Nutraceutical Potential of Five Mexican Brown Seaweeds

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In search of pharmaceutically active products to control type 2 diabetes, five brown seaweeds (Silvetia compressa, Cystoseira osmundacea, Ecklonia arborea, Pterygophora californica, and Egregia menziesii) from the Northwest Mexican Pacific coast were investigated. Proximate composition and total polyphenol content (TPC) as phloroglucinol equivalents (PGE) were determined for the five seaweed powders and their respective hydroethanolic (1:1) extracts. Extracts were screened for their radical scavenging activity (DPPH and ORAC) and glycosidase inhibitory activity. HPLC-DAD, HPLC-MS-TOF, and ATR-FT-IR methodologies were used to identify the most abundant phlorotannins and sulfated polysaccharides in the extracts. Hydroethanolic extracts contained minerals (17 to 59% of the dry matter), proteins (4 to 9%), ethanol-insoluble polysaccharides (5.4 to 53%), nitrogen-free extract (NFE) (24.4 to 70.1%), lipids (5 to 12%), and TPC (2.6 to 47.7 g PGE per 100 g dry extract).

S. compressa and E. arborea dry extracts presented the lowest ash content (26 and 17%, respectively) and had some of the highest phenolic (47.7 and 15.2 g PGE per 100 g extract), NFE (57.3 and 70.1%), and soluble polysaccharide (19.7 and 53%) contents. S. compressa and E. arborea extracts had the highest antioxidant activity (IC50 DPPH 1.7 and 3.7 mg mL−1; ORAC 0.817 and 0.801 mmol Trolox equivalent/g extract) and the highest α-amylase and α-glucosidase inhibitory capacities (IC50 940 and 1152 μg mL−1 against α-amylase and 194 and 647 μg mL−1 against α-glucosidase). The most abundant phlorotannins identified in the extracts were phloretol, fucophloroethol, and two- and three-phloroglucinol unit (PGU) phlorotannins. Laminarin, fucoidan, and alginate were among the sulfated polysaccharides identified in the extracts. The bioactivities of S. compressa and E. arborea extracts were mainly related with their contents of three PGU phlorotannins and sulfated polysaccharides (e.g., fucoidan, laminarin, and alginate). These results suggest S. compressa and E. arborea are potential candidates for food products and nutraceutical and pharmaceutical preparations, and as additives for diabetes management.

1. Introduction

Globally, there are approximately 350 million people currently suffering from diabetes (http://www.who.int/mediacentre/factsheets/fs312/en/). This number could potentially double by 2030, which would make diabetes the seventh most prevalent cause of death worldwide [1]. Ninety percent of diabetes cases are type 2 diabetes mellitus, a complex disorder characterized by hyperglycemia and associated with high oxidative stress caused by the production of reactive oxygen species (ROS) [2]. Dietary starch degradation by glycosidases is the major source of glucose in the blood [3, 4]. Dietary polysaccharides are hydrolyzed by α-amylase to oligosaccharides and disaccharides, which are further hydrolyzed to monosaccharides by α-glucosidase (a membrane-bound intestinal enzyme that aids glucose liberation by acting as a catalyst in the hydrolysis of the α-glycosidic bond found in oligosaccharides). Liberated glucose is absorbed from the intestine and contributes to postprandial hyperglycemia. Glycosidase inhibitors prevent...
or delay the hydrolysis or absorption of carbohydrates and reduce postprandial hyperglycemia, making such inhibitors useful in the management of type 2 diabetes [3, 5]. Thus, antidiabetic therapies that limit the postprandial increase of blood glucose levels after a mixed carbohydrate diet, such as the use of glycosidase inhibitors, are particularly relevant in blood glucose levels after a mixed carbohydrate diet, such as useful in the management of type 2 diabetes [3, 5]. Thus, reduce postprandial hyperglycemia, making such inhibitors or delay the hydrolysis or absorption of carbohydrates and effect against undigested carbohydrates in the colon [9]. Lower inhibitory might be caused by the excessive inhibition of pancreatic α-amylase, resulting in abnormal bacterial fermentation of undigested carbohydrates in the colon [9]. Lower inhibitory effect against α-amylase activity and stronger inhibition activity against α-glucosidase can be an ideal approach for managing hyperglycemia with minimal side effects [9]. Thus, there is a substantial need for natural α-amylase and α-glucosidase inhibitors that have no adverse or unwanted secondary effects [6, 7]. A number of studies suggest that marine compounds may be convenient alternatives [8].

Seaweeds are rich in dietary fibre, polyphenolic compounds, unsaturated fatty acids, and minerals, among other compounds, many of which can be beneficial to human health, including in managing diabetes [10–13]. In fact, dietary consumption of seaweeds was associated with a low incidence of diabetes in Korean men [14]. Particularly, numerous brown seaweed crude extracts (aceton, aqueous, methanolic, and ethanolic) have shown to possess antioxidant [15, 16] and antidiabetic (e.g., α-amylase and α-glucosidase inhibition) activities [14, 17–19]. These activities are related to the presence of phenolic compounds, phlorotannins, pigments, tocopherols, polysaccharides, fatty acids, and peptides in the seaweed extracts [15, 20–28]. The main compounds reported as potent α-amylase and α-glucosidase inhibitors are as follows: phloroglucinol derivatives such as dieckol, 8,8’-bieckol, phlorofucofuroeckol, fucophloethol, and phlorotannins with low PGU [23, 25, 29–31], fucoidan [3, 32, 33], and oleic, linoleic, and eicosapentaenoic acids [24].

On the other hand, the major compounds contributing to overall antioxidant activity in seaweed are phenolic compounds and polysaccharides, the latter alone or associated with other components such as polyphenols, amino acid, protein, lipids, and nucleic acids residues, and sometimes polysaccharide conjugates [28, 34]. Hence, TCP and polysaccharides, in combination with in vitro antioxidant assays, are typically used to screen for seaweed antioxidant activity [34–36]. Previous studies have found a positive correlation between high TCP content and high radical-scavenging capacity for seaweed extracts [34, 35, 37]. Powerful antioxidant bioactivity was observed in dieckol (A), 6-6’-bieckol (B), and fucophlorethol G (C) separated and refined from Ecklonia cava, an edible marine alga collected at Jeju Island [38]. Sulfated polysaccharides also possess excellent in vitro antioxidant activity, including both radical-scavenging capacity and metal chelating ability [34, 39–41]. Therefore, substantial evidence exists to support the claim that seaweed extracts and their fractions could act as functional ingredients in foods used to control hyperglycemia [19, 27].

