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ORIGINAL PAPER

Nutritional values, antioxidant, and cytotoxic activities of selected edible marine macroalgae: a comparative study

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Abstract

The objective of this study is to assess the chemical composition, nutritional values, and bioactivities of four macroalgae from the Egyptian Red Sea coasts using standard methods. Of these, three Rhodophyceae species, *Digenea simplex* (*D. simplex*), *Laurencia papillosa* (*L. papillosa*), and *Galaxaura oblongata* (*G. oblongata*), and one Phyaeophyceae species, *Turbinaria decurrens* (*T. decurrens*), were selected. The results of proximate and chemical composition analyses based on the algal dry weight (DW) showed that carbohydrate content was the highest, ranging from $32.47 \pm 1.03\%$ to $45.5 \pm 1.23\%$. Other algal constituents, including ash, protein, moisture, sulfate, lipid, phenolics, and flavonoids, have contents that depend on the algal species. Besides, HPLC analysis revealed that each algal extract contained varying amounts of nine phenolic acids. Atomic absorption spectrometry, the HPLC-Pico-Tag method, the ion chromatography technique, and GC/MS analyses were used to determine the chemical profiles of the elemental, amino acid, halide, and fatty acid of each algal extract. Bioactivities revealed that both the •DPPH and ABTS assays showed that all the algae studied had a significant ability to scavenge free radicals in a dosage-dependent way. They also had strong selective cytotoxic activity against HEPG-2 and HCT-116 cell lines, but only weak activity against MCF-7 and A549 cell lines. Finally, our findings suggested that the selected algae might be efficiently used as nutraceuticals and functional foods, indicating an increase in their proliferation.

Keywords Rhodophyceae · Phyaeophyceae · Algal extract · Proximate and chemical composition · Statistical analysis · Antioxidant and cytotoxic activities

Introduction

The necessity for alternate food sources possessing advantageous nutritional qualities has become imperative considering the global population's growth, particularly in developing countries. On the other hand, the immensity of the Earth's oceans and seas is responsible for 99% of the planet's total livable space. Additionally, there are a variety of salinities, temperatures, pressures, light intensities (ranging from high to low), heavy metals, chemicals, oxygen concentrations from anthropogenic contaminants, and allelopathic defenses in the oceans and seas. Because of this environmental diversity, there exists a rich assortment of marine organisms that provide a diversified array of resources for the discovery and development of innovative pharmaceuticals aimed at addressing various human ailments [1–4].

Marine macroalgae represent a vast array of species that are integral to marine ecology. Based on the kinds of pigments, they are put into three major groups: Phaeophyta, Rhodophyta, and Clorophyta. Because marine macroalgae are regarded as one of nature's biggest biologically active resources and because they contain a great deal of bioactive compounds, there has been a significant uptick in the number of people interested in researching these organisms [5–7]. These compounds were found to have

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[8, 9], anti-inflammatory (Barbalace et al. 2019; Antony & Chakraborty 2020) [10, 11], antioxidant [12], immunestimulant [13], anticancer [14, 15], and other bioactivities [16–18]. Also, many species of macroalgae are used commercially around the world, and most of them are consumed as human food, in particular red algae. These latter are high-protein sources, with some of them having protein contents that are higher than those of other high-protein foods like eggs, seafood, cereals, and soybeans [19]. Additionally, marine macroalgal polysaccharides consist of both digestible (ranging from 2 to 10%) and indigestible components. The digestible (nutritive) ones vary between the different types of algae [20]. Red algae are mostly composed of agarans and carrageenans, whereas brown algae predominantly consist of laminarin, fucoidans, and alginates. In addition, it should be noted that marine macroalgae possess a significant abundance of minerals, polyunsaturated fatty acids, and vitamins, as shown by the findings of Leandro et al. [6] and Øverland et al. [21]. Despite their low-fat content, these foods nonetheless provide nutritional value.

When compared to diets made from animals or terrestrial plants, marine macroalgae offer little energy and have lower rates of diabetes, obesity, heart disease, and cancer [22–24]. Thus, the use of marine macroalgae as a healthy, nutritious meal source is well documented. Moreover, marine macroalgae have been employed in the human diet since ancient times, whether baked, dried, uncooked, or pickled. They have also been incorporated into a variety of foods in Japan and China, including salads, soups, snacks, stews, and bread [25]. Due to the evolution of the food industry, there is now a growing interest in marine algal components as functional foods or nutraceuticals, where marine macroalgal phytoconstituents are harnessed in a variety of applications (such as pharmaceutical, biotechnological, food applications, and biodiesel production) [6, 26, 27]. There are other functions of food, like preventing diseases, modulating physiological systems, and improving human well-being. Because of this, making functional foods has become the main goal of new products.

Egypt is home to a diverse array of marine macroalgae species. Nevertheless, the emphasis on its use throughout various fields is a comparatively recent advancement when juxtaposed with other countries. Furthermore, it is worth noting that Egyptian marine algae are now facing a dearth of scholarly papers and a limited comprehension of their chemical composition. These factors are crucial to adequately assess the nutritional significance of these algae.

Based on the aforementioned information, a total of four marine macroalgae species were chosen for the current study. Among these species, three belong to the class Rhodophyceae [*Digenea simplex* (*D. simplex*), *Laurencia papillosa* (*L. papillosa*), and *Galaxaura oblongata* (*G. oblongata*)], while one belongs to the class Phyaeophyceae [*Turbinaria decurrens* (*T. decurrens*)]. These particular species were picked due to their high prevalence along the beaches of the Egyptian Red Sea. Subsequently, an examination was conducted to determine the biochemical composition, nutritional value, and antioxidant activity of the selected algae.

Materials and methods

Sampling collection and identification

The algae were collected over the months of September 2019 and May 2020 by scuba diving along the Red Sea shore in Sharm EL Shaikh, Egypt. The freshly collected algae were individually subjected to a comprehensive cleaning process using both seawater and tap water in order to eliminate any extraneous substances. These algae were identified as *Digenea simplex* (Wulfen) C. Agardh, *Laurencia papillosa* (C. Agardh) Greville, *Galaxaura oblongata* (J. Ellis & Solander) J.V. Lamour, and *Turbinaria decurrens* (Bory) J. Agardh by both Prof. Rawheya Salah El-Din and Prof. Ehab El Belely, Applied Phycology, Botany, and Microbiology Department, Faculty of Science, Al-Azhar University, Egypt. Each variety of algae was weighed to 500 g and thereafter air-dried in a shaded environment prior to being pulverized using a grinder.

Chemicals

DPPH of laboratory grade was obtained from Sigma-Aldrich Co LLC in Saint Louis, MO. Sigma Chemical Co. (Madrid, Spain) provided the ABTS and Trolox. Authentic amino acids were sourced from Merck, Germany. Other chemicals were analytically pure and didn't need to be further purified before use.

Estimation of proximate composition

The chemical components of the proximate analysis were determined using the methods documented by the Association of Official Analytical Chemists (AOAC). These components include moisture, crude protein, ash, and lipids [28].

To determine the moisture content, 20 g of each dried powdered algae sample were subjected to heating at a temperature of 110 °C for a duration of twenty-four hours in a crucible until a consistent weight was achieved.

$$\% \text{ Moisture} = \left[\frac{W_1 - W_2}{\text{Sample weight}}\right] \times 100$$

W_1 is the initial weight of the crucible plus the sample, and W_2 is the final weight of the crucible plus the sample.

