrate and reducing sugar without affecting food supply (Simon et al. 2022). *Ulva* species including *Ulva lactuca* can also effectively fix CO_2 and can utilize up to 100 % CO_2 at concentrations of 15 mg L^{-1} (Kaladharan et al. 2009). *Ulva*-derived polysaccharides, phenolic compounds including different pigments (such as chlorophyll and carotenoids) showed various biological activities (antioxidants, anti-inflammatory, anticancer, antibacterial, and antiviral activities) (Cindana et al. 2020; Costa et al. 2024; Khan et al. 2024a, b). However, the accumulation of these components and their biological activities in *Ulva* biomass depend on upstream (cultivation of seaweed such as temperature, salinity, irradiance and nutrient composition of water) and downstream processing (harvesting process, post-harvest treatment, extraction and purification) (Simon et al. 2022; Costa et al. 2024).

Post-harvest treatment is considered an essential stage of downstream processing to maintain the quality of freshly harvested biomass with the retaining of biological activities (Stedt et al. 2022). Cold storage of post-harvest biomass is a widely used technology to preserve the chemical, nutritional and biological properties, as respiration and other metabolic reactions are slowed down (Roy et al. 2020). Biomass can be prepared for cold storage either by drying or directly frozen of fresh biomass. Drying the biomass reduces its weight and volume, which makes the material more convenient and cheaper to transport and store (Roy et al. 2020). During drying, different methods such as air drying, sun drying, oven drying, and freeze drying are employed to process the seaweeds biomass (Khan et al. 2024a, b). The drying method influences the nutritional value and the stability of bioactive compounds that are responsible for different biological activities of seaweeds (Badmus et al. 2019; Lafeuille et al. 2023; Ullah et al. 2023). For example, vacuum-dried extract of the red seaweed *Kappaphycus alvarezii* showed the highest phenolic content but sun-dried extract showed the lowest antioxidant potential (Neoh et al. 2016). The comparison of different drying methods was investigated by Uribe et al. (2020) and showed the highest amino acid in freeze-dried and vacuum-dried and the highest polyunsaturated in solar and oven-dried *Pyropia orbicularis* biomass. Moreover, another report depicted that the highest quantities of carbohydrates, proteins, pigments, phenolic and flavonoid compounds were found in green seaweed using convective drying method (Uribe et al. 2019). Oven drying was also preferred over sun drying for *Ulva* sp. on account of its higher water retention capacity and higher content of highly unsaturated fatty acids (Hassanzadeh et al. 2023). An appropriate processing step can extend the shelf life of long-term storage of post-harvest biomass.

Bangladesh boasts a coastal expanse spanning 480 km (Ahmed and Taparhudee 2005). Due to the increasing emphasis on blue economy by the Government of Bangladesh, research on the exploitation of marine aquaculture and aquatic products is getting momentum (Hossain et al. 2021; Honey et al. 2024). The diversity of seaweeds in Bangladesh is rich with around 193 algal species, where 51 species are Chlorophyta, 54 Phaeophyta, and 88 Rhodophyta (Sarkar et al. 2016) which could play a potential marine resource for developing a sustainable blue economy. Various seaweed species have already started to be produced in open-sea farming either by locally or by commercially in coastal Bangladesh. *Ulva lactuca* is one of the commercial-scale grown seaweeds in coastal regions of Bangladesh (Farhaduzzaman et al. 2023). However, studies on the biochemical composition, nutritional value and bioactivities of different seaweeds including *U. lactuca* grown in Bangladesh is scant; only Bokhtiar et al., (2024) reported the effects of solvents on the extraction of phytochemicals and their antioxidant activities of green seaweeds collected from Bangladesh. Researchers have studied different seaweeds originating from Bangladesh, analysing the proximate and phytochemicals properties in green seaweed, *Ulva intestinalis* (Akter et al. 2023; Khan et al. 2024a, b; Ullah et al. 2024) and red and brown seaweeds, *Gracilariopsis longissima* (Ullah et al. 2023, 2024), *Padina tetrastromatica* (Khan et al. 2024a, b; Ullah et al. 2024). Though Ullah et al. (2023) and Khan et al. (2024a, b) reported the effects of different drying methods (freeze, sun, and oven drying) on the proximate and phytochemical profiles of *U. intestinalis*, *G. longissima*, and *P. tetrastromatica*, they did not investigate the antioxidant activities of reported seaweeds. To date, there is no published information on the impact of post-harvest drying treatment on *U. lactuca* produced from commercial farm in Bangladesh.

The aim of this study was to examine the nutritional profile, phytochemical content, and antioxidant activities of fresh *U. lactuca* collected from the Cox's Bazar coast of Bangladesh, and further investigate how freeze-drying, air-drying, sun-drying, and oven-drying influence its biochemical composition (primary and secondary metabolites) and antioxidant potential.

Materials and methods

Collection and preparation

Ulva lactuca was collected from the local harvester of Nunier Chara (21◦28′26.1′′N and 91◦57′51.5′′E), Cox's Bazar, Bangladesh. Freshly collected seaweed was cleaned

and washed thoroughly in seawater and transported to the laboratory immediately. Firstly, the biomass was cleaned well with tap water and then distilled water for removing sand, debris, epiphytes and other extraneous matter attached to the seaweed. The washed biomass stored at – 20 °C was denoted as fresh sample. Then a portion of freshly washed biomass was separated into four: freeze-dried (−50 °C, 0.027 KPa, 68 h) using a Freeze Dryer DC 801 (Yamato Scientific Co., Ltd.); air-dried (dried in open air under the shade for 3 days); sun-dried (dried under direct sunlight on aluminum foil for 3–4 h) and oven-dried (dried at 50 °C in a hot air oven for 2 days). All the dried biomasses were ground into powder using grinder and transferred into air-tight zipper bags and stored at −20 °C until further analysis. For the determination of total carbohydrate, protein, phenolic, flavonoid contents, and antioxidant activities, extractions were performed in duplicate and assays were conducted in triplicate for each extract, totaling 6 assays ($n = 6$). Ash and moisture analyses were carried out in triplicate ($n = 3$) and lipid content was also measured in triplicate ($n = 2$).

Determination of total solid, ash & moisture content

Total solid, ash and moisture contents were determined by following the protocol of Liu (2019) with few modifications. To determine the moisture content (%), 1 g of each biomass of fresh and all dried samples were separately dried in a convection drying oven at 105 ± 1 °C for 24 h. After that all samples were placed into a muffle furnace for 30 min at 250 °C and then at 600 °C for 3 h for measuring the ash content.

Element analysis

The total carbon (C), hydrogen (H), nitrogen (N) and sulfur (S) contents of the *U. lactuca* biomass were measured by elemental analysis (Thermo Scientific FLASH 1112 series CHN analyser) (Yang et al. 2021).

Determination of metal contents

Mineral contents (K, Ca and Mg) of the biomass were determined by an atomic absorption spectrophotometer (Agilent Technologies 200 Series AA, Australia) after digesting the samples following the procedure described in Parkinson and Allen (1975). Briefly, 0.50 g of oven-dried representative sample in a heat resistance pyrex tube was digested using 5 mL digestion mixture solution which was initially prepared by mixing 350 mL H_2O_2, 0.42 g Selenium (Se) powder, 14 g $LiSO_4$. H_2O and 420 mL concentrated H_2SO_4, and the digestion was performed for around 6–7 h in a digestion block with a starting temperature of 50 °C that was gradually increased to 350 °C until the digest becomes paste-like colorless substance. The concentrations of all minerals in the digest were measured against standard curves of analytical grade standard solutions which was prepared from stock solution supplied by Scharlab S.L, Spain. Phosphorus (P) content in the digested sample was measured by the ascorbic acid blue color method by using UV-visible spectrophotometer (Shimadzu, UV1800) at a wavelength of 882 nm (Murphy and Riley 1962). To determine heavy metal contents, oven-dried biomass was digested in acid in a temperature and pressure-controlled microwave assisted digestion system (CEM MARS 5 with XP-1500 vessels) according to Roy et al. (2022). Briefly, 0.5 g of oven-dried biomass transferred into the sample holder and 10 mL of concentrated nitric acid (70 % trace analysis grade, Fisher Scientific) and 0.25 mL of H_2O_2 (30 %) were added. After microwave-assisted digestion (20 min), the mixtures were made up to 50 mL with dH_2O water. Multi-element calibration solutions were prepared at different concentration levels (1 - 1000 µg L^{-1}) from the single element (1000 mg L^{-1}) ICP grade standards, to produce four-point calibration curves for each element ($r^2 = 0.999$).

