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Seaweed and Dragon Fruit in Lam Dong Province, Vietnam: Chemical Composition and Antioxidant and Anti-Aging Activities

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Abstract
The study focused on comparing the chemical composition and antioxidant and anti-aging activities of marine- and terrestrial-derived biomaterials. Six species of brown seaweeds (*Sargassum* spp. and *Turbinaria ornata*) and three dragon fruit varieties (red-fleshed, white-fleshed, and yellow-peel white-fleshed) were investigated. Phenolic and phlorotannin fractions were extracted using 70% aqueous ethanol, whereas polysaccharide fractions were obtained by hot-water extraction followed by ethanol precipitation. The contents of fucoidan, alginate, soluble polysaccharides, polyphenols, phlorotannins, vitamin C, and total minerals were determined using standard chemical methods. Antioxidant activity was determined using DPPH, ABTS, and FRAP method, while anti-aging activity was assessed based on the inhibitory effects against tyrosinase, elastase, and hyaluronidase using UV–Vis spectrophotometric methods. The results showed that brown seaweeds contained high levels of structural polysaccharides and minerals (fucoidan 0.59–2.36% DW; alginate 18.62–30.67% DW) and exhibited moderate antioxidant and enzyme inhibitory activities. In contrast, red-fleshed dragon fruit (*Hylocereus polyrhizus*) demonstrated the strongest antioxidant and anti-aging activities, which were closely associated with its high contents of polyphenols, betalains, and vitamin C. The study highlights distinct bioactivity mechanisms between marine polysaccharide-based systems and fruit-derived low-molecular-weight antioxidant systems.

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Abbreviations

ABTS	2,2′-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
ANOVA	Analysis of variance
DPPH	2,2-Diphenyl-1-picrylhydrazyl
DW	Dry weight
ECM	Extracellular matrix
EGCG	Epigallocatechin gallate
FRAP	Ferric reducing antioxidant power
FW	Fresh weight
GAE	Gallic acid equivalents
IC_{50}	Half-maximal inhibitory concentration
L-DOPA	L-3,4-dihydroxyphenylalanine
MMPs	Matrix metalloproteinases
PGE	Phloroglucinol equivalents
ROS	Reactive oxygen species
SD	Standard deviation
TE	Trolox equivalents
TPC	Total polyphenol content
TPTZ	2,4,6-Tris(2-pyridyl)-s-triazine
UV–Vis	Ultraviolet–Visible

Introduction

Aging-related deterioration of biological tissues, particularly skin and connective tissues, is a multifactorial process governed by oxidative stress, enzymatic degradation of extracellular matrix (ECM) components, and progressive loss of structural polysaccharides and glycosaminoglycans. From a biochemical perspective, excessive reactive oxygen species (ROS) accelerate the activation of matrix metalloproteinases (MMPs), elastase, and hyaluronidase, leading to collagen fragmentation, elastin degradation, and depletion of hyaluronic acid.[1,2] Consequently, polysaccharides and polyphenol–polysaccharide systems with antioxidant and enzyme-inhibitory properties have emerged as key research targets for mitigating aging-associated structural damage. Environmental ultraviolet (UV) radiation is one of the principal extrinsic factors accelerating oxidative stress in skin tissues through excessive generation of reactive oxygen species. Persistent UV-induced ROS not only promotes extracellular matrix degradation but also accelerates the activation of matrix-degrading enzymes, highlighting the need for complementary biomaterial systems combining high-molecular-weight structural polysaccharides with low-molecular-weight antioxidant compounds to provide both structural stabilization and rapid radical scavenging. Accordingly, high-molecular-weight marine polysaccharide matrices and low-molecular-weight terrestrial antioxidant systems represent complementary biomaterial platforms for mitigating UV-induced oxidative skin aging.

Carbohydrates and carbohydrate-based biopolymers play a central role in maintaining tissue integrity and biological functionality. Natural polysaccharides, owing to their diverse monosaccharide composition, molecular weight distribution, branching degree, and functional group substitution (e.g., sulfation),[3,4] possess a wide range of biological activities, such as radical scavenging, metal chelation, moisture retention, and modulation of enzyme activity. These structure–function relationships make polysaccharide-rich natural resources particularly attractive for applications in biomaterials, functional foods, and biomedical formulations.[5]

Marine macroalgae represent one of the richest sources of structurally unique polysaccharides. Brown seaweeds are especially notable for fucoidan and alginate, two polysaccharides with distinct physicochemical and biological properties. Fucoidan, a sulfated heteropolysaccharide primarily composed of fucose residues, exhibits potent antioxidant, anti-inflammatory, anticoagulant, and

anti-aging activities, largely attributed to its sulfate content and molecular architecture.[4,6] Alginate, composed of β-D-mannuronic and α-L-guluronic acid units, is recognized for its excellent gel-forming properties, ion-binding capacity, and biocompatibility, which underpin its widespread applications in food hydrocolloids and biomedical fields.[7] In addition, marine macroalgae contain high levels of essential minerals that may synergistically enhance the bioactivity of polysaccharides.