The ash content of various algal powders was determined by subjecting five grams of each sample to combustion in a muffle furnace at a temperature of 600 °C for a duration of five hours. The protein content was determined via a modified Kjeldahl technique, wherein the nitrogen concentration was measured and subsequently multiplied by a factor of 6.25. The Soxhlet extraction method was employed to quantify the total lipid content and afterwards express it as a percentage relative to the DW.

The El-Rafie et al. method [29] was used to synthesize fatty acid methyl esters (FAMEs), and a Perkin Elmer Clarus 680 GC/MS with gas chromatography and a mass spectrophotometer was used to analyze the FAMEs. Tentative identification of the four algae's FAMEs was accomplished by comparing their retention times and mass fragmentation patterns to those found in Wiley and NIST (USA) databases, commercially accessible libraries, and/or publicly available data [30]. Based on the results of the computerized peak area measurements, a quantitative determination was carried out.

To determine the total carbohydrate content as glucose, the phenol-sulfuric acid method was employed [31]. The colorimetric Folin-Ciocalteu method was used to determine the total flavonoid and phenolic content in terms of mg RE/g extract and mg GAE/g extract, respectively [32].

The sulfate content was determined using the sulfate hydrolysis procedure, followed by sulfate precipitation as $BaSO_4$ [33]. A known amount of each dried alga (W_1, g) was hydrolyzed in 50 mL of 1 N HCl at boiling temperature for 30 min before being added to 10 mL of 0.25 M $BaCl_2$. After 5 h of cooling at ambient temperature, the barium sulfate precipitates were filtered through ashless filter paper and burned at 700 °C for 1 h. The white ash (W_2) was weighed, and the sulfate concentration was calculated using the following equation:

$$\% \text{ Sulfate} = \left[\frac{W_2}{W_1}\right] \times 100 \times 0.4116$$

Phenolic acid profile

The HPLC analysis of the phenolic acid profile was performed using an Agilent 1260 series. The chromatographic separation was performed using a C-18 4.6 mm x 250 mm Eclipse column (5 µm particle size). In the mobile phase, a flow rate of 1 mL/min of water (A) and 0.05% trifluoroacetic acid in acetonitrile (B) was used. For the mobile phase, the following time intervals were programmed sequentially: 0 min (82% A), 0–5 min (80% A), 5–8 min (60% A), 8–12 min (6% A), 12–15 min (85% A), and 15–16 min (82% A). At 280 nm, the multi-wavelength detector was tracked. Each alga sample was fully extracted using 80% methanol in water. Following extraction, the supernatant was filtered, and each sample solution was injected into the chromatogram at a volume of 10 µL. According to Hasan et al. 2022, the temperature in the column was always kept at 35 ºC [33].

Elemental profile

Following wet digestion (acid digestion) of each algal sample, the elemental composition of the algal samples under investigation was evaluated by atomic absorption spectrometry, flame photometry, and spectrophotometry according to previous methods [34].

Halides profile

Ion chromatography was used following the process of wet digestion to determine the amounts of fluoride, chloride, bromide, and iodide present in each individual algal sample [35].

Amino acid profile

The amino acid content of each algal sample was determined using the HPLC-Pico-Tag technique, and the total amino acid composition was calculated using an amino acid analyzer [34].

Antioxidant activity

DPPH- radical scavenging method

The $^{\bullet}$ DPPH (2,2-diphenyl-1-picrylhydrazylhydrate) free radical method [36] was carried out as follows: In a microplate (96-well plate; $n=6$), 100 µL of newly made DPPH solution (0.1% in methanol) was added to algal samples as well as the standard drug, Trolox, at concentrations of 25, 50, 75, 100, and 150 g/mL. The reaction was allowed to incubate at room temperature and in the dark for 30 min. The $^{\bullet}$ DPPH color intensity at 515 nm was reduced after incubation. The data collected was analyzed by calculating the mean standard deviation (SD). The following formula was used to calculate the radical scavenging activity percentage:

$$\% \, DPPH \, radical \, scavenging \, activity = \left[\frac{A_1 - A}{A_1}\right] \times 100$$

A is the sample absorbance, while A1 is the reference absorbance (• DPPH without sample). A curve of each sample's concentration vs. DPPH scavenging activity (%) was made to find out how much of this sample was needed to reduce the initial DPPH concentration by 50%. This is called the "IC_{50}".

ABTS-radical scavenging activity

The experiment was conducted using the methodology outlined by Arnao et al. [37], with only a few modifications to allow the experiment to be done on microplates. A volume of 100 µL of a freshly prepared solution containing 0.1% of ABTS [2,2'-azinobis-(3- ethylbenzothiazoline-6-sulfonic acid)] reagent was added to 80% methanol-algal samples containing Trolox at various doses. The absorbance of the samples was measured at a wavelength of 734 nm using a microplate reader after a duration of ten minutes. This measurement was then compared to the absorbance of the methanol-based blank solution. Each individual sample within the experiment was replicated three times. Both the IC_{50} value and the percentage of inhibition were calculated.

$$\text{Inhibition}\ (\%) = \left[\frac{\text{A}_{\text{control}} - \text{A}_{\text{sample}}}{\text{A}_{\text{control}}}\right] \times 100$$

Cytotoxic activity

Human liver cancer HEPG2 (ATCC® HB8065™), human breast cancer MCF7 (ATCC® HTB-22™), human colon cancer HCT 116 (ATCC® CCL-247™), human lung cancer A549 (ATCC® CCL-185$^{TM)}$, and normal human lung fibroblasts WI-38 (ATCC® CCL-75™) cell lines were obtained from the American Type Culture Collection (Manassas, VA, USA). All normal human lung fibroblasts and cancer cell lines were kept alive in the prescribed RPMI-1640 and Dulbico media, supplemented with L-glutamine at a concentration of 3 mM, 10% fetal bovine serum that had been inactivated at a temperature of 56 °C, streptomycin at a concentration of 100 mg/mL, and penicillin at a concentration of 100 IU/mL. According to Meerloo et al. [38], the process of cell growth required the utilization of an incubator with a temperature of 37ºC and an atmosphere consisting of 95% air and 5% carbon dioxide. All cancer cell lines, and WI-38 were exposed for two days to both the methanol extract of the four algae and the standard drug Doxorubicin in a variety of different concentrations, serially diluted ten-fold *(*0.01, 0.1, 1, 10, 100 µg/mL*)* and zero concentration in the control well, just the nutritional medium was supplied to the cells during the ensuing two days. The cell survival was assessed using 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) [38]. An ELISA (enzyme-linked immunosorbent assay) microplate reader from Biotek (ELX-800) was used to determine the light intensity absorbance at 570 nm. The cell survival percentage was subsequently determined as follows:

$$Cell\ survival\ (\%) = \left[\frac{A_{sample} - A_{control}}{A_{control}}\right] \times 100$$

Each measurement was conducted in triplicate, and the outcomes are shown as the mean ± SD.