The coastline of Baja California, Mexico, is an abundant source of seaweeds with a broad diversity of species, some of which have been under commercial exploitation since the 1960s (e.g., Macrocystis pyrifera, Gelidium robustum, Chondracanthus canaliculatus, and Gracilariopsis lemaneliformis) to obtain alginate, agar, and carrageenan [42, 43]. In contrast, other commercially available edible brown seaweed species, such as Silvetia compressa (J. Agardh) (De Toni 1985), Cystoseira osmundacea (Turner) (C. Agardh 1820), Ecklonia arborea (Areschoug 1876), Pterygophora californica (Ruprecht, 1852), and Egregia menziesii (Turner) (Areschoug 1876), are incipiently being used as supplements for human and animal consumption, as well as in the elaboration of cosmetic products (https://www.bajakelp.net).

Although proximal composition, polyphenol content, and DPPH antioxidant activity have been previously reported for Ecklonia arborea (formerly Eisenia arborea) [15, 44–46], this information is incomplete or unavailable for S. compressa [46–48], E. menziesii [47], C. osumdacea, and P. californica from the Baja California coast. Neither the antidiabetic potential of these five seaweeds (α-amylase and α-glucosidase inhibition activities) nor the chemical composition of their hydroethanolic extracts has been previously reported. This study seeks to screen the antioxidant and glycosidases inhibiting potential of hydroethanolic extracts from these five brown seaweeds, as well as to identify the probable active compounds: phlorotannins (using HPLC-DAD and HPLC-MS-TOF methodologies) and sulfated polysaccharides (using ATR/FT-IR methodologies). Through this process, this study hopes to identify a potential commercial value for these five macroalgae native to Mexico’s Baja California coast and to find candidates for the development of pharmaceutically active products that can control type 2 diabetes.

2. Materials and Methods

2.1. Chemicals and Reagents. Potato soluble starch (S-2360), α-amylase from porcine pancreas (A-3176, 5 MU), acarbose (A-8980), rat intestinal aceton powders (1-1360), 4-nitrophenyl-α-D-glucopyranoside (N-1377), Folin–Ciocalteu reagent (F-9252), sodium carbonate (Na2CO3) (S-2127), phloroglucinol (P-3502), gallic acid (G-7384), 2,2-diphenyl-1-picrylhydrazyl (DPPH) (D-9132), 3,5-dinitro-2-hydroxybenzoic acid (DNS) (D-0550), HEPES (4-(2-hydroxyethyl)-1-piperazine ethanesulfonic acid) buffer solution (H3375), fucoidan from F. vesiculosus (F8190), laminarin from L. digitate (L9634), sodium alginate from brown algae (w201502), fluoresecin (F6377), and 2,2’-azobis (2-methylpropionamide) dihydrochloride (AAPH, 4409914) were purchased from Sigma Aldrich Co. (St. Louis, MO, USA). Ethanol (absolute) was obtained from Desarrollo de Especialidades Químicas SA de CV (Monterrey, NL, Mexico). Distilled water was purchased from Garvy SA de CV (Monterrey, NL, Mexico); HPLC-grade water (4218-03) was obtained from J. T. Baker Co. (Center Valley, PA, USA). Formic
acid 88% (A11-8P) and HPLC-grade methanol (A452-4) were purchased from Fisher Scientific Co. (Pittsburgh, PA, USA). EDTA (502-092) was purchased from LECO Co. (St. Joseph, MI, USA).

2.2. Seaweeds. Five edible dehydrated seaweed samples were obtained from BajaKelp (https://www.bajakelp.net) in Ensenada, Baja California, Mexico. Samples of S. compressa (formerly Pelvetia compressa), C. osmundacea, E. arborea, P. californica, and E. menziesii were collected from December 2014 to January 2015 at La Escalera, Baja California Peninsula, Mexico (31°30’59.1”N-116°38’51.1”W). Seaweed fronds were washed with seawater to remove sand and epiphytes, drained on clotheslines, and sun-dried inside a greenhouse in Ensenada, Baja California. Samples were ground at our lab in Monterrey, Nuevo León (Pulvex 200, CDMX, MEX), with a 500 μm sieve and vacuum-packed until use. Identity of all five seaweed species was confirmed using taxonomic keys [49].

2.3. Proximal Composition of Seaweeds. Moisture and ash content were determined using 930.15 and 942.05 AOAC [50] procedures, respectively. Crude protein (Nx6.25) was quantified by AOAC 930.03 method using a nitrogen analyzer (Truspec CHN, Leco Corporation, St. Joseph, MI, USA). Crude lipid was determined using the Bligh and Dyer analyzer (Truspec CHN, Leco Corporation, St. Joseph, MI, USA). Crude lipid was determined using the Bligh and Dyer method, following the methodology described by Li et al. [51]. Nitrogen-free extract (NFE) or carbohydrate value was estimated from the difference between dry weight (100) and the sum of total lipids, protein, and ash (minerals). Data were expressed as % of seaweed dry matter (DM).

2.4. Preparation of Hydroethanolic Extracts. For phenolic compound extraction, we used the methodology described by Xi et al. [52]. For this, 10 g of seaweed powder and 200 mL aqueous ethanol 50% were mixed in a 250 mL Erlenmeyer flask and sonicated (Ultrasonic cleaner 50HT, VWR International, West Chester, PA, USA) for 30 min. Samples were then incubated at 70°C with constant agitation at 100 rpm (Shak-R-bath, Lab-line, Melrose Park, IL, USA) for 2 h. Subsequently, samples were cooled down to room temperature and centrifuged at 2500 rpm (IEC Centra MP4R, International Equipment Company, Needham, MA, USA) for 15 min. The supernatant was transferred to an evaporator (Rocket Synergy evaporator, Genevac, Ipswich, UK) to remove ethanol and water. Then, crude extracts were stored at −80°C until analysis. To obtain the hydroethanolic extraction yield, a 1 mL extract sample was placed in pre-weighed test tubes, weighed, evaporated in a hot air oven (Shel Lab 1330 FX, Sheldon Manufacturing Inc., Cornelius, OR, USA) at 130°C for 60 min, cooled down in a desiccator, and weighed again. The solid extraction yield was calculated as

$$Y(\%) = \frac{g \text{ of dry extract obtained from 1 mL sample} \times (\text{mL of total extract})}{g \text{ dry seaweed}} \times 100.$$  \hspace{1cm} (1)$$

Three extractions were run for each seaweed sample.