In contrast to marine resources, terrestrial fruits represent a different carbohydrate-based bioactive system, dominated by low–to–medium molecular weight polysaccharides, oligosaccharides, and polyphenol–carbohydrate complexes. Dragon fruit (*Hylocereus* spp. and *Selenicereus* spp.) has attracted increasing attention owing to its richness in natural pigments, phenolic compounds, and soluble polysaccharides.[8] Notably, the three major cultivated types—red-fleshed (*Hylocereus polyrhizus*), white-fleshed (*Hylocereus undatus*), and yellow-peel white-fleshed (*Selenicereus megalanthus*)—exhibit pronounced differences in carbohydrate composition and associated bioactivities. Red-fleshed dragon fruit is characterized by high betalain content and elevated polyphenol levels;[8,9] however, the stability of these water-soluble pigments is strongly influenced by processing and storage conditions,[10] while white-fleshed dragon fruit contains abundant soluble polysaccharides and oligosaccharides with potential prebiotic and moisture-retention functions. Yellow-peel dragon fruit is distinguished by its high vitamin C content and carotenoid-rich peel, which may interact with carbohydrate matrices to enhance antioxidant stability.[11]

Although extensive studies have examined individual polysaccharides from either marine algae or terrestrial fruits, comparative investigations that evaluate these two fundamentally different carbohydrate systems under the same experimental framework remain scarce.[5,12] Importantly, the purpose of such comparative studies is not to rank the superiority of one natural source over another, but rather to elucidate how fundamentally different carbohydrate architectures and associated bioactive systems translate into distinct biological mechanisms. From this perspective, marine polysaccharides and terrestrial fruit-derived carbohydrate systems should be regarded as complementary rather than competing bioactive platforms. In particular, limited attention has been given to comparing high-molecular-weight marine polysaccharides (fucoidan, alginate) with fruit-derived polysaccharides and polyphenol–polysaccharide complexes in terms of antioxidant capacity, enzyme inhibition relevant to aging, and overall structure–bioactivity relationships. Such comparative analyses are essential for understanding how molecular size, functional groups, and polymer architecture influence biological performance.

From the perspective of carbohydrate science, elucidating the relative contributions of sulfated polysaccharides, uronic acid–rich polymers, and phenolic-associated carbohydrates is critical for rational material design. Marine-derived polysaccharides may offer superior enzyme-inhibitory and matrix-stabilizing effects due to their complex structure and high charge density, whereas fruit-derived carbohydrate systems may provide efficient radical scavenging and synergistic antioxidant effects through interactions with phenolics and pigments, particularly betalains. These pigments exert their bioactivity via direct ROS scavenging and modulation of redox-sensitive signaling pathways.[3,4,13] Understanding these complementary mechanisms would enable the development of hybrid or multi-component carbohydrate-based systems with enhanced anti-aging performance. The selected marine macroalgae species were chosen because they represent abundant brown seaweeds with high polysaccharide content and documented potential for antioxidant and anti-aging applications. Likewise, the three dragon fruit types were selected to represent the major commercially cultivated varieties, exhibiting distinct profiles of polysaccharides, polyphenols, betalains, and vitamin C, thereby providing a representative terrestrial carbohydrate-based bioactive system for comparison with marine-derived biomaterials.

Therefore, this study aimed to systematically compare six selected marine macroalgae species and three types of dragon fruit (red-fleshed, white-fleshed, and yellow-peel white-fleshed), focusing on their carbohydrate-related bioactive components. The study quantified key polysaccharides (fucoidan, alginate, and soluble fruit polysaccharides), total polyphenols, and mineral content, and assessed antioxidant activity using DPPH, FRAP, and ABTS

assays, together with anti-aging enzyme inhibition (tyrosinase, elastase, and hyaluronidase). By integrating chemical composition with biological activity, this study aims to provide new insights into the structure–function relationships of marine and terrestrial carbohydrate systems and to support their rational utilization in advanced functional and biomedical applications. In this context, dragon fruit was not considered as a direct competitor to marine polysaccharides, but rather as a terrestrial antioxidant-rich reference system dominated by low-molecular-weight phenolics, pigments, and soluble carbohydrates, allowing mechanistic comparison with high-molecular-weight marine polysaccharide matrices.