Statistical analysis

An analysis of variance (ANOVA) test was conducted on each item, using the mean and standard deviation ($\bar{x} \pm SD$), to generate a one-way analysis of variance table for each alga. Pearson's correlation coefficient was conducted to find a correlation between antioxidant activity IC_{50} and both total phenolic and flavonoid contents by ABTS and DPPH methods, as well as a correlation between the cytotoxic activity IC_{50} of the four studied cell lines and both total phenolic and flavonoid contents. The correlation coefficient with a negative value indicates a negative linear correlation, a positive value indicates a positive linear correlation, 0 indicates no linear correlation, 0-0.3 indicates a weak linear correlation, 0.3–0.7 indicates a moderate linear correlation, and 0.7-1 indicates a strong correlation.

Results and discussion

Proximate analysis

This study sheds light on the proximate compositions of the four selected algal species as a contribution to understanding the nutritional potential of these algae. Table 1 summarize the comparison of the proximate compositions as follows:

(a) All algal samples were found to have substantial amounts of ash, moisture, protein, and carbohydrate. However, the overall lipid content was shown to be rather low. *T. decurrens* has the greatest moisture content (14.11 ± 0.24%DW), while *L. pappillosa* follows with a moisture content of 11.36 ± 0.56%DW. *D. simplex* and *G. oblongata* have moisture contents of 7.40 ± 0.16%DW and 5 ± 0.34%DW, respectively. The ash content exhibited a range of values, specifically varying from 34.69 ± 1.11 to 42.88 ± 1.01. The ash values of the three red algae, namely *D. simplex*, *L. pappillosa*, and *G. oblongata*, were recorded as

35.18 ± 1.41%, 34.69 ± 1.11%, and 39.38 ± 1.34%DW accordingly. However, the ash value of the brown alga, *T. decurrens*, exhibited the greatest percentage at 42.88 ± 1.01%DW The ash obtained from the sea algae in this study was consistent with the findings published in previous scientific publications [39]. In general, the high ash concentrations observed in algae can be attributed to their capacity for absorbing minerals from their surrounding environment [40].

(b) The algal protein content (APCs) exhibits a high variation, averaging from 25.1 ± 1.12–14.31%. The red algae exhibited the greatest average percentage cover (APCs) among the studied species, with *L. pappillosa* having the highest APCs of 25.1 ± 1.12%, followed by *D. simplex* with 18.1 ± 0.73% and *G. oblongata* with 14.31 ± 0.21%. In contrast, the brown alga *T. decurrens* showed somewhat lower APCs of 14.75 ± 0.13%. The present findings demonstrate a lack of consistency with the results obtained in previous investigations [41], while aligning with the findings reported in another research study [42]. The APCs' findings are expected as they depend on a variety of climate-related factors (including seasonal variations, sunshine variability, temperature variability, sea level rise, etc.) as well as the specific location where the algae were collected [43, 44].

(c) The lipid content of the algae being investigated exhibited a range of 1.9 ± 0.12 to 2.43 ± 0.02%DW. The lipid content of *L. pappillosa* had the highest value at 2.43 ± 0.02%. This was followed by *D. simplex* with a lipid content of 2.22 ± 0.02%, *G. oblongata* with a lipid content of 2.06 ± 0.01%, and *T. decurrens* with a lipid content of 1.9 ± 0.12%. While marine macroalgae typically possess relatively low lipid levels, the nutritional value of these lipids is notably significant. The nutritional significance of these lipids is also ascribed to the substantial quantities of unsaturated fatty acids they contain [45].

(d) The carbohydrate concentrations of the four algae varied between 32.47 ± 1.03 and 45.5 ± 1.23%DW. Red algae have the largest concentrations of carbohydrates, with *D. simplex*, *L. pappillosa*, and *G. oblongata* having carbohydrate levels of 45.5 ± 1.23, 38.78 ± 0.98, and 45.25 ± 1.11%DW, respectively. This might perhaps be attributed to the greater amount of phycocolloids present in the cellular structures, as has been previously documented [46–48].

The quantitative chemical compositions of the algae under investigation were presented in Table 1. The flavonoid contents of the algae exhibited considerable variation, with the highest recorded value of 3.41 ± 0.12 mg RE/g extract observed in *D. simplex*. This was followed by *L. papillosa* and *T. decurrens*, which had flavonoid contents of 1.39 ± 0.16 mg RE/g extract and 1.56 ± 0.31 mg RE/g extract, respectively. The lowest flavonoid concentration of 1.04 ± 0.24 mg RE/g extract was found in *G. oblongata*. Furthermore, it was observed that red algae exhibited a high concentration of phenolic compounds. Specifically, the quantities of phenolic compounds in *D. simplex*, *L. papillosa*, and *G. oblongata* were measured to be 13.33 ± 0.6, 11.25 ± 0.42, and 3.90 ± 0.11 mg GAE/g extract, respectively. In contrast, the brown alga *T. decurrens* had a lower quantity of phenolic compounds, measuring at 4.62 ± 0.3 mg GAE/g extract. These findings are consistent with previous research on the phenolic and flavonoid compositions of red algae [49, 50]. Regarding the quantity of sulfate, it was found that the four algae species contained it in the following sequence: *G. oblongata* (2.5 ± 1.15) > *L. papillosa* (1.89 ± 0.98) > *D. simplex* (1.80 ± 1.22) > *T. decurrens* (1.46 ± 1.09). The observed outcome was anticipated due to the documented presence of very modest quantities of sulfated polysaccharide in brown algae, in contrast to the substantial levels found in red algae [51].

Elemental profile

The investigation of the mineral content of marine macroalgae has great importance in the assessment of the nutritional and toxicological implications associated with algae. The variation in metal accumulation among marine macroalgae can be attributed to several factors, such as the composition of their cell wall, morphological disparities across organisms, variances in life cycle duration, growth rates, and

Table 1 Proximate and biochemical composition of the four algae*

Pharmacopoeial Constant	*D. simplex*	*L. pappillosa*	*G. oblongata*	*T. decurrens*
Moisture [%DW]	7.40 ± 0.16^{abcd}	11.36 ± 0.56^{bacd}	5.0 ± 0.34^{cabd}	14.11 ± 0.24^{dabc}
Total ash [%DW]	35.18 ± 1.41^{acd}	34.69 ± 1.11^{bcd}	39.38 ± 1.34^{cabd}	42.88 ± 1.01^{dabc}
Lipid [%DW]	2.22 ± 0.02^{abcd}	2.43 ± 0.02^{bacd}	2.06 ± 0.01^{cabd}	1.9 ± 0.12^{dabc}
proteins [%DW]	18.1 ± 0.73^{abcd}	25.1 ± 1.12^{bacd}	14.31 ± 0.21^{cab}	14.75 ± 0.13^{dab}
Total carbohydrates [%DW]	45.5 ± 1.23^{abd}	38.78 ± 0.98^{bacd}	45.25 ± 1.11^{cbd}	32.47 ± 1.03^{dabc}
Sulfate [%DW]	1.80 ± 1.22^{a}	1.89 ± 0.98^{b}	2.5 ± 1.15^{c}	1.46 ± 1.09^{d}
Phenolics [mg GAE /g extract]	13.33 ± 0.6^{abcd}	11.25 ± 0.42^{bacd}	3.90 ± 0.11^{cabd}	4.62 ± 0.3^{dabc}
Flavonoids [mg RE /g extract]	3.41 ± 0.12^{abcd}	1.39 ± 0.16^{ba}	1.04 ± 0.24^{cad}	1.56 ± 0.31^{dac}

*In each column, the values followed by different letters are statistically different according to Tukey's post hoc test ($p < 0.05$)