2.5. Total Phenolic Content (TPC). TPC was measured using the Folin–Ciocalteu method [53], where 200 μL of each liquid seaweed extract (eventually after some dilution) was transferred into a 1.5 mL Eppendorf tube and mixed with 50 μL of Folin–Ciocalteu (2 M) reagent and 750 μL of sodium carbonate (7.5% w/v). The mixture was homogenized for 15 s in a vortex (Standard Heavy-Duty Vortex Mixer VWR, Radnor, PA, USA), after which the tubes were allowed to stand in complete darkness for 2 h and centrifuged at 2500 rpm for 15 min. 200 μL of each sample reaction was transferred to a 96-well microplate, and absorbance was registered at 620 nm in a microplate reader (Epoch 2, BioTek Instruments Inc, Winooski, VT, USA). TPC was determined by comparison of the values obtained with the calibration curve of phloroglucinol using a seven-point calibration curve (0 to 1.25 mg mL−1). Results were expressed as g of phloroglucinol equivalents (PGE) per 100 mL of dry extract or per 100 g of dry seaweed by considering an average of 140 mL hydroethanolic extract obtained from a 10 g seaweed meal sample.

2.6. Proximal Composition of Seaweed Extracts. These analyses were performed for all extracts following the methods described above. In addition, polysaccharide content of each extract was determined using the method described by Tako et al. [54]. Ethanol (4:1 v/v ratio) was added to the hydroethanolic liquid extract to precipitate the polysaccharides. After that, samples were centrifuged for 10 min at 3500 rpm, the supernatant filtered, and the precipitate dried overnight at 60°C and weighed. Data were expressed as % of dry extract.

2.7. Antioxidant Capacity. DPPH free radical-scavenging activity was determined following the methodology described by García-Becerra et al. [55]: 100 μL of the extract serial dilutions using ethanol 50% (1:1) and 100 μL of methanol-DPPH solution (20 μg mL−1) were transferred in a 96-well microplate. Samples were incubated for 30 min at room temperature, and absorbance was measured at 550 nm (Epoch 2, BioTek Instruments Inc., Winooski, VT, USA). The IC50 (i.e., the concentration of antioxidant required to cause a 50% reduction in the original DPPH concentration) was calculated using a dose-inhibition curve in a linear range by plotting the extract concentration (mg mL−1) versus the IC50.
corresponding scavenging effect. The oxygen radical absorbance capacity (ORAC) was determined as described by Ou et al. [56]. Briefly, aliquots of 25 μL seaweed extract were diluted in 75 mM phosphate buffer and transferred to a 96-well round opaque bottom microplate. Reaction fluorescence was measured using a Synergy HT microplate reader with an auto dispenser (BioTek, Instruments, Winooski, VT, USA) at a wavelength of 485 nm (excitation) and 580 nm (emission) at intervals of 70 s for 70 minutes. Equipment was programmed to dispense 200 μL of 0.96 mM fluorescein and 75 μL of 95.8 μM AAPH (2,2′-azobis (2-amidinopropane) dihydrochloride) used as free radical. Protective effects of experimental and control samples were calculated by subtracting the net integrated area under the curve (AUC) of the control from that of the experimental sample (AUC sample–AUC control). Results were quantified using Trolox as standard and expressed as Trolox equivalents (TE) millimolar concentration: mmol TE/g dry mass seaweed extract.

2.8. Glycosidase Inhibitory Enzyme Activities. Inhibitory activity for α-amylase was obtained following the method of Kazeem et al. [57] by using different concentrations of the dry extract (200, 400, 600, 800, 1000, and 1200 μg mL⁻¹) and using acarbose (200, 400, 600, 800, 1000, and 1200 μg mL⁻¹) as a positive control. Briefly, tubes containing 250 μL acarbose (1 mg mL⁻¹) or seaweed extract along with a sodium phosphate buffer (0.02 M pH 6.9) or 500 μL α-amylase solution in a phosphate buffer (with 0.006 M de NaCl, 13 μL) were preincubated at room temperature for 10 min with 250 μL 1% starch solution (sodium phosphate buffer). Tubes were then boiled for 5 minutes after adding 1 mL of DNS (method of Miller, 1959) [58] to stop the reaction. Tubes were then boiled for 5 minutes after adding 1 mL of DNS (method of Miller, 1959) [58] to stop the reaction. Samples were diluted in 10 mL of distilled water, and absorbance was measured at 540 nm (UNICON S1200, Dayton, NJ, USA). α-Amylase inhibition was calculated using equation (2), where \[ K = \frac{S_1 - S_0}{S_0} \times 100. \] (2)

The α-glucosidase test was performed using different extract concentrations (200, 400, 600, 800, 1000, and 1200 μg mL⁻¹), as described by Mayur et al. [59]. Rat intestinal acetone powder was mixed with distilled water (10 mg mL⁻¹) and centrifuged for 10 min at 10,000 rpm. The assay buffer was 100 mM HEPES at pH 6.8, and the substrate was 2 mM 4-nitrophenyl-α-d-glucopyranoside. The assay constituents were added to 96-well microplates in the following order: 100 μL of enzymatic solution (10 mg rat intestinal acetone powder per 1 mL distilled water), then 50 μL of acarbose or seaweed extract or buffer, and finally 50 μL of substrate. Samples were incubated at 25°C for 2 hours. Absorbance was recorded at the beginning and end of the incubation time at 405 nm. α-Glucosidase inhibition was calculated using equation (2). Acarbose (1 mg mL⁻¹) was used as a positive control. The inhibitory activity was expressed as the concentration required to obtain half maximal inhibitory activity (IC₅₀). Extracts' IC₅₀ values were determined from the plots of percent inhibition versus inhibitor concentration.

2.9. Preliminary Identification of Possible Active Compounds

2.9.1. Identification of Major Phlorotannins in Seaweed Extracts. Identification of major phlorotannins was performed by high-performance liquid chromatography (Agilent Technologies 1200 series chromatograph, Santa Clara, CA, USA) coupled with a diode array detector (HPLC-DAD). The analysis was carried out on a Luna C18 column (250 mm x 4.6 mm, 5 μm particle size, Phenomenex, Macclesfield, UK) at a flow rate of 0.8 mL min⁻¹ (injection volume 10–20 μL). The isocratic mobile phase consisted of water acidified with 1% of formic acid. Spectral data from all peaks were accumulated in the range 230–550 nm, and chromatograms were recorded at 270 nm. Chromatographic data were collected using Chemstation for LC software (Hewlett-Packard-Agilent Technologies, Waldbronn, Germany). Phloroglucinol was used as a standard to quantify bioactive compounds by linear regression. The concentration of bioactive phenolic compounds (n = 3) was expressed as μg of PGE per mL extract, using equation (3) as the calibration curve (\[ R^2 = 0.9996 \]):

\[ y = 24112x - 2.0812. \] (3)

The same chromatographic conditions described above were used to identify bioactive compounds by HPLC coupled to time-of-flight mass spectrometry (MS-TOF) technique (G1969A, Agilent Technologies 1100, Santa Clara, CA, USA). Mass spectra were collected using electrospray source in the positive mode (ESI+) under the following conditions: m/z range 100 to 1500, nitrogen gas, gas temperature 300°C, drying gas flow rate 8 L/min, nebulizer pressure 20 psi, capillary voltage 4000 V, and fragmentor voltage 70 V. Extracted ion chromatograms were obtained using the Analyst QS 1.1 software (Applied Biosystems, Carlsbad, CA, USA) and considering the accurate mass from each compound or its adducts with Na or K with an error range of 0.01 units. Mass spectra were used to identify the different phenolic compounds based on their fragmentation patterns, which were subsequently compared to previous studies [21, 22] and verified.