Primary metabolites

Total carbohydrate

Crude extract was prepared and total carbohydrate content in the extract was estimated by using the method described in Roy et al. (2023) with some modification. In brief, fresh seaweed was ground using a mortar and pestle. 0.95 g of paste and 0.1 g of all dried samples were separately homogenised in HCl (2.5 N, 10 mL) in an orbital shaker (200 rpm, 40 °C, 1:30 h) and then incubated in a water bath at 90 °C for 3 h. 10 mL of 2.5 N hydrochloric acid was added and sonicated for 1 h at 60 ℃. After cooling to room temperature, solid sodium carbonate was added to the extracts until the ceasing the effervescence. After centrifugation (5000 rpm, 15 min, 4 °C), supernatant was collected. The extraction procedure was repeated for the residue for two times. Three extracts were combined and filtered. 0.1 mL of extract (10× diluted) was added to 0.5 mL of phenol solution (5 %) and 2.5 mL of sulfuric acid (96 %). The solution was mixed by shaking and was incubated in a water bath (25–30 °C, 20 min). The optical density was measured at 490 nm against a blank (prepared by mixing all reagents without a sample). Calibration graphs were prepared using the glucose standard (0.02 - 0.1 mg).

Total protein

The extracts were prepared according to the procedure as described in Roy et al. (2021). Briefly, 0.24 g of paste and 0.025 g of all dried samples were homogenized in NaOH (25 mL, 0.1 mM) separately and sonicated for 30 min at 40 °C using ultrasonic bath (UCP-20). After incubation on an

orbital shaker (200 rpm, 3 h, 40 °C), the supernatant was separated by centrifugation (5,000 rpm, 4 °C, 30 min) and collected as the first extract. The residue was used for the second extract through addition of NaOH (25 mL, 0.1 mM), sonication for 30 min at 40 °C, incubation in an orbital shaker (200 rpm, 3 h, 40 °C) and then centrifugation (5,000 rpm, 4 °C, 30 min). The third and fourth extracts were collected in the procedure. The four extracts were combined and used for protein assay. The total protein content in the crude extract was determined by the method of Lowry using bovine serum albumin (BSA) as the protein standard (0.04 - 0.64 mg).

Total lipid

The total lipid content was estimated according to the procedure described in Matyash et al. (2008) with some modification. After adding 100 % methanol (10 mL) separately to 5.68 g of paste and 0.6 g of all dried samples, the mixture was sonicated (30 min, 60 °C) and then 20 mL of chloroform was added followed by incubation in an orbital shaker (200 rpm, 40 °C, 60 min). Then dH_2O (6 mL) was added with the mixture and kept at room temperature for phase separation (10 min). After centrifugation (1000×*g*, 4 °C, 10 min), the lower dark greenish organic layer was collected into a glass vial by filtering using Whatmann no. 1. The extracts were dried overnight at 50 °C. The weight of the dried lipid was determined by subtracting the weight of the empty glass vial from the total weight of the sample with a glass vial.

Secondary metabolites

Preparation of sample extract

The extract was prepared according to the method used by Dey and Kuhad (2014). Briefly, 5.0 g of paste and 0.5 g of each dried samples were homogenised separately in an aqueous methanol solution (70 % v/v, 20 mL) using a shaker (200 rpm, 40 °C, 2 h) with continuous shaking. After filtration, the residue was re-extracted with the fresh solvent. The two extracts were pooled and used for estimating total phenolic and flavonoid contents, and antioxidants activities.

Determination of total phenolic content

The total phenolic content was estimated by Folin–Ciocalteau colorimetric method using gallic acid as standard (Roy et al. 2021). 0.2 mL of extract was mixed with 1.09 mL distilled water, Folin–Ciocalteau reagent (10 % v/v, 0.05 mL) and incubated (3 min, room temperature). After adding Na_2CO_3 (10 % w/v, 0.15 mL), the reaction mixture was incubated (1 h at room temperature in the dark). The absorbance was read at 765 nm against a blank (prepared by mixing all the reagents without the sample).The total phenolic content in the crude extract was expressed as gallic acid equivalent (GAE) per gram of dry weight (mg GAE g^{-1}, DW).

Determination of total flavonoid content

Total flavonoid content (TFC) for each extract was determined using the aluminum chloride colorimetric method by Roy et al. (2023) with few modifications. Briefly, 0.15 mL of the sample was mixed with methanol (0.65 mL) and potassium acetate (9.8 %, 0.04 mL) and aluminum chloride (9.8 %, 0.04 mL) were added. After incubation (30 min) in the dark, the optical density of the solution was recorded against the blank (prepared by mixing all reagents without the sample) at 415 nm. The calibration curve was prepared using the quercetin standard in methanol, and the total flavonoid in the crude extract was expressed as quercetin equivalent per gram of dry weight (mg QCE g^{-1} DW).

Antioxidant activities

Total antioxidant capacity (TAC)

The total antioxidant capacities of the extracts were evaluated by phosphomolybdenum method (Prieto et al. 1999). An aliquot of 0.08 mL of extract was mixed with 0.32 mL of 70 % methanol and 4 mL of reagent solution (0.6 M sulfuric acid, 28 mM sodium phosphate, and 4 mM ammonium molybdate) and incubated in a thermal block at 95 °C for 90 min. After cooling to room temperature, the absorbance was read at 695 nm against a blank (prepared by mixing all reagents without a sample extract). The antioxidant capacity was evaluated with a calibration curve (0.0125- 0.125 mg of ascorbic acid per mL, $R^2 = 0.994$), with the results being calculated as mg AAE g^{-1} DW.

Reducing power (RP) assay

For determination of reducing power assay, 0.15 mL of extract was mixed with 0.2 M phosphate buffer (pH 6.6, 0.85 mL) and 1% potassium ferricyanide [$K_3Fe(CN)_6$] (1.0 mL). After incubating the reaction mixture at 50°C for 20 min in a water bath, 10 % trichloroacetic acid (1.0 mL) was added immediately. The resulting mixture was centrifuged (3000 rpm, 10 min) and 2.0 mL of supernatant from upper layer was mixed with distilled water (2.0 mL) and 0.1 % of $FeCl_3$ (0.4 mL). After incubation (10 min), the optical density of the mixture was measured at 700 nm. The reducing power was evaluated with a calibration curve (0.083- 0.50 mg of ascorbic acid per mL, $R^2 = 0.997$), with the results being calculated as mg AAE g^{-1} DW.

Table 1 Characterization of biomass of *U. lactuca*

Parameters	Post-harvest treatment of biomass				
	Fresh	Freeze-dried	Air-dried	Sun-dried	Oven-dried
Moisture (% DW)	89.88 ± 0.36^{a}	7.97 ± 0.38^{d}	10.26 ± 0.95^{c}	14.05 ± 0.44^{b}	9.75 ± 0.71^{c}
Total solid (% DW)	10.12 ± 0.36^{d}	92.03 ± 0.38^{a}	89.74 ± 0.95^{b}	85.95 ± 0.44^{c}	90.25 ± 0.71^{b}
Ash (% DW)	1.62 ± 0.07^{c}	10.13 ± 0.03^{a}	10.06 ± 0.27^{a}	10.27 ± 0.05^{a}	9.70 ± 0.10^{b}

Data are mean ± standard deviation ($n = 3$). Same letters in different rows showed no significant difference at $p < 0.05$

DPPH free radical-scavenging activity assay

The reaction mixture (total volume 3 mL), consisting of 0.5 mL of a 0.5 M acetic acid buffer solution at pH 5.5, 1 mL of 0.2 mM DPPH in methanol, and 1.5 mL of a 50 % (v/v) methanol aqueous solution with the 0.5 mL extracts, was shaken vigorously. The mixer was then kept in the dark for 30 min. The amount of DPPH remaining was determined by reading the absorbance at 517. The control was prepared in the same manner, except that 50 % (v/v) methanol aqueous solution was added instead of sample. The DPPH free radical inhibition calibration curve (ascorbic acid equivalent, $R^2 = 0.995$) was calculated as mg AAE g^{-1} DW (Bentoulla et al. 2024).