Table 2 Elemental profile of the four algae

Element	*D. simplex*	*L. papillosa*	*G. oblongata*	*T. decurrens*
Macroelement concentration (mg/g)				
Calcium	0.59 ± 0.05	0.77 ± 0.05	0.22 ± 0.01	13.31 ± 0.10
Magnesium	0.81 ± 0.16	1.45 ± 0.27	0.94 ± 0.25	1.56 ± 0.56
Sodium	1.09 ± 0.42	2.00 ± 1.56	0.25 ± 0.14	0.45 ± 0.06
Potassium	1.84 ± 0.37	2.72 ± 0.47	0.55 ± 0.26	1.16 ± 0.14
Sodium/Potassium ratio	0.59 ± 0.28	0.74 ± 0.49	0.46 ± 0.09	0.39 ± 0.28
Phosphorus	0.06 ± 0.02	0.06 ± 0.01	0.03 ± 0.02	0.03 ± 0.01
Microelement concentration (µg/g)				
Iron	218.06 ± 2.852	118.05 ± 1.119	121.98 ± 1.405	225.80 ± 2.345
Manganese	013.70 ± 2.866	008.10 ± 1.639	003.50 ± 0. 549	002.00 ± 0.1342
Zinc	001.14 ± 0.614	000.85 ± 0.453	000.87 ± 0.482	001.16 ± 0.648
Copper	002.80 ± 1.572	001.20 ± 0.453	002.40 ± 0.482	001.20 ± 0.648
Cadmium	000.80 ± 0.417	000.30 ± 0.135	000.30 ± 0.153	000.10 ± 0.037

Table 3 Halides profile of the four algae

Halide	Percentage (W/W)			
	D. simplex	*L. papillosa*	*G. oblongata*	*T. decurrens*
Fluoride	0.05 ± 0.65	0.01 ± 0.56	0.01 ± 0.63	0.01 ± 0.45
Chloride	4.92 ± 0.45	4.32 ± 0.45	3.87 ± 0.34	5.12 ± 0.57
Bromide	0.22 ± 0.34	0.01 ± 0.52	0.01 ± 0.53	0.04 ± 0.41
Iodide	1.45 ± 0.72	1.67 ± 0.43	1.29 ± 0.54	1.05 ± 0.50
Total halides	6.64 ± 0.54	6.01 ± 0.49	5.18 ± 0.51	6.22 ± 0.48
Average halide concentration	5.93			6.22 ± 0.48

environmental pollution. Generally, marine macroalgae are widely recognized for their significant mineral content, which is vital for the nutritional needs of both people and animals.

Table 2 demonstrated that the predominant macroelements in the studied powdered algae, in addition to traces of phosphorus, are potassium, sodium, magnesium, and calcium. Iron and manganese have the highest quantities of microelements in both red and brown algae, followed by copper and zinc. The lowest concentration is in cadmium. Similar patterns have been noted in earlier data publications [51]. The high potassium and low sodium content of red and brown algae is significant, as it reflects the safety of their use in food, preventing both atherosclerosis and hypertension. The abundance of minerals in both three red and one brown algae suggests that they could be used as nutritive fertilizers and as supplements for minerals, particularly potassium, sodium, and calcium. Furthermore, they serve as a valuable reservoir of iron, a mineral that is ubiquitously present in all cells of the human body and has a crucial role in promoting overall well-being, both mentally and physically. All the algae under investigation exhibited notable mineral content because of their elevated ash level. This finding confirms their availability to be used as a sustainable and plentiful food source with high nutritional content and vital minerals to help address food shortages.

Halides profile

Marine algae are important halide intermediaries in sea water and play an important role at the interface between the ocean, the atmosphere, and land. The wide range of halogenated compounds present in and emitted from algae is believed to act as a self-defense mechanism [52, 53] According to the findings shown in Table 3, it can be observed that the average halide concentration in *T. decurrens* (6.22) is comparatively greater than that found in the red algae (5.93). Furthermore, it is noteworthy that chloride emerges as the most prevalent halide among the four algae species examined. Over the last few decades, researchers have extensively examined the biological attributes of algal halides. Their investigations have revealed that these compounds possess many properties, including insecticidal, antibacterial, anti-inflammatory, antifungal, antiviral, antiproliferative, antifeedant, antifouling, and cytotoxic activities [54].

Amino acids profile

The nutritional benefits of the four examined algae as a source of protein were further investigated by looking at the amino acid composition. Table 4 displays the four algal amino acid profiles. The following inferences can be drawn from these profiles:

(a) A total of seventeen amino acids have been found, with the eight essential amino acids (EAAs) comprising 21.90 ± 1.38, 21.90 ± 1.38, 8.30 ± 0.34, and 9.40 ± 0.62 µg/g dry algae in *D. simplex*, *L. pappillosa*, *G. oblongata*, and *T. decurrens*, respectively. Additionally, the nine non-essential amino acids (non-EAAs) constitute 32.50 ± 2.15, 31.30 ± 1.05, 14.00 ± 0.50, and 14.20 ± 0.49 µg/g dry algae of the total amino acids in the corresponding species mentioned above.

Table 4 Amino acids profile of the four algae (µg/g dry algae)

Amino Acids	*D. simplex*	*L. pappillosa*	*G. oblongata*	*T. decurrens*
Essential amino acids (EAAs)				
Therionine (Thr)	2.80 ± 0.71	3.00 ± 0.71	1.30 ± 0.71	1.30 ± 0.59
Phenylalanine (Phe)	2.60 ± 0.76	2.90 ± 0.59	1.10 ± 0.65	1.40 ± 0.48
Hisitidine (His)	1.01 ± 0.13	1.00 ± 0.14	0.30 ± 0.06	0.30 ± 0.06
Lysine (Lys)	5.80 ± 0.59	4.10 ± 0.94	1.70 ± 0.35	1.10 ± 0.33
Valine (Val)	2.70 ± 0.88	3.40 ± 0.71	1.30 ± 0.94	1.60 ± 0.54
Methionine (Met)	1.00 ± 0.30	1.00 ± 0.14	0.30 ± 0.06	0.60 ± 0.06
Isoleucine (IIe)	2.40 ± 0.65	2.40 ± 0.42	0.80 ± 0.37	1.20 ± 0.37
Leucine (Leu)	3.50 ± 1.05	3.60 ± 0.83	1.50 ± 0.26	1.90 ± 0.99
Total EAAs	21.90 ± 1.38	21.40 ± 0.75	8.30 ± 0.34	9.40 ± 0.62
Nonessential amino acids (Non-EAAs)				
Aspartic Acid (Asp)	5.60 ± 1.57	5.90 ± 0.41	2.50 ± 0.39	2.80 ± 0.21
Serine (Ser)	2.80 ± 0.59	2.60 ± 0.59	1.10 ± 0.41	1.10 ± 0.49
Glutamic (Glu)	6.10 ± 1.98	6.40 ± 1.81	3.20 ± 1.67	3.50 ± 1.50
Proline (Pro)	2.20 ± 0.51	5.00 ± 0.54	1.00 ± 0.87	1.10 ± 0.25
Glycine (Gly)	2.90 ± 0.82	2.90 ± 0.77	1.40 ± 0.65	1.50 ± 0.65
Alanine (Ala)	3.20 ± 0.99	3.40 ± 0.83	1.50 ± 0.94	1.80 ± 0.83
Tyrosine (Tyr)	3.80 ± 0.36	0.50 ± 0.13	1.30 ± 0.27	0.70 ± 0.17
Argnine (Arg)	3.40 ± 0.59	2.50 ± 0.59	1.10 ± 0.42	1.10 ± 0.94
Cysteine (Cys)	2.50 ± 0.31	2.10 ± 0.48	0.90 ± 0.19	0.60 ± 0.42
Total Non-EAAs	32.50 ± 2.15	31.30 ± 1.05	14.00 ± 0.50	14.20 ± 0.49

(b) While the composition of essential amino acids (EAAs) and non-essential amino acids (non-EAAs) is almost comprehensive, it should be noted that tryptophan is not present in the profile of EAAs, whilst glutamine and asparagine are not present in the profile of non-EAAs.