2.9.2. Sulfated Polysaccharides. Identification of the principal functional groups in sulfated polysaccharides present in the dry hydroethanolic seaweed extracts was done using a Fourier transform infrared (FT-IR) spectroscopy (Perkin Elmer Spectrum-ONE, Shelton, CT, USA, equipped with an attenuated total reflectance sampling device (ATR)). Spectra samples (including the standards algicin acid, laminarin, and fucoidan) with any previous preparation were recorded between the 4000 and 650 cm⁻¹ range (10 scans, pressure 90–100 Gauges at room temperature) and the analytical
spectral range from 1700 to 650 cm$^{-1}$ in transmittance mode. A background spectrum air was scanned under the same instrumental condition before each series of measurements.

2.10. Statistical Analysis. Each variable was determined in triplicate. All reported data were expressed as mean ± standard deviation and submitted to one-way ANOVA statistical analysis and Tukey’s post test ($P < 0.05$) using SPSS Software, version 20 (IBM Corporation, Armonk, NY, USA). Correlations (r-Pearson correlation coefficient) between activities and chemical compounds present in seaweed extracts were determined using Microsoft Excel.

3. Results and Discussion

3.1. Proximal Composition and Total Polyphenol Content in Seaweeds. The chemical composition of the seaweed samples presented in Table 1 agreed with previous information reported for brown seaweeds [60, 61]. S. compressa, E. arborea, and E. menziesii presented the highest protein contents, ranging from 10 to 12% DM, agreeing with the values (8–12%) reported for the same species in previous studies [45, 47]. In contrast, C. osmundacea and P. californica presented a lower protein content (9-10% DM), but no previous studies were available for comparison. Lipid content in all seaweed species was low, as expected: S. compressa had the highest lipid content (2.93% DM), followed by C. osmundacea (1% DM), while E. arborea, P. californica, and E. menziesii were very poor in lipids (0.6% DM). These values coincide with those previously reported for E. arborea (0.19%) [45] and E. menziesii (0.14%) [47], but not for S. compressa, which had twice the content (1.46%) reported by Guerra-Rivas [47]. Ashes and carbohydrates were the major compounds in all seaweeds, ranging between 23–34% and 54–65% DM, respectively. E. arborea and S. compressa presented the lowest ash (23 and 25%) and the highest NFE (62 and 65%) contents, respectively, while the other three algae were richer in ashes (30–34%) and poorer in NFE (54–59%). These results coincide with previously reported values for E. arborea (27.2 ash and 55.30% NFE +5.04% fibre) [45], S. compressa (15.9% ash and 50.6% NFE +6.47% fibre), and E. menziesii (28.9% ash and 40 NFE +7.2% fibre) [47]. They are also in accordance with the high total dietary fibre content recently reported by Tapia-Salazar et al. [46] for S. compressa and E. arborea (59 and 55% DM, respectively).

In the case of seaweed TPC, S. compressa and E. arborea also had the highest concentrations (8.32 and 5 PGE per 100 g dry seaweed), followed by C. osmundacea (4%), P. californica (1.9%), and finally E. menziesii, which distinguished itself for having the lowest content (0.53%) (Table 1). E. arborea TPC was in the high range compared to Japanese E. arborea and E. bicyclis, 60% methanol extracted (2.7–6.6 g PGE per 100 g dry seaweed) [62]. TPC in S. compressa was higher than the previously reported concentration for the same species (formerly known as Pelvetia fastigata) extracted with 80% methanol (5.2 to 6 g PGE per 100 g dry seaweed) [63]. C. osmundacea presented higher TPC when compared to methanol extracts of C. neglecta and C. osmundacea (1.37 and 1.60 g PGE per 100 g dry seaweed) [63]. TPC of Egregia menziesii was within the values previously reported for methanol extracts (0.36 to 2.16 g PGE per 100 g dry seaweed) [63]. In the case of P. californica, no previous studies for TPC were found. Differences in TPC between this and previous studies could be attributed to several factors such as seaweed collection area, season, drying method, solvents, and extraction conditions. In summary, among the five species studied, S. compressa and E. arborea had the highest carbohydrate and phenolic contents.

3.2. Seaweed Hydroethanolic Extracts. Extraction yield, proximal composition, and total phenolic content of hydroethanolic extracts were significantly different between seaweed species ($P < 0.001$, Table 2). The best extraction yield (32.8% of dry seaweed) was obtained from E. arborea, while the mass yield for E. menziesii, P. californica, C. osmundacea, and S. compressa was very similar and ranged from 17.5 to 20.3%. Under the extraction conditions used in this study, 50% ethanol efficiently extracted inorganic and organic polar compounds, resulting in seaweed extracts consisting of minerals (17 to 59% DM), proteins (4.23 to 9.30% DM), lipids (5 to 12% DM), soluble polysaccharides (5.4 to 53.2% DM), NFE (16.9 to 70.1% DM), and polyphenols (2.6 to 47.7% PGE DM). These results fall within the ranges previously reported for 60% ethanol extracts from L. cichoroides, C. costata, and F. evanescens [64] (24 to 60% ash, 4 to 8% protein, 1.4–10.1% PGE, 23 to 67% NFE, 3.6–12% lipophilic matter), except for polyphenol

| Moisture* | Ash | Lipid | Protein N×6.25 | NFE** | TPC |
|-----------|-----|-------|---------------|-------|-----|
| S. compressa | 10.9 ± 0.1b | 24.9 ± 0.9b | 2.93 ± 0.10c | 10.4 ± 0.6bc | 61.8 ± 0.9b | 8.32 ± 0.39e |
| C. osmundacea | 10.6 ± 0.1b | 33.9 ± 0.5d | 1.08 ± 0.07b | 9.1 ± 0.1a | 55.9 ± 0.3a | 3.98 ± 0.17c |
| E. arborea | 9.2 ± 0.3a | 23.0 ± 0.5a | 0.56 ± 0.12a | 11.1 ± 0.4cd | 65.4 ± 0.5c | 5.00 ± 0.18d |
| P. californica | 13.4 ± 0.7c | 30.1 ± 0.1c | 0.55 ± 0.12a | 9.6 ± 0.9ab | 59.7 ± 1.1b | 1.88 ± 0.04b |
| E. menziesii | 12.5 ± 0.5c | 33.1 ± 1.0d | 0.67 ± 0.05a | 11.8 ± 0.5d | 54.4 ± 1.1a | 0.53 ± 0.02a |
| F value | 48.890 | 161.33 | 317.637 | 15.867 | 83.206 | 109.013 |
| Sig. ANOVA | <0.001 | <0.001 | 0.001 | <0.001 | <0.001 | <0.001 |