Ferric reducing antioxidant power (FRAP) assay

The FRAP assay was determined by the method described by Ghosh et al. (2021) with few modifications. 100 µL of the sample was combined with 3 mL of the FRAP reagent [1:1:10 mixture of 20 mM ferric chloride ($FeCl_3$), 10 mM 2,4,6-tripyridyl-S-triazine (TPTZ), and 0.3 M acetate buffer at pH 2.6]. The mixture was incubated for 5 min and then the absorbance was read at 593. Finally, the ferric-reducing power was evaluated with a calibration curve (1.73–8.63 µg of Fe^{2+}, $R^2 = 0.999$), with the results being calculated as mg Fe^{2+} E g^{-1} DW.

Statistical analysis

All data are represented as mean ± SD. One-way ANOVA and Tukey's multiple comparisons were used to compare any significance differences among samples, which were carried out using GraphPad Prism 10 software. The level of significance was set at $p < 0.05$.

Results

The biochemical composition (primary and secondary metabolites, pigments) of seaweed are influenced by factors like seasonal, geographical, and taxonomic variations. Beyond these natural influences, the primary factor impacting the quality and/or quantity of the nutritional and bioactive components is the postharvest handling of seaweed (Zhu et al. 2021). The effect of post-harvest drying (by freeze, air, sun or oven) of fresh biomass on the primary metabolites, secondary metabolites in *U. lactuca* was investigated and compared here. Further, antioxidant activities of post-harvest treated biomasses (fresh, freeze-dried, air-dried, sun-dried, and oven-dried) were evaluated to obtain the optimal post-harvest processing condition.

Characterization of *U. lactuca* biomass

The moisture contents, total solids and ash contents of dried samples were presented in Table 1. The highest moisture content (89.88 ± 0.36 % DW) was measured in the fresh sample, indicating the lowest content (10.12 ± 0.36 % DW) of total solid in the biomass. The freeze-dried sample showed the lowest moisture content (7.97 ± 0.38 % DW) with corresponding the highest solid content in the biomass (92.03 ± 0.38 % DW). The ash content of freeze-dried, air-dried and sun-dried samples showed higher ash content with no significant differences.

Element and minerals analysis

The contents of C, H, N, S and P, and the contents of K, Ca, Mg, Se, Cu, Mn, Cr, Ni, Zn, Co, As, Pb, Cd, Hg and Be of *U. lactuca* were determined to investigate the presence of elements, minerals and heavy metals in the biomass and the concentrations were shown in Table 2, and presented in %, DW for elements and in ppm for minerals and heavy metals.

Primary metabolites

As shown in Fig. 1a and 1b, total carbohydrate (35.43 ± 4.71 to 37.50 ± 2.72 % DW) and total protein (9.69 ± 0.27 to 8.35 ± 0.71 % DW) contents showed no significant differences among the samples, except oven-dried samples had significantly lower total protein content (Fig.1b). On the other hand, the total lipid content differed significantly among treatments (Fig. 1c). Sun drying yielded the highest lipid content (5.77 ± 0.25 % DW) and fresh samples had the lowest value.

Table 2 Element and micronutrient contents in *U. lactuca*

Elements	%, DW	Minerals/ heavy metals	Concentration (ppm)
C	31.37 ± 2.01	K	6500 ± 10
H	7.01 ± 0.38	Ca	9400 ± 1360
N	2.91 ± 0.19	Mg	4320 ± 795
S	4.78 ± 0.32	Se	0.22 ± 0.01
P	0.91 ± 0.01	Cu	10.52 ± 0.97
C/N ratio	10.79	Mn	204.79 ± 25.76
C/H ratio	4.47	Cr	6.19 ± 0.48
		Ni	6.94 ± 0.52
		Zn	121.03 ±5.8
		Co	0.83 ± 0.05
		As	2.63 ± 0.35
		Pb	2.62 ± 0.19
		Cd	0.51 ± 0.029
		Hg	0.098 ± 0.011
		Be	0.016 ± 0.001

Data are mean ± standard deviation (n =3)

Secondary metabolites

As shown in Fig. 2a, sun-dried samples recorded the highest (52.86 ± 0.33 mg GAE g^{-1} DW), whereas fresh samples contained the lowest TPC (41.05 ± 2.47 mg GAE g^{-1} DW). Other drying treatments produced comparable intermediate values, all significantly ($p < 0.05$) higher than fresh but lower than sun-dried samples. In the case of TFC (Fig. 2b), fresh samples exhibited the highest value (9.58 ± 0.08 mg QCE g^{-1} DW), which was statistically not significant compared to freeze-dried samples. Drying with oven or air resulted in a moderate decrease with no significant difference between them. The lowest TFC was observed in sun-dried samples, which was significantly different from all other treatments.

Antioxidant activities

In terms of TAC (Fig. 3a), sun-dried samples exhibited the highest value (16.19 ± 1.09 mg AAE g^{-1} DW), while the other drying methods and fresh samples showed

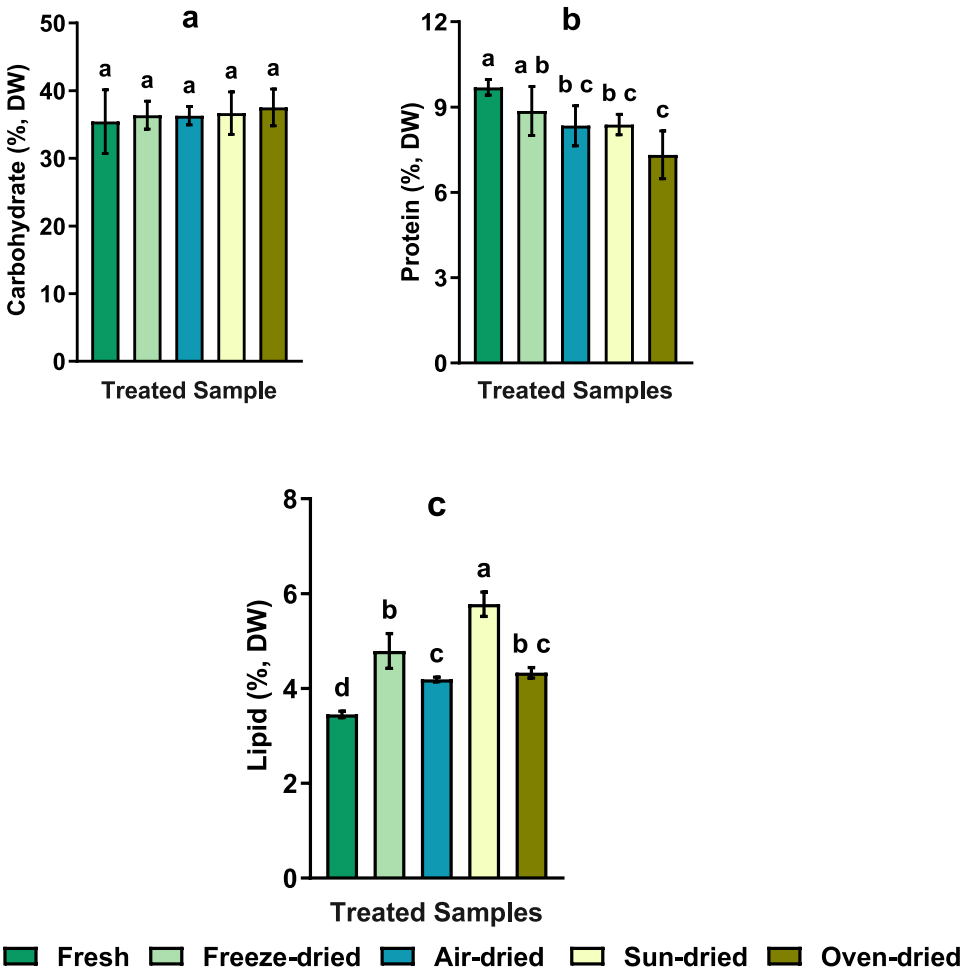


Fig. 1 Carbohydrate (**a**), protein (**b**) and lipid (**c**)] content in fresh, all dried biomass (*U. lactuca*). Data are mean ± standard deviation (n = 6), for lipid (n = 3). Different letters on the bars show significant difference at p<0.05