(c) The ratio of essential amino acids (EAAs) to non-essential amino acids (non-EAAs) in *D. simplex*, *L. pappillosa*, *G. oblongata*, and *T. decurrens* was found to be 0.67, 0.68, 0.59, and 0.66, respectively.

(d) Among the three red algae species, *D. simplex*, *L. pappillosa*, and *G. oblongata*, lysine is found to be the most prevalent essential amino acid (EAA) [55]. On the other hand, in the brown alga *T. decurrens*, leucine is identified as the most abundant EAA. Furthermore, it was observed that all the examined algae had very minimal quantities of methionine.

(e) In both *G. oblongata* and *T. decurrens*, cysteine is found in the lowest abundance among the non-essential amino acids (non-EAAs). However, glutamic acid and aspartic acid are the most abundant non-EAAs in all the algae studied.

The findings (a–e) indicate that the examined algae have potential as a viable and sustainable substitute for protein and amino acids in human nutrition and food processing [55].

Fatty acid profile

Table 5 illustrates the variations in fatty acid content among the algae species under investigation. The results of the study unequivocally demonstrated that:

(a) The primary saturated fatty acid (SFA) is palmitic acid methyl ester. The percentages for *D. simplex*, *L. pappillosa*, *G. oblongata*, and *T. decurrens* were 41%, 58%, 44%, and 26%, respectively. The findings presented here exhibit similarities to those documented in the study conducted by Berneira et al. [56].

(b) Methyl cis, cis-9,12-octadecadienoate, which is a highly concentrated omega-6 fatty acid, constitutes 8.90% of the fatty acid composition in *D. simplex*. In contrast, its proportions in *L. papillosa*, *G. oblongata*, and *T. decurrens* are 2.29%, 1.31%, and 0.76% respectively, as reported by Olsson et al. [52] and Berneira et al. [56].

(c) The fatty acid composition of *L. papillosa* includes a supplementary omega-6 fatty acid, specifically docosadienoic acid (methyl docosa-13,16-dienoate), which constitutes 1.5% of the overall profile. In the case of *D. simplex*, *L. pappillosa*, *G. oblongata*, and *T. decurrens*, the presence of an omega-3 fatty acid, methyl octadecatrienoate, is observed at percentages of 10.53, 8.31, 0.24, and 15.23%, respectively.

(d) Four species, namely *D. simplex*, *L. pappillosa*, *G. oblongata*, and *T. decurrens*, have been found to contain mono-unsaturated fatty acids. These fatty acids are specifically identified as methyl cis-9-octadecenoate (methyl oleate) and methyl eicosenoate (methyl gondoate). The percentages of methyl oleate in *D. simplex*, *L. pappillosa*, *G. oblongata*, and *T. decurrens* are 13.02%, 3.37%, 1.68%, and 1.73%, respectively. Additionally, the percentages of methyl gondoate in the same species are 1.42%, 0.50%, 0.44%, and 0.78%, respectively.

The findings pertaining to the fatty acid profile (Table 5) indicate that the four macroalgae in this study have the

Table 5 Fatty acid methyl esters profile of the four algae

No.	Fatty acid name	R_t	BP	M^+	MF	Relative Area%			
						I	II	III	IV
1	Methyl octanoate	6.96	74	158	$C_9H_{18}O_2$	ND	ND	0.07	ND
2	Methyl nonanoate	9.29	74	172	$C_{10}H_{20}O_2$	ND	ND	0.18	ND
3	Methyl decanoate	11.68	74	186	$C_{11}H_{22}O_2$	0.30	ND	0.54	ND
4	Methyl undecanoate	14.15	74	200	$C_{12}H_{24}O_2$	0.28	ND	0.16	ND
5	Methyl dodecanoate	16.56	74	214	$C_{13}H_{26}O_2$	2.43	10.40	24.17	ND
6	Methyl Tridecanoate	18.86	74	214	$C_{14}H_{26}O_2$	ND	0.20	0.40	ND
7	Methyl tetradecanoate	21.06	74	242	$C_{15}H_{30}O_2$	0.74	5.99	13.89	1.15
8	Methyl pentadecenoate	21.57	55	252	$C_{16}H_{28}O_2$	ND	0.12	ND	0.93
9	Methyl pentadecanoate	23.16	74	256	$C_{16}H_{32}O_2$	8.53	0.10	0.06	ND
10	Methyl hexadecenoate	24.73	55	268	$C_{17}H_{32}O_2$	0.20	ND	ND	0.12
11	Methyl hexadecanoate	25.23	74	270	$C_{17}H_{34}O_2$	41.19	58.40	44.03	26.72
12	Methyl heptadecenoate	26.61	55	282	$C_{18}H_{34}O_2$	ND	0.09	0.30	1.39
13	Methyl cis, cis-9,12-octadecadienoate	28.29	67	294	$C_{19}H_{34}O_2$	8.90	2.29	1.31	2.03
14	Methyl cis-9-octadecenoate	28.44	55	296	$C_{19}H_{36}O_2$	13.02	3.37	1.68	1.73
15	Methyl octadecanoate	28.79	74	298	$C_{19}H_{38}O_2$	5.72	1.46	0.98	6.36
11	Methyl nonadecenoate	29.71	74	310	$C_{20}H_{38}O_2$	ND	0.08	ND	0.66
17	Methyl octadecatrienoat	29.90	74	292	$C_{19}H_{32}O_2$	10.53	8.31	0.24	15.23
18	Methyl eicosenoate	30.60	55	324	$C_{21}H_{40}O_2$	1.42	0.50	0.44	0.78
19	Methyl eicosanoate	31.19	74	326	$C_{21}H_{42}O_2$	3.64	3.44	10.98	8.20
20	Methyl heneicosanoate	32.18	74	340	$C_{22}H_{44}O_2$	1.54	1.79	ND	ND
21	Methyl Docosahexaenoate	32.24	67	342	$C_{23}H_{34}O_2$	ND	0.16	ND	ND
22	Methyl docosa-13,16-dienoate	32.84	67	350	$C_{23}H_{42}O_2$	ND	1.50	ND	ND
23	Methyl docosenoate	33.28	55	352	$C_{23}H_{44}O_2$	ND	ND	ND	1.86
24	Methyl docosanoate	34.06	74	354	$C_{23}H_{46}O_2$	ND	0.48	0.13	14.31
25	Methyl tricosanoate	35.40	74	368	$C_{21}H_{42}O_2$	ND	0.66	ND	ND
26	Methyl cis-15-tetracosenoate	36.22	55	380	$C_{25}H_{48}O_2$	ND	ND	ND	4.68
	Total identified fatty acids					98.73	99.34	99.57	86.15
	Unsaturated fatty acids					34.36	16.42	3.74	28.48
	Saturated fatty acids					64.37	82.92	95.83	57.67
	ω-6 Fatty acid					8.90	3.79	1.31	2.03
	ω-3 Fatty acid					10.53	8.47	0.24	15.23
	ω-6/ω-3 Fatty acid ratio					0.85	0.45	5.46	1.33