* Moisture in the ground seaweed sample. ** Nitrogen-free extract, by difference NFE (100 – ash + lipid + protein contents); different letters in a column indicate different homogeneous subsets as defined by a multiple means comparison test (Tukey).
compounds, which were higher in our extracts. Nevertheless, direct comparison to other studies is complicated due to potential differences in solvent type, concentration, seaweed/solvent volume ratio, extraction methods, and species tested, which influence the extracts moisture, minerals, polysaccharide and polyphenol content, and the extraction yield.

E. arborea and S. compressa extracts presented a proximal composition very similar to that of the dried seaweed. These seaweed extracts presented the highest polysaccharide (53 and 20%, respectively), NFE (70.1 and 57.3%, respectively), phenolic (15.2 and 47.7% PGE, respectively), and protein (11.1 and 10.4%) contents. In the case of F. vesiculosus, the free radical-scavenging potential of the different species follows a different order than for DPPH; this is due to the presence (in different samples) of distinct antioxidants that may be responsible for the observed differences in various methods.

Table 3: Antioxidant activities and half maximal inhibitory concentrations of hydroethanolic seaweed extracts against α-amylase and α-glucosidase.

| Hydroethanolic extract | DPPH IC50 mg mL−1 | ORAC mmol TE g−1 | α-Amylase IC50 μg mL−1 | α-Amylase IC10 μg mL−1 | α-Glucosidase IC50 μg mL−1 | α-Glucosidase IC10 μg mL−1 |
|------------------------|------------------|------------------|------------------------|------------------------|-----------------------------|-----------------------------|
| S. compressa           | 3.73 ± 0.11c     | 0.817 ± 0.07c    | 940.1 ± 8.3a           | 240                    | 194.2 ± 16.1a               | 40                          |
| C. osmundacea          | 4.20 ± 0.36c     | 0.257 ± 0.01a    | >1200                  | 2000                   | >1200                       | 105                         |
| E. arborea             | 1.67 ± 0.15b     | 0.801 ± 0.03c    | 1152 ± 19.9b           | 840                    | 646.8 ± 0.7b                | 65                          |
| P. californica         | 8.07 ± 0.50d     | 0.542 ± 0.05b    | >1200                  | 170                    | >1200                       | 105                         |
| E. menziesii           | 0.93 ± 0.12a     | 0.192 ± 0.01a    | >1200                  | 920                    | >1200                       | 420                         |
| Acorbose               |                  |                  |                        |                        |                             |                             |
| F. vesiculosus         |                  |                  |                        |                        |                             |                             |

PGE: phloroglucinol equivalents; DS: dry seaweed; TE: Trolox equivalents; IC50: the half maximal inhibitory concentration. Each value represents the average of three analytical replicates with standard deviation. Different letters (down column) represent significant differences at P < 0.05.

3.3. Antioxidant Activity. The five macroalgae extracts were evaluated as radical scavengers against DPPH, showing significant differences (P < 0.0001) among IC50 values (Table 3): E. menziesii extract was the most effective (IC50 0.93 mg mL−1), followed by E. arborea and S. compressa extracts showing intermediate IC50 values (1.7 and 3.7 mg mL−1), and the least potent were C. osmundacea and P. californica extracts with the lowest scavenging activities (IC50 4.2 and 8.1 mg mL−1). None of the extracts evaluated were equivalent to Trolox (DPPH IC50 0.018 mg mL−1). The DPPH scavenging capacity of different extracts (100% methanol) of E. arborea and C. osmundacea collected from the Baja California Peninsula has already been reported [16]: the DPPH IC50 for these two species were 0.069 and 0.227 mg mL−1, respectively, being classified as the most potent among 17 species tested and with a similar or superior scavenging capacity than butylated hydroxytoluene (BHT) (IC50 = 0.0867 mg mL−1). Differences between these values and our results could be attributed to not only differences in solvents and extraction methodologies but also differences in collection sites and seasons. To our knowledge, DPPH IC50 values of S. compressa, P. californica, and E. menziesii extracts are described for the first time in this article.

The DPPH IC50 values among the seaweed extracts tested were lower (therefore, better) (0.93–8.07 mg mL−1) compared to 80% Ethanolic extracts from brown seaweeds (IC50 >10 mg mL−2) reported by other authors [65]. However, the IC50 values observed were higher when compared to the most potent antioxidant seaweed extracts such as: E. cava 80% ethanol (IC50 0.01 mg mL−1) and F. vesiculosus 50–70% ethanol extract (IC50 0.03 mg mL−1) [15].

The five macroalgae hydroethanolic extracts were also able to quench oxygen-free radicals in a test tube and showed significant differences among them (Table 3). ORAC scavenging potential of the different species follows a different order than for DPPH; this is due to the presence (in each extract) of different mixtures of antioxidants, with different physicochemical properties or structural features and with different mechanisms of in vitro antioxidant activity and therefore different sensitivities for each method [34]. S. compressa and E. arborea were the most potent...
species (0.82 and 0.80 mmol TE g dry extract\(^{-1}\)), followed by \textit{P. californica} (0.54 mmol TE g dry extract\(^{-1}\)) and \textit{C. osmundacea} and \textit{E. menziessii} (0.26 and 0.192 mmol TE g dry extract\(^{-1}\)). The ORAC of the five seaweeds’ hydroethanolic extracts, to our knowledge, is described herein for the first time.

ORAC values found in this study were higher than those reported for other brown seaweed species [15]. It must be noted, however, that the ORAC value for \textit{C. osmundacea} was in the range of values reported for other species of the same genus: \textit{C. abies-marina} (0.275–1.314 mmol TE g\(^{-1}\)) [66].