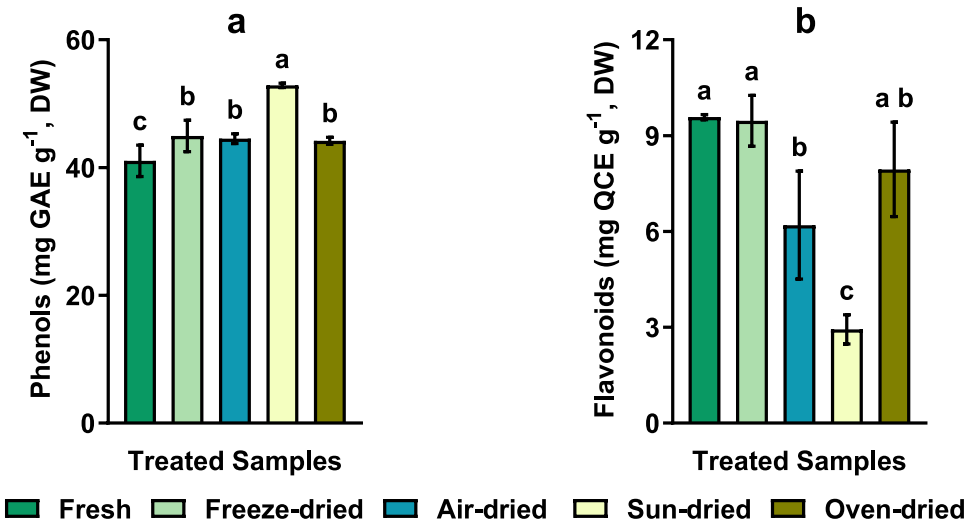


Fig. 2 TPC (**a**) and TFC (**b**) in fresh and differently dried biomass (*U. lactuca*). Data are mean ± standard deviation (n = 6). Different letters on the bars show significant difference at $p < 0.05$

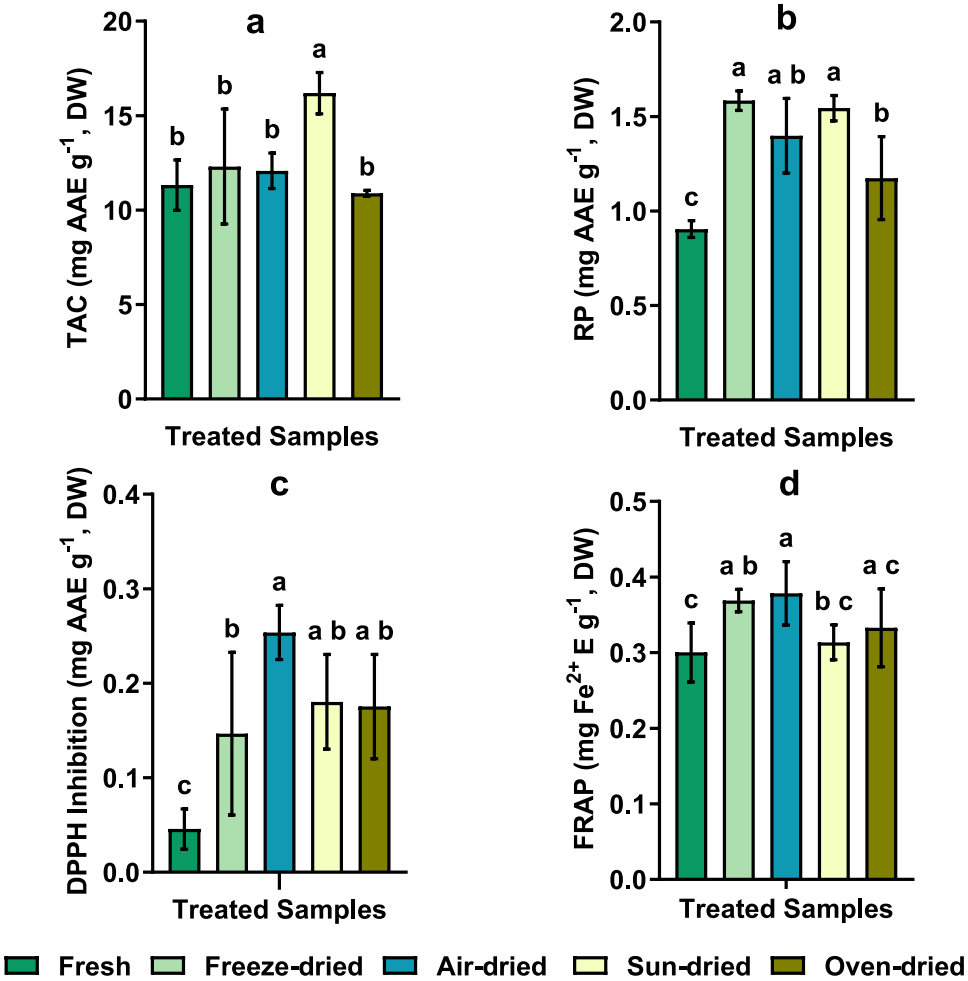


Fig. 3 Antioxidant capacities in fresh, freeze-dried, air-dried, sun-dried and oven-dried *U. lactuca* biomass. Data are mean ± standard deviation ($n = 6$). Different letters on the bars show significant difference at $p < 0.05$

comparatively lower but statistically similar values. RP was the highest in freeze-dried samples (1.59 ± 0.05 mg AAE g^{-1} DW) followed by sun-dried sample, air-dried and oven-dried samples, and all were significantly ($p < 0.05$) higher than fresh sample (Fig. 3b). In Fig. 3c, DPPH radical scavenging activity was significantly lowest in fresh samples but increased substantially in dried treatments, with air-dried samples showing the maximum activity (0.25 ±

0.03 mg AAE g^{-1} DW). For FRAP (Fig. 3d), air-dried sample showed the highest value which was significantly higher than the value of fresh and sun-dried samples, but not the freeze- and sun-dried samples.

Discussion

Different drying treatment strongly influenced the biochemical compositions (total carbohydrates, total proteins, total lipids content, total phenolic and flavonoid content) and antioxidant properties of post-harvest *U. lactuca* (locally grown in Bangladesh) biomass. From the comparison of four different drying treatment, no specific drying method is representative to preserve all nutritional and antioxidant properties, we recommend the suitable treatment method for post-harvest processing of commercial-scale *U. lactuca* production.

The moisture content greatly influences the stability and properties of bio-compounds preserved in the materials (Choudary et al. 2023), therefore it is crucial to maintain appropriate level of moisture to retain the quality of these compounds in the storage seaweeds biomass. The moisture content was decreased during the drying of fresh biomass through all sort of drying. The value for sun-dried sample was slightly similar to the values reported for *U. lactuca* (16.90 %) from Indonesia (Rasyid 2017). Sun drying and air drying are traditional and effective methods for dehydration, but its results are more variable due to environmental conditions (EI Majnaoui et al. 2025). Likewise, the moisture content by air drying such as 14.57 % for *U. lactuca* (Khairy and El-Shafay 2013), 14.55 % for *Ulva fasciata* (Anis et al. 2018) and 16.36 % for *Caulerpa racemosa* (Khan et al. 2016) from Asian region are moderately higher compared to the presented finding. Though high drying temperatures may reduce the drying time and cost, however, there is a possibility to degrade and to lose the bioactivity of compounds during drying of fresh sample (Alghazeer et al. 2022). The removal of moisture by drying of fresh seaweeds at the optimal temperature and condition is a crucial step to maintain the nutritional quality as food or to retain their biochemical properties.

Fresh samples showed the lowest ash content, likely due to their high moisture levels that diluted the mineral fraction. Following drying, the ash content increased substantially and remained relatively consistent across all dried samples (Table 1). The ash contents in this study are consistent with those observed by Ortiz et al. (2006) (11.01 %), Abirami and Kowsalya (2011) (10.50 %) and Rasyid (2017) (11.20 %). However, they are lower than the 20–44% reported for *U. lactuca* by Barot et al. (2019), which may be attributed to the seasonal variation, post-harvest washing procedures and geographic differences (Nikolaisen et al. 2011).