I: *D. simplex*; **II**: *L. papillosa*; **III**: *G. oblongata*; **IV**: *T. decurrens*; **ND**: Not detected; $\mathbf{R_t}$: Retention time; **BP**: base peak; $\mathbf{M^+}$: Molecular ion peak; **MF**: Molecular formula

potential to serve as sustainable and beneficial sources of fatty acids for human consumption. Specifically, the ratio of omega-6 to omega-3 fatty acids in these macroalgae ranges from 0.45 to 5.46, suggesting that they can contribute to a healthy and well-rounded diet. According to the World Health Organization, it is recommended that the aforementioned ratio be maintained at a level below 10 in order to mitigate the risk of developing heart, nervous system, and inflammatory disorders [56].

Phenolic acid profile

Because phenolic contents have been related to a variety of biological activities [57, 58], the phenolic acid content of the chosen algae was determined by HPLC analysis. This study focused on investigating the antioxidant and cytotoxic activities of phenolic acids and their derivatives derived from four macroalgae.The data presented in Table 6 illustrates the presence of phenolic acids, which can be categorized as either benzoic acid derivatives (such as gallic acid, methyl gallate, syringic acid, and vanillic acid) or pyrocatechol or cinnamic acid derivatives (including chlorogenic acid, caffeic acid, ferulic acid, and coumaric acid). The concentrations of these phenolic acids vary depending on the specific algal species, as reported by Cotas et al. [59]. The antioxidant properties of phenolic acids and/or their derivatives have been documented in previous studies [60, 61]. Phenolic acids and their derivatives exhibit antioxidant activity through many pathways, such as hydrogen atom transfer, single-electron transfer through proton transfer, sequential proton loss electron transfer, and transition metal binding [62]. Furthermore, it has been observed that marine phenolic acids and their derivatives have significant anticancer activity [59].

Table 6 Profile of phenolic acids and their derivatives of the four algae

Peak No.	Name	R_t (min)	Concentration (mg/g)			
			I	II	III	IV
1	Gallic acid	2.605	8.84	8.13	9.52	2.86
2	Chlorogenic acid	3.152	0.95	0.92	2.35	2.56
3	Methyl gallate	4.642	0.82	0.71	0	8.45
4	Caffeic acid	4.840	2.10	2.00	0.22	0.41
5	Syringic acid	5.46	0	8.68	3.31	8.32
6	Pyrocatechol	5.978	0	0	0.23	0.30
7	Vanillin	9.325	2.15	2.10	2.03	10.10
8	Ferulic acid	10.382	1.36	1.36	0.37	1.44
9	Coumaric acid	10.765	1.80	1.79	1.54	0.82

I: *D. simplex*; **II**: *L. papillosa*; **III**: *G. oblongata*; **IV**: *T. decurrens*

Antioxidant activity

It is crucial to emphasize that marine macroalgae have a plethora of antioxidant compounds, which help the organism mount an endogenous defense mechanism against the effects of environmental stress [63]. The utilization of natural antioxidants, including those derived from algal extracts, is increasingly being considered as a potential substitute for synthetic antioxidants, which have been associated with various health issues [63]. The DPPH and ABTS tests were employed to evaluate the antioxidant activity of the methanol extracts derived from the algal samples under examination.

The findings pertaining to the antioxidants were depicted in Fig. 1, showcasing the percentages of radical scavenging activity and IC50 (µg/mL) values (A-D). These findings demonstrate that *L. papillosa* exhibits the most pronounced ABTS radical scavenging activity, as evidenced by its IC50 value of 69.15 ± 0.87 µg/mL. In comparison, both *D. simplex* and *T. decurrens* have similar levels of activity, with IC50 values of about 98.35 ± 0.29 µg/mL. The algae *G. oblongata* exhibited the lowest recorded activity, measuring at 151.86 ± 0.27 µg/mL. Notably, the activity levels of all four algae were found to be lower than those of the positive control, Trolox, which measured at 49.38 ± 0.42 µg/mL. The assessment of antioxidant activity in marine algae extracts often involves the utilization of the DPPH technique, which measures the radical scavenging ability. The antioxidants present in algal phytoconstituents are responsible for scavenging nitrogen-free radicals in the reaction. This scavenging process leads to a reduction in the intensity of the violet color of the solution. The extent of this reduction is then measured quantitatively using spectrophotometry at a wavelength of 515 nm. The results shown in Fig. 1 demonstrate a parallel trend between the DPPH activity and ABTS activity. The results indicate that *L. papillosa* exhibited the highest DPPH radical scavenging activity (24.99 ± 0.63 µg/mL), surpassing that of the positive control, Trolox (33.02 ± 0.7 µg/mL). The activities shown by *D. simplex* and *T. decurrens* were found to be almost same, with values of 60.28 ± 0.05 and 60.28 ± 0.05 µg/mL, respectively. In contrast, *G. oblongata* had a little lower activity level of 56.23 ± 0.95 µg/mL. The algae species *L. papillosa* exhibits a greater concentration of phenolic and flavonoid compounds compared to the three other algae species investigated [64]. This finding suggests a positive correlation between antioxidant activity and the overall content of polyphenolic and flavonoid compounds. Furthermore, the antioxidant levels of the four algal species, as measured using the DPPH assay, were shown to be greater in comparison to the levels reported through the ABTS assay.

In the case *of D. complex*, the ABTS technique revealed a substantial negative correlation between antioxidant activity IC_{50} and both total phenolic and flavonoid contents, with correlation coefficients of -0.96 and − 0.999. The IC_{50} of *T. decurrens* and *L. papillosa* antioxidants correlates strongly with total phenolic and flavonoid contents, with correlation coefficients of 0.841, 0.859, 0.984, and 0.972, respectively. In the case of *G. oblongata*, the correlation coefficient was positive (0.963) for flavonoids and weakly negative (-0.002) for phenolic contents (Table 7). According to the DPPH method, the correlation between antioxidant activity IC_{50} and total phenolic contents for *D. simplex* and *L. papillosa* was moderate (correlation coefficients of 0.361 and 0.379, respectively), while the correlation for *G. oblongata* and *T. decurrens* was weak (correlation coefficients of 0.094 and 0.246, respectively) (Table 7).