In this study, no correlation between the five seaweed extracts’ TPC and DPPH radical-scavenging activity (\(R^2 = 0.005\)) was observed. TPC and extract ORAC values showed a slight correlation (\(R^2 = 0.36\)), but this was improved (\(R^2 = 0.87\)) when \textit{C. osmundacea} was not considered in the regression. \textit{C. osmundacea} with high phenolic content displayed lower activity than expected, suggesting that other compounds were also responsible for this result. NFE extract content and ORAC radical-scavenging activity also showed a strong correlation (\(R^2 = 0.91\)). The two algae extracts with the highest ORAC activities (\textit{S. compressa} and \textit{E. arborea}) were the richest in NFE and were among the richest in polyphenols, suggesting that in both seaweeds, carbohydrates and polyphenols were the main components working as antioxidants. The antioxidant effect of brown seaweed extracts rich in these two major polymeric fractions has been reported by numerous authors [24–26, 34]. The correlation between these compounds and the antioxidant activity is strong for some extracts or inexistent for others. The change in the chemical structure of these compounds during the extraction and the interferences caused by some components present in the extracts are some of the multiple reasons for which there may be variations in the correlation [15, 67, 68].

### 3.4. Glycosidase Inhibition

The capacity to inhibit enzymes was different among hydroethanolic seaweed extracts. \textit{S. compressa} and \textit{E. arborea} extracts displayed the highest \(\alpha\)-amylase and \(\alpha\)-glucosidase inhibitory activities (the lowest IC\(_{50}\)) (Figures 1 and 2; Table 3). The rest of the seaweed extracts were inefficient in inhibiting 50% of both glycosidase activities (IC\(_{50} > 1200 \mu\text{g mL}^{-1}\)). The IC\(_{50}\) values against \(\alpha\)-amylase and \(\alpha\)-glucosidase were 940.1 \(\mu\text{g mL}^{-1}\) and 194.2 \(\mu\text{g mL}^{-1}\), respectively, for \textit{S. compressa} extract, and 1151.8 and 646.8 \(\mu\text{g mL}^{-1}\), respectively, for that of \textit{E. arborea}. Values found for acarbose, the positive control in this study (152.9 and 184.1 \(\mu\text{g mL}^{-1}\), respectively), were close to values observed in previous studies [29, 32]. In comparison to acarbose, \textit{S. compressa} and \textit{E. arborea} showed poor inhibitory efficiencies against \(\alpha\)-amylase (16 and 13%). In contrast, \textit{S. compressa} extract was almost as effective as acarbose (95%) in inhibiting glucosidase, while \textit{E. arborea} extract was less effective, displaying 28% of the acarbose activity. To our knowledge, \(\alpha\)-glucosidase or \(\alpha\)-amylase inhibitory activity of the five seaweed extracts evaluated in this work is described here for the first time.

Currently, there is not much information about other \textit{Silvetia} species’ capacity to inhibit amylase activity; an IC\(_{50}\) value reported for \textit{a Pelvetia caniculata} ethanol: water (80 : 20) extract (51.0 \(\mu\text{g mL}^{-1}\)) was almost twenty times lower [19]. In contrast, \textit{Ecklonia} species have been recognized as good sources of carbohydrate inhibitors. Moon et al. [69] examined the effect of methanolic extracts (ethyl acetate fraction) from two \textit{Ecklonia} (\textit{Eisenia}) species, \textit{E. stolonifera} and \textit{E. bicyclis}, on \(\alpha\)-glucosidase activity and found that their inhibitory effect was substantially stronger than that of acarbose. \(\alpha\)-Amylase IC\(_{50}\) was >500 \(\mu\text{g mL}^{-1}\) for \textit{E. bicyclis} (85.3 mg PGE g\(^{-1}\) dry weight) [18].

When comparing IC\(_{50}\) values of our seaweed extracts with those reported for the ethanolic extracts of other species, \textit{S. compressa} and \textit{E. arborea} hydroethanolic extracts were relatively ineffective as \(\alpha\)-amylase inhibitors.
hibitor seaweed extracts studied to date, whose IC50 is 4220 g phloroglucinol equivalents per mL of extract, one of the most potent glucosidase inhibitors. The ethanolic extract was not as efficient as S. compressa (IC50 260 μg PGE per mL of extract) and produced by other brown seaweed species, such as S. compressa extract was 2 to 22 times higher than that of A. nodosum, F. serratus, and F. vesiculosus, F. caniculata and F. spiralis ethanol extracts (80:20) were 10 to 20 times lower: 44.7, 70.6, 59.1, 51.0, and 109 μg mL−1, respectively [19].

The potency of the α-glucosidase inhibition produced by S. compressa extract was 2 to 22 times higher than that produced by other brown seaweed species, such as P. arborescens (IC50 260 μg mL−1, water extract) and H. macroraola (IC50 4220 μg mL−1, water extract) [17]. Nonetheless, S. compressa extract was not as efficient as F. vesiculosus ethanolic extract, one of the most potent glucosidase inhibitors. The seaweed extracts studied to date, whose IC50 is less than 0.5 μg mL−1 [19]. As previously mentioned, environmental differences, seasonal variations, differences in the extraction methods, and the degree of purity of the extracts, as well as the chemical structure and molecular weight of the active compounds may explain the differences in the potency of seaweed-derived extracts.

Since we did not obtain α-amylase and α-glucosidase IC50 values for every seaweed extract, the IC10 was calculated for correlation analysis with the chemical compounds present in the extracts (Table 3). With these values, a negative linear correlation was found for α-amylase with NF (R2 = 0.54) and for α-glucosidase IC10. A negative potential correlation was found with TPC (R2 = 0.89), as well as a slight polynomial correlation with soluble polysaccharides (R2 = 0.67). Indeed, the S. compressa extract with the best amylase and glucosidase IC50 was the one richest in TPC and second richest in carbohydrates. On the other hand, E. arboarea extract, with the second-best amylase and glucosidase activities, was the seaweed richest in carbohydrates. The ability of naturally occurring polyphenols from brown seaweeds to inhibit enzymes, including α-amylase and α-glucosidase, has been widely reported [14, 19, 69, 70]. Furthermore, a number of these studies have demonstrated a strong correlation between phenolic content, enzyme inhibition, and antioxidant properties [19]. Recently, it has been shown that ethyl acetate fractions obtained from brown seaweeds, rich in oligomers of phloroglucinol, evidenced a pronounced inhibitory effect on α-amylase and α-glucosidase activities [18, 29].