The element contents of *U. lactuca* are comparable to the values reported for *Ulva* species by Yang et al. (2021). Seaweeds contain two types of nitrogen: protein nitrogen and non-protein nitrogen. Protein nitrogen makes up about 3.10 % –17.40 % of the total nitrogen, while non-protein nitrogen can be much higher, ranging from 7.20 % – 59.50 % (Amano and Noda 1990). In this study, the protein content of *U. lactuca* was low (9.69 %), which is probably because it contains a large amount of non-protein nitrogen. The C/N ratio (10.79) also supports this finding and is consistent with the high carbohydrate content (~36 %) and low protein level in *U. lactuca*.

Seaweeds are recognized as an potential source of essential minerals, particularly calcium (Ca), magnesium (Mg), phosphorus (P), potassium (K), zinc (Zn), copper (Cu), manganese (Mn), and selenium (Se) etc. (Lomartire et. al. 2021). These minerals play key roles in the synthesis of hormones and enzymes, in healing, prevention and management of various diseases (Shirin et. al. 2010). *Ulva lactuca* is rich in high amounts of Ca and K, and also contain good levels of Mg, P (Mohan et al. 2023). The presented finding also demonstrates that *U. lactuca* is rich in various minerals at health-beneficial levels, indicating both effective mineral uptake from the marine environment and its commercial potential as a mineral-rich seaweed product for health-oriented markets. Besides essential minerals, seaweeds may accumulate heavy metals from the environment, particularly arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg), posing serious health risks such as carcinogenicity, neurotoxicity, and oxidative damage (Huang et al. 2025). Recommended maximum limits for heavy metals in edible seaweed differ among geographical locations. For example, allowable limits for As in edible seaweeds vary widely across countries (Huang et al. 2022). The measured heavy metal concentrations in *U. lactuca* in the presented study are comparable to the acceptable limits according to some regulations but exceed the thresholds set by others. This discrepancy underscores the need for further *in vitro* and *in vivo* analyses to accurately evaluate heavy metal accumulation in *U. lactuca* from Bangladesh.

Primary metabolites

The measured carbohydrate content with negligible variation demonstrates that there is no impact on carbohydrate levels in *U. lactuca,* when the post-harvest fresh biomass is processed under four different drying treatments. On average, the determined carbohydrate in fresh and other treated biomasses was found to be ~36 %, which is comparable to the typical range reported for this genus. For instance, Uribe et al. (2019), Rasyid (2017), Pangestuti et al. (2021), Yohannan et al. (2025) and Yaich et al. (2011) showed that the carbohydrate contents of *U. lactuca* from the Chile, Indonesia

and Tunisian coast were in a broad range (17–65 %). Above reported results highlight the broad variability in *Ulva*'s carbohydrate content, which is primarily governed by environmental conditions (temperature, light, nutrient availability).

No significant difference in protein content was observed between the fresh and freeze dried and among the air, sun and oven dried of *U. lactuca*. However, air-, sun- and oven-drying methods significantly lower protein levels compared to those were measured in fresh or freeze-dried biomass. The presented finding demonstrates that elevated drying temperatures can reduce the protein content in *U. lactuca* biomass, most likely due to thermal denaturation, which decreases the solubility and extractability of proteins. Moreover, the heterogeneous and species-specific architecture of seaweed cell walls, together with phenolic–protein interactions, often results in proteins being entrapped within polysaccharide networks or forming insoluble complexes with phenolics, thereby reducing extraction (Juel et al. 2024). Consequently, low-temperature drying techniques such as air- or sun-drying could be considered more suitable options, offering a balance between maintaining protein integrity and ensuring cost-effective, durable preservation of seaweed biomass. The presented protein level in *U. lactuca* is relatively lower compared to previously reported findings (10.89 to 17.88 %, DW) (Abirami and Kowsalya 2011; Tabarsa et al. 2012; Khairy and El-Shafay 2013; Abdel-Khaliq et al. 2014; Rasyid 2017; Raja et al. 2020). This finding is supported by the C/N ratio (Table 2) which is consistent with the low protein level and relatively high carbohydrate content in *U. lactuca*.

The highest lipid content in sun-dried or freeze-dried biomass indicates that drying under sun or freeze dryer are beneficial compared to the fresh and other drying processes such as air drying or oven drying. Previous reports also agree with the variations in total lipid contents mostly for drying treatment, regional and seasonal variation. For example, Lipid contents were found significantly varied in different drying treatment of red seaweeds, *Gracilariopsis longissima* such as for freeze drying (1.49 %, DW), sun drying (1.34 %, DW) and oven-drying (1.26 %, DW) (Ullah et al. 2023). El Maghraby and Fakhry (2015) also reported that the lipid content in seaweeds (grown in Egypt) (shaded-dried), ranging from 1.56 to 4.14 %, DW and varies significantly between different algae (*Jania rubens*, *U. linza* and *Padina pavonica*), and different seasons (spring, summer and autumn). Moreover, the lipid content in *U. lactuca* from Iran and *U. intestinalis* from Bangladesh were found 3.60 % and 3.50 %, DW respectively, which are comparable to that was reported study by Rohani-Ghadikolaei et al. 2012 and Mohibbullah et al. 2024. Lipid content was found to be 0.19 to 0.38 %, DW in different *Ulva* species (Rasyid 2017; Jatmiko et al. 2019 and Raja et al. 2020), which are lower compared to that was determined *U. lactuca* in the presented findings.

There are many incomprehensive and contradictory reports of drying effect showing increasing or decreasing, or even no effect on the extraction of metabolites from different seaweeds, which may be attributed to the variation of temperature and methods of drying, species varieties and geographical location of seaweeds (Silva et al. 2019; Uribe et al. 2019; Alghazeer et al. 2022; Sravani et al. 2023; Ullah et al. 2023). Moreover, seasonal variations also has immense impact on the contents of carbohydrates, proteins and lipids in seaweeds (Lafeuille et al. 2023).

Secondary metabolites

Unlike carbohydrate metabolites, all drying methods exerted a strong influence on TPC and TFC, though the magnitude and direction of the changes depend markedly on the used drying techniques. In this study, the phenolic contents were found in the rage of 40 - 52 mg GAE g^{-1} DW. The findings both align and contrast with other studies. In support of the influence of drying methods on phenolic retention, Uribe et al. (2019) reported for *Ulva* sp. that sun drying resulted in a slight increase in phenolic content (1.43 ± 0.05 mg GAE g^{-1} DW) compared to freeze-drying (1.35 ± 0.05 mg GAE g^{-1} DW), while oven-drying caused a greater reduction (0.90 ± 0.04 mg GAE g^{-1} DW). The TPC in the fresh sample (1.45 ± 0.13 mg GAE g^{-1} DW) did not differ significantly from that of the sun-dried sample, suggesting that moderate solar exposure may not degrade phenolics substantially. However, contrasting patterns have also been documented. For example, EI Majnaoui et al. (2025) reported a lower TPC in sun-dried (11.03 ± 1.13 mg GAE g^{-1} DW) *U. lactuca* biomass compared to that was obtained from oven drying of biomass at 60 °C (42.03 ± 1.56 mg GAE g^{-1} DW) and 40 °C (29.50 ± 0.99 mg GAE g^{-1} DW).

There was no significant variation of TFC in fresh, freeze-dried, and oven-dried samples, however, sun drying led to a significant reduction in total flavonoid content compared to other treatments, which suggests that exposure to direct sunlight may enhance degradation or oxidation of flavonoid compounds (Hassanpour et al. 2023). Similar findings were reported by Uribe et al. (2019), who observed lower flavonoid levels in sun-dried *Ulva sp.* (20.62 ± 0.77 mg CE (100 g)$^{-1}$ DW) compared to oven-dried samples (30.01 ± 2.25 mg CE (100 g)$^{-1}$DW). Likewise, *U. lactuca* has been shown to experience a marked decline in flavonoid levels under sun drying (3.00 ± 0.74 mg QCE g^{-1}, DW), whereas oven drying preserved significantly higher values (4.89 ± 0.14 mg QCE g^{-1}, DW) (EI Majnaoui et al. 2025). Taken together, these findings indicate that the effect of drying on TPC and TFC is species specific and condition-dependent and may

reflect both degradation and enhanced extractability of phenolics and flavonoids during thermal processing.