Cytotoxic activity

The effectiveness of four ethanolic extracts derived from algae was examined in relation to their potential anticancer properties. To achieve the objective, four cancer cell lines were employed, along with an MTT test, to conduct a comparative analysis of the cytotoxic effectiveness of the four algal extracts. Table 8; Fig. 2 show that the cell viability of all algal extracts was high at all doses tested against human lung fibroblasts (WI-38) during the assessment of

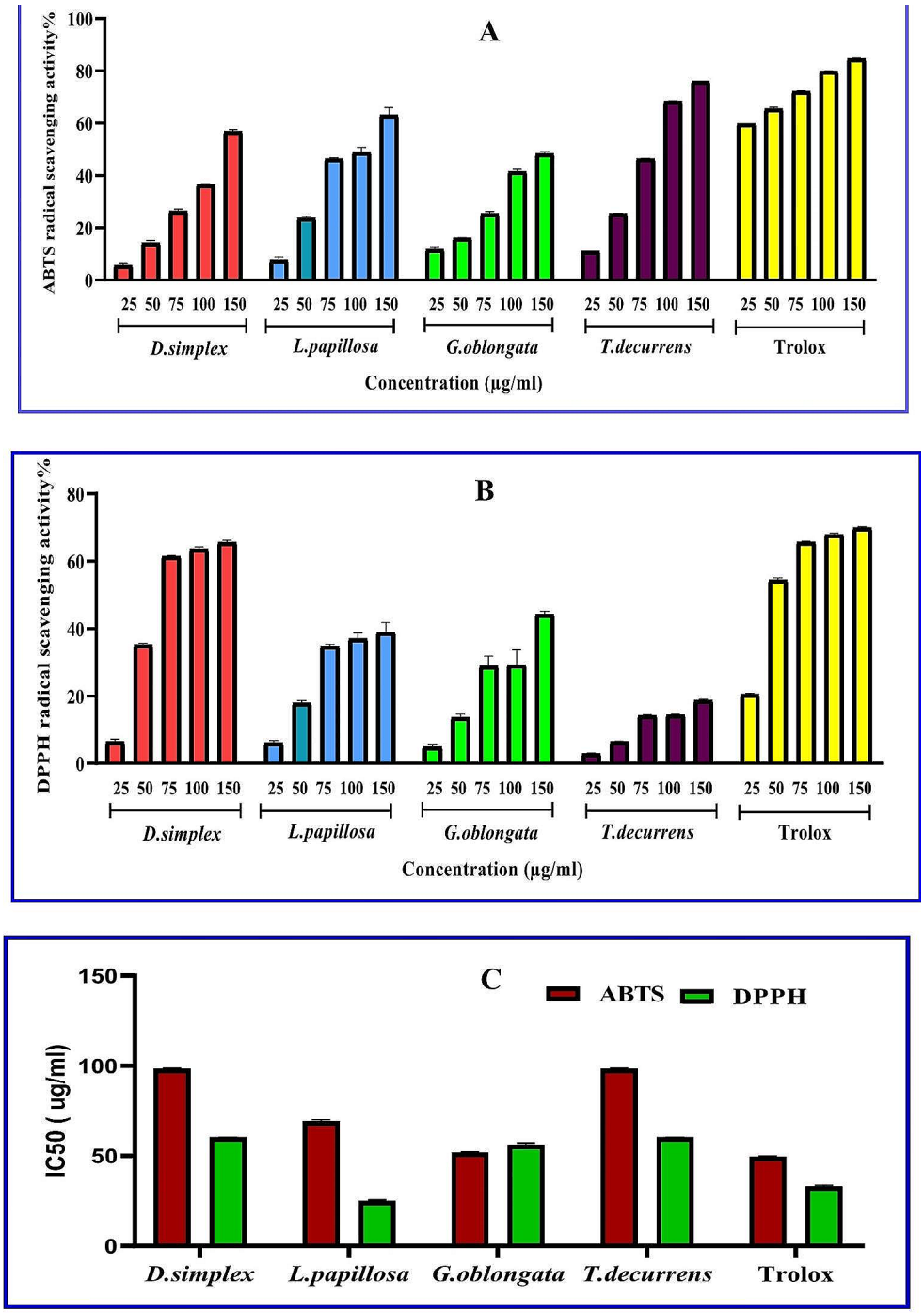


Fig. 1 Bar graph representing radical scavenging activity % (**A** and **B**) and IC_{50}% (**C**) of the four algae using ABTS and DPPH methods using Graph Pad Prism 8.02(263)

Table 7 Correlation between antioxidant activity (IC_{50}) and total phenolic and flavonoid contents using ABTS and DPPH techniques

Agal species	Correlation coefficient (*r*)			
	Phenolic content		Flavonoid content	
	ABTS	DPPH	ABTS	DPPH
D. simplex	-0.964	0.361	-0.999	0.190
L. papillosa	0.984	0.379	0.972	0.488
G. oblongata	-0.002	0.094	0.963	0.456
T. decurrens	0.841	0.246	0.859	0.287

cytotoxicity. Consequently, all examined algal extracts exhibited non-toxic properties and, therefore, were subjected to in vitro screening to assess their potential anticancer efficacy against four distinct human cancer cell lines (MCF-7, HEPG-2, HTC-116, and A549).

The results showed that all examined algal extracts had dose-dependent cell inhibition. However, their action against HTC-116 cells was only moderate, while their activity against both MCF-7 and A549 cells was modest.

Table 8 Cytotoxic activity of the four algae against four Human cancer cell lines, normal fibroblast and Doxorubicin (standard drug)

Conc. (µg/ml)	Cell Viability (%)				
	MCF-7	HEPG-2	HCT-116	A549	WI-38
D. simplex					
0	100 ± 1.3	100 ± 0.33	100 ± 1.12	100 ± 3.3	100 ± 6.3
0.01	96.73 ± 1.06	85.13 ± 2.6	83.89 ± 2.72	90.42 ± 2.8	95.9 ± 1.98
0.1	83.40 ± 0.18	72 ± 3.2	73.50 ± 1.9	87.36 ± 3.9	98.15 ± 1.54
1	67.96 ± 8.37	55.22 ± 4.7	61.42 ± 3.16	82.57 ± 2.6	80.27 ± 1.59
10	63.09 ± 4.9	52.55 ± 0.97	32.98 ± 1.12	76.01 ± 2.58	79.01 ± 0.92
100	59.9 ± 1.77	38.81 ± 5.25	29.22 ± 1.5	62.39 ± 1.07	78.26 ± 0.25
L. papillosa					
0	100 ± 2	100 ± 2.7	100 ± 0.68	100 ± 1.01	100 ± 1.7
0.01	88.28 ± 1.16	86.45 ± 7.16	86.66 ± 0.66	78.89 ± 2.21	96.97 ± 6.2
0.1	73.20 ± 6.29	78.18 ± 1.9	60.86 ± 0.87	73.20 ± 7.3	85.52 ± 13.9
1	62 ± 6.4	58.14 ± 1.05	58.5 ± 1.4	69.91 ± 7.4	78.59 ± 1.98
10	58.06 ± 10.4	45.25 ± 9.16	57.47 ± 1.06	66.76 ± 6.4	73.43 ± 1.16
100	43.45 ± 8.18	44.12 ± 1.9	48.22 ± 1.48	47.45 ± 2.9	66.32 ± 5.4
G. oblongata					
0	100 ± 0.61	100 ± 1.27	100 ± 1.9	100 ± 7.19	100 ± 0.24
0.01	93.34 ± 0.94	84.56 ± 1.16	96.50 ± 1.8	96.14 ± 1.38	95.47 ± 0.65
0.1	88.71 ± 1.8	66.87 ± 3.22	81.58 ± 1.96	89.74 ± 7.08	93.82 ± 2.33
1	82.76 ± 4.2	40 ± 2.7	79.42 ± 1.94	82.17 ± 8.55	85.96 ± 0.73
10	70 ± 3.37	39.4 ± 1.7	44.38 ± 6.05	71.09 ± 1.46	84.17 ± 1.11
100	67.74 ± 6.62	31.83 ± 2.01	30.38 ± 2.6	59.12 ± 1.90	60.37 ± 0.57
T. decurrens					
0	100 ± 0.61	100 ± 9.06	100 ± 0.54	100 ± 3.2	100 ± 1.7
0.01	88.27 ± 5.5	77.12 ± 3.7	94.58 ± 4.58	96.22 ± 0.67	94.64 ± 2.58
0.1	84.47 ± 0.35	44.60 ± 4.5	83.84 ± 9.25	94.76 ± 2.58	90.59 ± 3.6
1	64.96 ± 4,9	44.18 ± 1.9	68.87 ± 5.48	86.12 ± 0.67	86.80 ± 9.8
10	61.60 ± 3.8	40.95 ± 6.5	47.72 ± 5.4	62.81 ± 1.08	86.62 ± 5.8
100	51.64 ± 4.5	24.6 ± 2.012	41.75 ± 6.8	59.33 ± 1.48	78.78 ± 3.19
Doxorubicin					
0	100 ± 7.09	100 ± 0.55	100 ± 3.5	100 ± 1.69	100 ± 1.3
0.01	87.1 ± 0.6	94.16 ± 2.73	84.2 ± 0.6	76.47 ± 3.5	91.974 ± 0.3
0.1	51.03 ± 1.78	74.45 ± 2.87	54.29 ± 3.46	69.5 ± 2.33	89.5 ± 0.84
1	29.5 ± 1.105	48.27 ± 2.09	33.9 ± 1.9	60.23 ± 1.02	88.5 ± 2.73
10	14.9 ± 0.77	10.7 ± 0.276	4.69 ± 0.26	56.13 ± 0.71	83.4 ± 0.87
100	8.83 ± 1.21	7.7 ± 0.11	3.51 ± 0.2	32.22 ± 1.23	76.32 ± 4.57