Water soluble carbohydrates (e.g., fucoidan) found in great abundance in our active seaweed extracts, mainly in E. arboarea, have also been reported as potent carbohydrate inhibitors [32, 67]; the synergy of these two types of compounds has also been suggested. Interestingly, the enzyme inhibition activity in our extracts was lost when polysaccharides were removed from the extract by precipitation with ethanol (results not shown). Therefore, the synergistic effect of different compounds present in the hydroethanolic extract deems further research.

### 3.5. Phlorotannin Quantification and Identification.

It has been demonstrated that phlorotannins made up more than 82% of the crude polyphenol fraction in a variety of brown seaweeds [71]. Phlorotannins are oligomers or dehydropolymers of phloroglucinols commonly known as marine algal polyphenols [71]. Main phlorotannins were detected in a positive mode (M + H) and included its protonated ions (M + H)+, a few of them which were present as sodium or potassium adducts. HPLC-MS-TOF allowed the identification of four main compounds in the m/z range of 190 to 377 m/z (Table 4). To our knowledge, this is the first report of phlorotannins in our five seaweeds. The main phlorotannins detected in the seaweed extracts were phloretol, fucophloretol, and phlorotannins with two and three-PGU (Figure 3, Table 4). These compounds were found in all seaweed hydroethanolic extracts, with the exception of two-PGU phlorotannin that was not present in E. arboarea. The concentration of the sum of the four major phlorotannins evaluated was highest for S. compressa (723.9 μg PGE per mL of extract), followed by E. menziesii (232.1 μg PGE per mL of extract), E. arboarea (179.7 μg PGE per mL of extract), C. osmundacea (101.4 μg PGE per mL of extract), and P. californica (72.5 μg PGE per mL of extract).

**Table 4: Fragments adducts, λ max, and molar mass of most abundant phlorotannins identified by HPLC-DAD and HPLC-MS-TOF methodologies for the hydroethanolic extracts of seaweeds collected from Baja California.**

| Peak | Bioactive compound | Phloretol | Fucophloretol | Two units of phloroglucinol | Three units of phloroglucinol |
|------|-------------------|-----------|---------------|-----------------------------|------------------------------|
| 1    | Silvetia compressa | 19.1 ± 1.5a | 71.2 ± 2.5d | 480.9 ± 4.7c | 152.7 ± 3.2d |
| 2    | Cystoseira osmundacea | 37.1 ± 2.1b | 24.8 ± 0.8b | 29.9 ± 2.1a | 14.6 ± 1.4a |
| 3    | Ecklonia arboarea | 37.1 ± 0.5b | 25.1 ± 1.0b | NF | 117.5 ± 4.7c |
| 4    | Pterygophora californica | 13.2 ± 2.8a | 30.7 ± 1.1c | 103.6 ± 2.4b | 38.8 ± 3.1b |
| 5    | Egregia mensienzii | 42.3 ± 2.6b | 11.2 ± 0.5c | 113.6 ± 2.4b | 45.5 ± 1.2b |

### References

1. Isaza Martínez and Torres Castañeda [21]; 2. Steevens et al. [20]; 3. Tierney et al. [22]; NF: not found.

**Table 3: Bioactivity of Phlorotannins.**

| Bioactive compound | Phloretol | Fucophloretol | Two units of phloroglucinol | Three units of phloroglucinol |
|-------------------|-----------|---------------|-----------------------------|------------------------------|
| Signature ANOVA | PGE | PGE | PGE | PGE |

For example, IC50 values for A. nodosum, F. serratus, F. vesiculosus, P. caniculata and F. spiralis ethanol extracts (80:20) were 10 to 20 times lower: 44.7, 70.6, 59.1, 51.0, and 109 μg mL−1, respectively [19].
Figure 3: Chromatograms obtained at 270 nm from the ethanolic crude extract of (a) *Silvetia compressa*, (b) *Ecklonia arborea*, (c) *Cystoseira osmundacea*, (d) *Egregia menziesii*, (e) *Pterigophora californica*. (1) Phloretol; (2) fucophloretol; (3) two units of phloroglucinol; (4) three units of phloroglucinol.

Table 5: Signals assigned in the ATR/FT-IR second-derivative spectrum of the hydroethanolic extracts from different brown seaweeds and fucoidan, laminarin, and alginate standards.

| Functional groups | Seaweed/absorption frequency (cm⁻¹) | O-H stretching vibrations (3371–3700 cm⁻¹)¹,₄,₆ | C-H stretching vibrations (2941–2944 cm⁻¹)¹,₂,₄,₇ | Carbonyl group stretching (1616–1732 cm⁻¹)¹,₅ | Asymmetrical bending vibration of CH₃ and OH bending (1369–1420 cm⁻¹)¹,₂,₄,₇ | Stretching vibrations of sulfoxides (S=O)-CN stretching (1034–1075 cm⁻¹)¹,₂,₄ | Sulfate groups at the axial C4 position of C-O-S symmetrical stretching vibrations (822–849 cm⁻¹)¹,₅ |
|-------------------|------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Silvetia compressa | 3317.11                            | 1603.2                                        | 1416.68                                       | 1040.32                                       | 893.22/828.88                                 |                                               |                                               |
| Cystoseira osmundacea | 3324.58                           | 2924.93                                       | 1627.84                                       | 1416.73                                       | 1083.6/1041.00                                | 893.38/824.84                                 |                                               |
| Ecklonia arborea   | 3326.23                            | 2892.87                                       | 1635.92                                       | 1070/1039.85                                  |                                               | 893.34                                       |                                               |
| Pterigophora californica | 3317.17/3695.33             |                                               |                                               |                                               |                                               |                                               |                                               |
| Egregia menziesii  | 3239.7/3662.76                    | 2988.65/2972.72/2901.72                      | 1406.59/1394.17                               | 1075.94/1066.32; 1056.99/1028.03              |                                               | 892.97/879.27/869.42                          |                                               |
| Fucoidan           | 3413.56                            | 2989.01/2935.16/2924.67                      |                                               |                                               | 1079.42                                       | 827.51                                       |                                               |
| Laminarin          | 3318.46/3710.74                   |                                               |                                               |                                               | 1071.75                                       | 892.62/838.90                                |                                               |
| Sodium alginate    | 1403.89                            |                                               |                                               |                                               |                                               |                                               |                                               |
|                    |                                    |                                               |                                               |                                               |                                               |                                               |                                               |
|                   |                                    |                                               |                                               |                                               |                                               |                                               |                                               |