The TPC and TFC observed in the present findings were higher compared to previously published values (Silva et al. 2019; Uribe et al. 2019; Charles et al. 2020; Nunes et al. 2024; EI Majnaoui et al. 2025). For instance, Ouahabi (2024) reported the phenolics in the methanolic extracts of *U. lactuca*, 47.53 ± 0.05 mg GAE g^{-1} DW, which was comparable with the data found in the presented study, but the corresponding flavonoid content (27.18 ± 0.09 mg QE g^{-1} DW) was considerably higher than the values obtained in present study. In another study reported by (Ullah et al. 2024), TFC recorded for *U. intestinalis* was 7.92 ± 1.97 mg QE g^{-1} DW), that was aligned closely with the present findings. These differences among species and studies likely reflect variations in extraction solvents, harvest season, environmental conditions, and tissue maturity (Hurmat et al. 2025, Santulli 2023 and Jeon et al. 2021).

Antioxidant activities

Total antioxidant capacity (TAC), reducing power (RP), ferric reducing antioxidant power (FRAP) and DPPH scavenging activities were determined to assess the effects of post-harvest treatments on antioxidant properties of *U. lactuca* in this study. No single drying process did lower the antioxidant activities of *U. lactuca*, rather the antioxidant activities were found to be significantly elevated after some type of drying processes compared with fresh biomass. The variation in antioxidant activities among dried seaweeds can be attributed to differences in species, seasonal biochemical composition, extraction solvent, and particularly the drying method and temperature applied. For example, Sravani et al. (2023) reported that *U. lactuca* exhibited a higher DPPH radical scavenging activity in sun-dried (51.71 ± 1.37 %) compared to shade-dried (48.33 ± 0.41 %) and oven-dried samples (46.81 ± 1.67 %). In contrast, for *Gracilaria edulis*, shade drying produced significantly greater scavenging capacity (52.46 ± 0.51 %) than both direct sun drying (48.12 ± 1.25 %) and oven drying (48.24 ± 0.06 %). These findings highlight that the optimal drying approach for preserving antioxidant potential is species-specific, rather than universally consistent. Different antioxidant assays also yielded distinct results for the similar treatment of sample. For example, in *U. lactuca*, oven-dried extract at 25 °C demonstrated superior DPPH scavenging activity (IC_{50} = 32.71 ± 0.38 µg mL^{-1}) compared to the freeze-dried extract (40.30 ± 1.64 µg mL^{-1}, whereas in the FRAP assay, the freeze-dried sample (39.33 ± 1.17 µg mL^{-1}) exhibited a higher value than oven-dried sample (43.04 ± 0.03 µg mL^{-1}) (EI Majnaoui et al. 2025). The variations in different antioxidant activities among different extracts or drying treatments are expected since each antioxidant assay measures a different chemical mechanism. Radical-scavenging assays such as DPPH primarily assess hydrogen atom or electron donation capacity, whereas FRAP evaluate electron-transfer–based reducing power (Apak et al. 2016; Munteanu and Apetrei 2021). Thus, extracts enriched in compounds that are strong electron donors may perform well in FRAP but not necessarily show equally strong radical-scavenging outcomes in DPPH.

Conclusion

In this study, a green seaweed of Bangladeshi origin, *Ulva lactuca,* was examined for effect of drying on proximate composition, nutritional value and antioxidant properties and how drying affect these parameters in compare to the fresh seaweed. Though seaweed is a good source of high level of minerals, bioactive components and antioxidants, however, their level of nutrition values is affected by the process of cooking or drying which is important for commercial applications. This study shows that drying does not reduce the nutrient and secondary content as well as antioxidant activities when compared to the fresh biomass. However, choosing the right drying method is important. No single method gave the best results for all parameters. Instead, each drying method affected different metabolites, and none was clearly superior in every aspect.For examples, total contents of carbohydrate and protein were not affected by drying processes, except protein content for oven drying. Lipid content was significantly higher in sun-dried sample in compare to air- and oven-dried samples. Fresh, freeze drying and oven drying preserves higher levels of flavonoids, but the level of phenolics was the highest for sun drying. FRAP was elevated in air drying, sun drying and oven drying, and RP was found higher in freeze drying, air drying and sun drying. DPPH scavenging activity and TAC were found the highest in air drying and sun drying, respectively. Since freeze drying and oven drying processes are expensive, therefore, lower-temperature and low-cost approaches—particularly air drying or sun drying—appear to be the most practical and effective options for industrial and commercial use, with preserving the antioxidant potentials of *U. lactuca*, but it is necessary to check effect of storage in different temperatures and period in future.

Acknowledgments We acknowledge Professor Dr. Sheikh Aftab Uddin, Marine Sciences, University of Chittagong, for kindly identifying the seaweed.

Authors' contributions Uttam Kumer Roy (UR), Dwaipayan Sikdar (DS) and Suman Mojumder (SM) participated in the study and experimental design. Mita Nur Akter (MNA) performed experiments. Oishee Barua, MNA and Rahul Sharma (RS) collected and processed the samples. SM and RS analysed data and interpreted the results. Sajal Roy and Rajib Banik performed AAS and ICP-OS. SM and DS drafted the

manuscript. UR, DS edited and critically revised the manuscript. It is declared that all authors have contributed to this work and approved the final manuscript.

Funding This study was partially funded by Research and Publication Cell, University of Chittagong, Chattogram, Bangladesh.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Abdel-Khaliq A, Hassan HM, Rateb ME, Hammouda O (2014) Antimicrobial activity of three *Ulva* species collected from some Egyptian Mediterranean seashores. Int J Eng Res Gen Sci 2:648–669

Abirami RG, Kowsalya S (2011) Nutrient and nutraceutical potentials of seaweed biomass *Ulva lactuca* and *Kappaphycus alvarezii*. J Agric Sci Technol 5:109–115

Ahmed N, Taparhudee W (2005) Seaweed cultivation in Bangladesh problems and potentials. Fish Res Bull Kasetsart Univ 28:13–21

Akter TMM, Hamim FA, Rahman MM, Khatun MM (2023) Phytochemical screening, cytotoxic activity, antibacterial assay and proximate analysis of *Ulva intestinalis* algae from the Bay of Bengal, Bangladesh. Biores Commun 10:1424–1431

Alghazeer R, EL Fatah H, Azwai S, Elghmasi S, Sidati M, EL Fituri A, Althaluti E, Gammoudi F, Yudiati E, Talouz N, Shamlan G, Al-Farga A, Alansari WS, Eskandrani AA (2022) Nutritional and nonnutritional content of underexploited edible seaweeds. Aquacult Nutr 2022:8422414

Amano H, Noda H (1990) Proteins from protoplasts of red alga *Porphyra yezoensis*. Nippon Suisan Gakkaishi 56:1859–64

Anis M, Yasmeen A, Ghousia Baig S, Ahmed S, Rasheed M, Hasan MM (2018) Phycochemical and pharmacological studies on *Ulva fasciata* Delile. J Pharm Sci 31:875–883

Apak R, Özyürek M, Güçlü K, Çapanoğlu E (2016) Antioxidant activity/capacity measurement. 1. Classification, physicochemical principles, mechanisms, and electron transfer (ET)-based assays. J Agric Food Chem 64:997–1027

Badmus UO, Taggart MA, Boyd KG (2019) The effect of different drying methods on certain nutritionally important chemical constituents in edible brown seaweeds. J Appl Phycol 31:3883–3897

Barot M, Nirmal Kumar JI, Kumar RN (2019) An evaluation of the nutritional composition of seaweeds as potential source of food and feed. Natl Acad Sci Lett 42:459–464

Bentoulla T, Kotsou K, Kalompatsios D, Alibade A, Athanasiadis V, Bozinou E, Lalas SI (2024) Investigation and enhancement of the antioxidant compound recovery of *Pyrus communis* peel. Waste 2:382–396