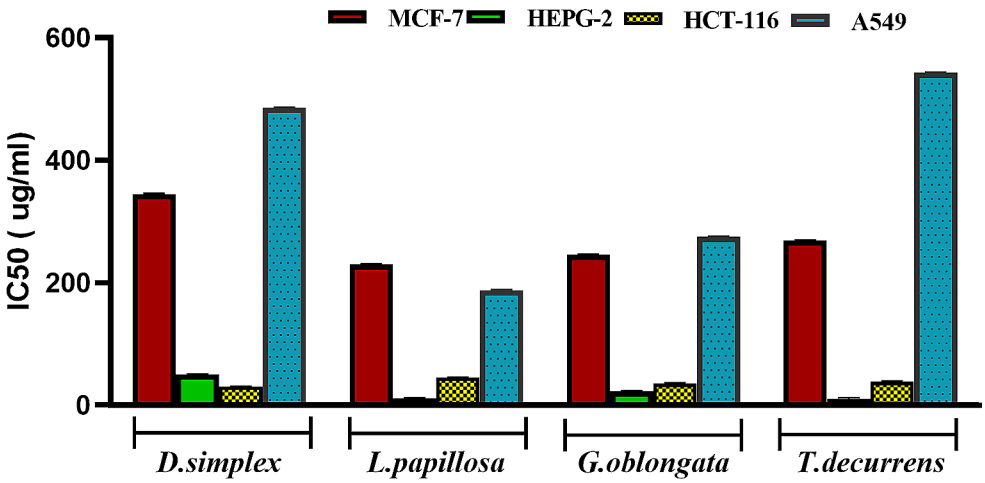


Fig. 2 Bar graph displaying the IC_{50}% of the four algae against cancer cell lines

Table 9 Correlation between total phenolic and flavonoid levels and the four cell lines under study's cytotoxic activity (IC_{50})

Agal species	Correlation coefficient (*r*)							
	Phenolic content				Flavonoid content			
	MCF-7	HEPG-2	HCT-116	A549	MCF-7	HEPG-2	HCT-116	A549
D. simplex	-0.542	-0.306	-0.549	-0.474	-0.664	-0.160	-0.682	-0.419
L. papillosa	-0.972	-0.605	-0.775	0.464	-0.951	-0.611	-0.766	0.447
G. oblongata	-0.434	0.128	0.377	0.352	-0.864	0.270	0.121	0.432
T. decurrens	-0.208	-0.573	0.529	-0.232	-0.267	− 0.057	0.523	-0.209

In contrast, the HEPG-2 cancer cell lines exhibited significant susceptibility to algal extracts, with *T. decurrens* demonstrating the highest impact, followed by *L. papillosa*, *G. oblongata*, and *D. simplex*, respectively. The presence of phenolics, particularly phenolic acids, in algal extracts is expected to result in cytotoxic effects, as demonstrated by their impact on the growth of several human tumors [65]. In addition, the ω-3, ω-6, and ω-9 fatty acids included in their fatty acid profile have been shown to play a role in the treatment and prevention of various types of tumors [66, 67].

Table 9 illustrates the correlation between the cytotoxic activity (IC_{50}) of the examined cell lines and the total phenolic and flavonoid content of the four algae. The phenolic and flavonoid contents of *L. papilosa* were strongly negatively correlated with the cytotoxic activity IC_{50} values of MCF-7 and HCT-116 cell lines, with phenolic correlation coefficients of -0.972 and − 0.775, and flavonoid correlation coefficients of -0.951 and 0.766, respectively, and moderately correlated with HEPG-2 and A549 cell lines. On the other hand, *D. simplex* had a moderate correlation with all of the investigated cell lines except the HEPG-2 cell line, whereas *T. decurrens* had a moderate correlation with the HEPG-2 and HCT-116 cell lines but a weak correlation with the MCF-7 and A549 cell lines. The correlation coefficients of *G. oblongata*'s phenolic and flavonoid contents showed varying relationships with IC_{50} values, ranging from strongly to weakly correlated.

Conclusion

The results of the current study suggest that the four marine macroalgae found along the Egyptian Red Sea shores possess a significant abundance of biochemical constituents and nutritional components. These entities provide intriguing potential as sources of proteins, exhibiting well-balanced amino acid profiles, carbohydrates, phenolics, and flavonoids. Despite their relatively low lipid content, these organisms exhibit a composition of fatty acids that encompasses ω-3, ω-6, and ω-9 fatty acids. Consequently, they hold promise as a viable dietary option for human consumption and can serve as a valuable source of nutritional supplements within the food sector. They can also serve as valuable sources of mineral supplements. Based on the nutritional composition of the algae under investigation, the findings presented in this study suggest that these algae have the potential to serve as a viable alternative to conventional food sources. Moreover, these results provide tangible evidence supporting the notion that marine algae can play a substantial role in addressing global food security concerns in the coming years. Furthermore, the proximate and chemical profiles of the constituents derived from these algae have exhibited significant antioxidant and cytotoxic properties. Consequently, these algae can be exploited as efficacious therapeutic agents.

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Author contributions HM El-Rafie conceived and planned the study, performed the experiments, conducted formal analysis and data curation, and wrote the original draft. HH Hammam performed the experiments and the formal analysis. EA Ahmed performed formal and statistical analysis.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical approval This article contains no studies on human or animal objects.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no conflict of interest regarding the publication of this paper.

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