¹Lim et al. [73]; ²Park et al. [74]; ³Yee et al. [75]; ⁴Kannan [76]; ⁵Shekhar et al. [77]; ⁶Guo and Zhang [78]; ⁷D’Souza et al. [79].
Figure 4: Continued.
Phlorotannins identified in the present study have been previously reported in other brown seaweeds [14, 20–22]. Among the identified phlorotannins in the extracts, only a negative linear correlation was found between phlorotannin and DPPH ($R^2 = 0.69$) and a positive linear correlation was found between three-PGU units of phlorotannin content and ORAC ($R^2 = 0.62$), reinforcing the fact that NFE was also responsible of antioxidant activity. $\alpha$-Amylase IC$_{10}$ did not show any correlation with phlorotannins. In contrast, $\alpha$-glucosidase IC$_{10}$ showed strong negative linear correlation with the sum of phlorotannins ($R^2 = 0.78$), with fucophlorotannin ($R^2 = 0.73$) and a very high correlation with three-PGU phlorotannin ($R^2 = 0.98$) contents, but this happened only when E. menziesii data were not considered in the regressions. E. menziesii extract stands out from other seaweed extracts because of its very low phenolic content but relatively strong antioxidant activity, higher than expected, suggesting that other compounds were also responsible for these actions. A distinct inverse correlation between phenolic contents of A. nodosum and IC$_{20}$ for $\alpha$-glucosidase inhibition was also observed by Apostolidis and Lee [70].

Dieckol, 8,8$'$-bieckol, phlorofucofuroeckol, fucophloroethol, and phlorotannins with low PGU are the main phlorotannins reported as antioxidants and potent $\alpha$-amylase and $\alpha$-glucosidase inhibitors [24, 25, 29]. Fucofuroeckol A and dioxinodehydroeckol have been previously reported as potent carbohydrate inhibitors for Ecklonia arborea [18]. Phloroglucinol was described by Moon et al. [69] as inhibiting 50% $\alpha$-glucosidase at 0.017 mg mL$^{-1}$, and Andrade et al. [72] also related the presence of phloroglucinol (0.23 mg dry algae mL$^{-1}$) in C. tamariscifolia with the inhibition of glucosidase. In this study, the samples with the highest content of three-PGU phlorotannin, S. compressa and E. arborea, were the best inhibitors of this enzyme (Table 4).

S. compressa extract, the strongest $\alpha$-glucosidase inhibitor in this study, had the highest concentration of phlorotannins, fucophloroetol, and two- and three-PGU phlorotannins.

### 3.6. Sulfated Polysaccharides Identification

Infrared absorption frequencies corresponding to functional groups of different seaweed extracts are presented in Table 5. Sodium alginate, laminarin, and fucoidan standards were compared with the spectra of different seaweed extracts in the region between 3700 and 650 cm$^{-1}$ (Figures 4(a) and 4(b)). Particularly, in our E. menziesii sample, no carboxyl group stretching frequency (1616–1732 cm$^{-1}$) was observed as in the rest of the samples and standards, since this extract had the lowest polysaccharide content. Additionally, E. menziesii spectra did not show the characteristic signal around 3400 cm$^{-1}$ corresponding to sulfated polysaccharides. Asymmetrical bending vibration (1404–1417 cm$^{-1}$) of CH$_3$ and O-H was not observed in S. compressa and C. osmundacea extracts. A stretching vibration of sulfoxides (S=O) and CN stretching (1028–1083.6 cm$^{-1}$) and sulfate groups at the axial C4 position and C-O-S symmetrical stretching vibrations (824.84–893.38 cm$^{-1}$) were present among seaweed samples: E. menziesii, S. compressa, and E. arborea showed the strongest peaks. Results observed are in agreement with previous studies [73–79]. S. compressa showed stronger signals at the frequencies related to sulfate and carbonyl groups compared to E. arborea. FTIR of seaweed extracts showed the characteristic signals of

![Figure 4](https://example.com/figure4.png)

**Figure 4**: (a) ATR-FT-IR spectra of seaweed extract samples and polysaccharide standards: (A) Cystococera osmundacea, (B) Silvetia compressa, (C) Pterygophora californica, (D) Egregia menziesii, (E) Ecklonia arborea, (F) sodium alginate, (G) laminarin, and (H) fucoidan. Numbers 1 to 7 in FTIR spectra indicate most characteristic bands. (b) ATR-FT-IR spectrum of experimental seaweed extracts, sodium alginate, laminarin, and fucoidan standards: C. osmundacea seaweed extract (black line); S. compressa seaweed extract (green line); P. californica seaweed extract (red line); E. menziesii seaweed extract (royal blue line); E. arborea seaweed extract (aqua line); sodium alginate standard (purple line); laminarin standard (yellow line); fucoidan standard (navy line).
sulfated polysaccharides with different chemical characteristics; therefore, the polysaccharides in combination with phlorotannins in the extracts seem responsible for the antioxidant and enzyme inhibitory effects [34, 80].

4. Conclusion

This study demonstrates the nutraceutical potential of brown seaweed species from Baja California. *S. compressa* and *E. arborea* present the highest activities to protect against oxidation, as well as to inhibit enzymes involved in intestinal carbohydrate digestion and assimilation. Their lower inhibitory effect against α-amylase activity and stronger inhibition activity against α-glucosidase is ideal for managing hyperglycemia with minimal side effects. The correlations between in vitro biological activities and extracts’ chemical composition suggest that the bioactivities of *S. compressa* and *E. arborea* extracts could be attributed to their high content of polyphenols, phlorotannins (in particular, three-PGU phlorotannin), and associated polysaccharides (fucoidan, laminarin, and alginate). These seaweeds are potential candidates for food products and nutraceutical and pharmaceutical preparations and additives for diabetes management. Moreover, as *S. compressa* and *E. arborea* are edible species, their consumption should be encouraged.

5. Future Perspectives

In the future, studies on the optimization of *S. compressa* and *E. arborea* extraction conditions to maximize yields of the active compounds and on the properties of polysaccharides useful for the antioxidant activity and anti-diabetic benefits are required. Furthermore, the evaluation of these seaweeds and their extracts as antidiabetic agents both at preclinical and clinical levels is imperative for material application in functional food and pharmaceutical industries.

Data Availability

The data (analytical results spreadsheets) used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors’ Contributions

ARMG and MTS contributed equally to this work. ARMG, MTS, and MMM participated in the execution of the experiments, as well as in the data analysis and the manuscript redaction. JRM participated in enzyme inhibition analysis. MMM and LSZ participated in ORAC analysis, LSZ, MMM, and JAGU contributed to HPLC-MS analysis and characterization. BABD participated in FTIR analysis and characterization. LECS and DRM contributed to writing draft and review and editing. LECS and JAGU conceived and designed the experiments and contributed in supervision and project administration. All authors read and approved the final manuscript.

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