Bokhtiar SM, Sarker D, Alima A, Salam MA, Ahmed KU, Anwar MM, Hossain MF, Ahmed M, Bhuiyan MS, Kanta RA, Asaduzzaman AKM, Ahmed KS, Hemayet H, Rafiquzzaman SM (2024) Nutritional profiling, phytochemical screening, cytotoxicity and antioxidant content analysis for different crude extracts of *Ulva lactuca* from coast of Bangladesh. Future Foods 2024:100513

Charles AL, Sridhar K, Alamsjah MA (2020) Effect of drying techniques on color and bioactive potential of two commercial edible Indonesian seaweed cultivars. J Appl Phycol 32:563–572

Choudhary B, Khandwal D, Gupta NK, Patel J, Mishra A (2023) Nutrient composition, physicobiochemical analyses, oxidative stability and antinutritional assessment of abundant tropical seaweeds from the Arabian Sea. Plants 12:2302

Cindana MFR, Wilar G, Devkota HP, Wathoni N (2020) Ulvan, a polysaccharide from macroalga *Ulva* sp.: a review of chemistry, biological activities and potential for food and biomedical applications. Appl Sci 10:5488

Costa SP, Cotas J, Pereira L (2024) Laminar *Ulva* species: a multi-tool for humankind? Appl Sci 14:3448

Dey TB, Kuhad RC (2014) Enhanced production and extraction of phenolic compounds from wheat by solid-state fermentation with *Rhizopus oryzae* RCK2012. Biotechnol Rep 4:120–127

EI Majnaoui S, Lekrati M, EI Broudi S, Benkhalti F, Zehhar N, ElKaoua M, Houari A, El Kadmiri N (2025) Effect of drying methods on phenolic compounds, antioxidant activity and surface colour of the potentially valuable Moroccan seaweeds *Gracilaria gracilis* and *Ulva lactuca*: modelling the optimal treatment. Appl Phycol 6:223–235

El Maghraby DM, Fakhry EM (2015) Lipid content and fatty acid composition of Mediterranean macro-algae as dynamic factors for biodiesel production. Oceanologia 57:86–92

Farhaduzzaman A, Khan S, Hasan M, Islam R, Osman MH, Shovon NH, Haider SMB, Kunda M, Islam T, Bhuyan S (2023) Seaweed culture, post-harvest processing, and market generation for employment of coastal poor communities in Cox's Bazar. J Appl Life Sci Environ 56:231–244

García-Poza S, Leandro A, Cotas C, Cotas J, Marques JC, Pereira L, Gonçalves AMM (2020) The evolution road of seaweed aquaculture: cultivation technologies and the industry 4.0. Int J Environ Res Public Health 17:6528

Ghosh R, Barua P, Sikder O, Saha S, Mojumder S, Sikdar D (2021) Comparison of phenolic content and antioxidant activity of two common fruits of Bangladesh in solvents of varying polarities. Food Res 5:187–196

Hassanzadeh H, Rahimabadi EZ, Babakhani A (2023) Effects of sun/open-air drying and oven-drying on chemical composition and functional properties of dried *Ulva intestinalis*. Casp J Environ Sci 21:1265–1271

Honey O, Nihad SAI, Rahman MA, Rahman MM, Islam M, Chowdhury MZR (2024) Exploring the antioxidant and antimicrobial potential of three common seaweeds of Saint Martin's Island of Bangladesh. Heliyon 10:e26096

Hossain MT, Sohag AAM, Haque MN, Tahjib-Ul-Arif M, Dash R, Chowdhury MTH, Hossain MA, Moon IS, Hannan MA (2021) Nutritional value, phytochemical profile, antioxidant property and agar yielding potential of macroalgae from coasts of Cox's Bazar and St. Martin's Island of Bangladesh. J Aquat Food Prod Technol 30:217–227

Huang L, Lee J-Y, Park Y-K, Lee J (2025) Heavy metals in seaweed: implications for health benefits, risks, and safety regulations. J Agric Food Res 21:101830

Huang Z, Bi R, Musil S, Pétursdóttir ÁH, Cheng B, Zhao P, Tan X, Jia Y (2022) Arsenic species and their health risks in edible seaweeds collected along the Chinese coastline. Sci Total Environ 847:157429

Jatmiko TH, Prasetyo DJ, Poeloengasih CD, Hernawan Khasanah Y (2019) Nutritional evaluation of *Ulva* sp. from Sepanjang coast, Gunungkidul, Indonesia. IOP Conf Series: Earth Environ Sci 251:012011

Jeon YH, Seo JE, Kim JH, Lee YJ, Choi SW (2021) Quantitative changes of flavonol glycosides from pine needles by cultivar, harvest season, and thermal process. Prev Nutr Food Sci 26:100–108

Juel N, Juul L, Tanambell H, Dalsgaard TK (2024) Extraction and purification of seaweed protein from *Ulva* sp.—challenges to overcome. LWT Food Sci Technol 198:115944

Kaladharan P, Veena S, Vivekanandan E (2009) Carbon sequestration by a few marine algae: observation and projection. J Mar Biol Assoc India 51:107–110

Khairy HM, El-Shafay SM (2013) Seasonal variations in the biochemical composition of some common seaweed species from the coast of Abu Qir Bay, Alexandria, Egypt. Oceanologia 55:435–452

Khan ABS, Ullah MR, Akhter M, Hasan MM, Yasmin F, Bosu A, Haque MA, Islam MM, Al-Amin Islam MA, Ali MZ (2024) Effect of distinct drying approach on bioactive compounds and nutritional profiling of *Ulva intestinalis* and *Padina tetrastromatica* from the Bay of Bengal. Bangladesh. Food Chem Adv 5:100778

Khan MSK, Hoq ME, Haque MA, Islam MM, Hoque MM (2016) Nutritional evaluation of some seaweeds from the Bay of Bengal in contrast to inland fishes of Bangladesh. IOSR J Environ Sci 10:59–65

Khan N, Sudhakar K, Mamat R (2024) Eco-friendly nutrient from ocean: exploring *Ulva* seaweed potential as a sustainable food source. J Agric Food Res 17:101239

Lafeuille B, Tamigneaux É, Berger K, Provencher V, Beaulieu L (2023) Impact of harvest month and drying process on the nutritional and bioactive properties of wild *Palmaria palmata* from Atlantic Canada. Mar Drugs 21:392

Lawton RJ, Sutherland JE, Glasson CRK, Magnusson ME (2021) Selection of temperate *Ulva* species and cultivars for land-based cultivation and biomass applications. Algal Res 56:102320

Liu K (2019) Effects of sample size, dry ashing temperature and duration on determination of ash content in algae and other biomass. Algal Res 40:101486

Lomartire S, Marques JC, Gonçalves AMM (2021) An overview to the health benefits of seaweeds consumption. Mar Drugs 19:341

Mantri VA, Kazi MA, Balar NB, Gupta V, Gajaria T (2020) Concise review of green algal genus *Ulva* Linnaeus. J Appl Phycol 32:2725–2741

Matyash V, Liebisch G, Kurzchalia TV, Shevchenko A, Schwudke D (2008) Lipid extraction by methyl-tert-butyl ether for high-throughput lipidomics. J Lipid Res 49:1137–1146

Mohamed HA-R, Abdelhameed RFA, Mohamed RA (2023) Ulva species usage in aquaculture: current status and future prospective. Biomed J Sci Tech Res 51:42985–43009

Mohan EH, Madhusudan S, Baskaran R (2023) The sea lettuce *Ulva sensu lato*: future food with health-promoting bioactivities. Algal Res 71:103069

Mohibbullah M, Hossain MA, Mithu MA et al (2024) Edibility of cultivated green seaweed *Ulva intestinalis* from Monkhali Beach, Cox's Bazar coast of Bangladesh: bio-toxicity and heavy metal contents. Sci Rep 14:32124

Morais T, Cotas J, Pacheco D, Pereira L (2021) Seaweeds compounds: an ecosustainable source of cosmetic ingredients? Cosmetics 8:8

Munteanu IG, Apetrei C (2021) Analytical methods used in determining antioxidant activity: a review. Int J Mol Sci 22:3380

Murphy J, Riley P (1962) A modified single solution method for the determination of phosphate in natural waters. Anal Chim Acta 27:31–36

Neoh YY, Matanjun P, Lee JS (2016) Comparative study of drying methods on chemical constituents of Malaysian red seaweed. Dry Technol 34:1745–1751

Nikolaisen L, Daugbjerg Jensen P, Svane Bech K, Dahl J, Busk J, Brødsgaard T, Rasmussen MB, Bruhn A, Bjerre A-B, Bangsø Nielsen H, Albert KR, Ambus P, Kádár Z, Heiske S, Sander B, Schmidt ER (2011) Energy production from marine biomass (*Ulva lactuca*). Danish Technological Institute

Nunes A, Dutra FS, Brito SNS, Pereira-Vasques MS, Azevedo GZ, Schneider AR, Oliveira ER, Santos AA, Maraschin M, Vianello F et al (2024) Effect of biomass drying protocols on bioactive compounds and antioxidant and enzymatic activities of red macroalga *Kappaphycus alvarezii*. Methods Protoc 7:88

Ortiz J, Romero N, Robert P, Araya J, Lopez-Hernández J, Bozzo C, Navarrete E, Osorio A, Rios A (2006) Dietary fiber, amino acid, fatty acid and tocopherol contents of the edible seaweeds *Ulva lactuca* and *Durvillaea antarctica*. Food Chem 99:98–104

Ouahabi S, Daoudi NE, Loukili EH, Asmae H, Merzouki M, Bnouham M, Challioui A, Hammouti B, Fauconnier M-L, Rhazi L et al (2024) Investigation into the phytochemical composition, antioxidant properties, and in-vitro anti-diabetic efficacy of *Ulva lactuca* extracts. Mar Drugs 22:240

Pangestuti R, Haq M, Rahmadi P, Chun BS (2021) Nutritional value and biofunctionalities of two edible green seaweeds (*Ulva lactuca* and *Caulerpa racemosa*) from Indonesia by subcritical water hydrolysis. Mar Drugs 19:578

Parkinson JA, Allen SE (1975) A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. Commun Soil Sci Plant Anal 6:1–11

Prieto P, Pineda M, Aguilar M (1999) Spectrophotometric quantitation of antioxidant capacity through the formation of a phosphomolybdenum complex: specific application to the determination of vitamin E. Anal Biochem 269:337–341

Raja R, Hemaiswarya S, Sridhar S, Alagarsamy A, Ganesan V, Elumalai S, Carvalho IS (2020) Evaluation of proximate composition, antioxidant properties, and phylogenetic analysis of two edible seaweeds. Smart Sci 8:95–100

Rasyid A (2017) Evaluation of nutritional composition of the dried seaweed *Ulva lactuca* from Pameungpeuk waters, Indonesia. Trop Life Sci Res 28:119–125

Rohani-Ghadikolaei K, Abdulalian E, Ng WK (2012) Evaluation of the proximate, fatty acid and mineral composition of representative green, brown and red seaweeds from the Persian Gulf of Iran as potential food and feed resources. J Food Sci Technol 49:774–780

Roy UK, Nielsen BV, Milledge JJ (2020) Effect of post-harvest conditions on antioxidant enzyme activity in *Dunaliella tertiolecta* biomass. Biocatal Agric Biotechnol 27:101661

Roy UK, Nielsen BV, Milledge JJ (2021) Tuning *Dunaliella tertiolecta* for enhanced antioxidant production by modification of culture conditions. Mar Biotechnol 23:482–500

Roy UK, Radu T, Wagner J (2022) Hydrothermal carbonisation of anaerobic digestate for hydro-char production and nutrient recovery. J Environ Chem Eng 10:107027

Roy UK, Wagner J, Radu T (2023) Production of metabolites in microalgae under alkali halophilic growth medium using a dissolved inorganic carbon source. Waste Biomass Valori 14:3339–3354

Santulli C (2023) Extraction of flavonoids from agrowaste. In: Bhawani SA, Khan A, Ahmad FB (eds) Extraction of natural products from

agro-industrial wastes, a green and sustainable approach. Elsevier, Amsterdam, pp 111–130
Sarkar MSI, Kamal M, Hasan MM, Hossain MI (2016) Present status of naturally occurring seaweed flora and their utilization in Bangladesh. Res Agric Livest Fish 3:203–216
Shirin K, Imad S, Shafiq S, Fatima K (2010) Determination of major and trace elements in the indigenous medicinal plant *Withania somnifera* and their possible correlation with therapeutic activity. J Saudi Chem Soc 14:97–100
Silva AFR, Abreu H, Silva AMS, Cardoso SM (2019) Effect of oven-drying on the recovery of valuable compounds from *Ulva rigida*, *Gracilaria* sp. and *Fucus vesiculosus*. Mar Drugs 17:90
Simon C, McHale M, Sulpice R (2022) Applications of *Ulva* biomass and strategies to improve its yield and composition: a perspective for *Ulva* aquaculture. Biol 11:1593
Sobuj MKA, Rahman S, Ali MZ (2024) A review on commercially important seaweed resources from the Bangladesh coast. Food Chem Adv 4:100655
Sravani K, Ganesan P, Balasundari S, Muralidharan N, Chrisolite B, Dhanapal K (2023) Effect of different drying methods on the nutritional, functional, and bioactive properties of *Gracilaria edulis* and *Ulva lactuca*. J Coast Res 39:940–948
Stedt K, Trigo JP, Steinhagen S, Nylund GM, Forghani B, Pavia H, Undeland I (2022) Cultivation of seaweeds in food production process waters: evaluation of growth and crude protein content. Algal Res 63:102647
Tabarsa M, Rezaei M, Ramezanpour Z, Waaland JR (2012) Chemical compositions of the marine algae *Gracilaria salicornia* (Rhodophyta) and *Ulva lactuca* (Chlorophyta) as a potential food source. J Sci Food Agric 92:2500–2506
Thawabteh AM, Swaileh Z, Ammar M, Jaghama W, Yousef M, Karaman R, Bufo SA, Scrano L (2023) Antifungal and antibacterial activities of isolated marine compounds. Toxins 15:93
Ullah MR, Akhter M, Khan ABS, Yasmin F, Hasan MM, Bosu A, Haque MA, Islam MS, Islam MA, Mahmud Y (2024) Nutritional composition and phenolic contents of *Gracilariopsis longissima*, *Padina tetrastromatica* and *Ulva intestinalis* from the Bay of Bengal, Bangladesh coast. Heliyon 10:e31128
Ullah MR, Akhter M, Khan ABS, Yasmin F, Hasan MM, Bosu A, Haque MA, Islam MM, Islam MA, Mahmud Y (2023) Comparative estimation of nutritionally important chemical constituents of red seaweed, *Gracilariopsis longissima*, affected by different drying methods. J Food Qual 2023:6623247
Uribe E, Vega-Gálvez A, García V, Pastén A, López J, Goñi G (2019) Effect of different drying methods on phytochemical content and amino acid and fatty acid profiles of the green seaweed, *Ulva sp*. J Appl Phycol 31:1967–1979
Uribe E, Vega-Gálvez A, García V, Pastén A, Rodríguez K, López J, Scala KD (2020) Evaluation of physicochemical composition and bioactivity of a red seaweed (*Pyropia orbicularis*) as affected by different drying technologies. Dry Technol 38:1218–1230
Yaich H, Garna H, Besbes S, Paquot M, Blecker C, Attia H (2011) Chemical composition and functional properties of *Ulva lactuca* seaweed collected in Tunisia. Food Chem 128:895–901
Yang Y, Zhang M, Alalawy AI, Almutairi FM, Al-Duais MA, Wang J, Salama ES (2021) Identification and characterization of marine seaweeds for biocompounds production. Environ Technol Innovat 24:101848
Yohannan ASK, Mookkan P, Nagabhushana S (2025) Phytochemistry, bioactive potential, and chemical characterization of free-floating algae *Ulva profunda* W.R.Taylor — a lesser known species from Andhra Pradesh, India. Biomass Convers Biorefin 15:2223–2241
Zhu X, Healy L, Zhang Z, Maguire J, Sun D, Tiwari BK (2021) Novel postharvest processing strategies for value-added applications of marine algae. J Sci Food Agric 101:4444–4455

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.