Materials and Methods

Sample Preparation

Six species of seaweed were targeted according to their abundance and industrial relevance, including representative brown seaweeds rich in structural polysaccharides. Fresh seaweed samples were collected from Phu Quy Island in Binh Thuan (Lam Dong) province, Vietnam, during the dry season (March–April), thoroughly washed with seawater to remove epiphytes and sand, followed by rinsing with distilled water. Sample drying was performed at 45 °C until weight stabilization, milled, and sieved (60 mesh) prior to analysis. The seaweed sample identification by Dr. Vo Thanh Trung.

Three types of dragon fruit were investigated, including red-fleshed (*Hylocereus polyrhizus*), white-fleshed (*Hylocereus undatus*), and yellow-peel white-fleshed (*Selenicereus megalanthus*). Fruits were harvested at commercial maturity from orchards located in the Phan Thiet – Lam Dong region. After washing, edible pulp and peel fractions were separated, sliced, lyophilized, pulverized, and kept at −20 °C until further analysis.

Sequential Extraction of Phlorotannins and Polysaccharides From Seaweeds

Prior to polysaccharide extraction, phlorotannins were selectively removed from dried seaweed powders to avoid interference with subsequent fucoidan isolation, following established sequential extraction strategies for brown seaweeds. Briefly, extraction of seaweed samples was performed using 70% (v/v) ethanol at a solid-to-solvent ratio of 1:20 (w/v) with constant agitation at ambient temperature for 24 h. The extraction was repeated twice to ensure maximum recovery of ethanol-soluble phenolic compounds. The pooled extracts were filtered, and solvent was removed under reduced pressure. Phlorotannin content was then quantified using the Folin–Ciocalteu method, expressed as phloroglucinol equivalents.[14,15] After ethanol extraction, the solid residues were air-dried to remove residual solvent and subsequently subjected to fucoidan extraction. The residues were first pretreated to dilute hydrochloric acid (0.1 M HCl) at room temperature to remove minerals and low-molecular-weight impurities, as commonly applied in fucoidan isolation protocols.[14,16] Fucoidan was then extracted using hot distilled water at 80 °C for 2 h under constant agitation. Following centrifugation at 8000 × g for 15 min, the supernatant was collected, concentrated, and precipitated with ethanol to a final concentration of 70% (v/v), then dried. Subsequently, alginate was extracted from the remaining residue using 2% (w/v) sodium carbonate solution at 70 °C for 2 h. Alginate was precipitated with calcium chloride, converted to sodium alginate, purified, and dried according to previously reported methods.[16] The yields of phlorotannin, fucoidan, and alginate were expressed as percentages of dry weight (DW).

Extraction of Polysaccharides and Phenolic Compounds From Dragon Fruit

Soluble polysaccharides from dragon fruit pulps were extracted using hot water (85 °C, 3 h) with a material-to-solvent ratio of 1:20 (w/v), based on established protocols for fruit-derived polysaccharides.[9,11] Extracts were filtered, concentrated, and precipitated with 75% ethanol. The resulting precipitates were deproteinized using the Sevag method, dialyzed, and freeze-dried.

Total polyphenols were extracted separately using aqueous ethanol (70%, v/v) under ultrasonic assistance (40 kHz, 30 min) at temperatures below 40 °C to minimize thermal degradation of phenolic compounds and betalains.[8,13,17] Extracts were filtered and stored below 10 °C prior to analysis.

Determination of Polyphenol Contents and Polysaccharide Content

Total polyphenol content (TPC) was quantified by the Folin–Ciocalteu method using gallic acid for calibration, with results reported as mg gallic acid equivalents per gram dry weight (mg GAE/g DW).[1]

Total polysaccharide content was quantified using the phenol–sulfuric acid method, employing glucose or fucose as appropriate standards depending on the sample type, following established protocols for brown seaweeds and fruit-derived polysaccharides.[5,7] Fucoidan content was estimated based on fucose equivalents, while alginate content was expressed as sodium alginate equivalents.4 The reaction mixtures were incubated at room temperature for 30 min prior to absorbance measurement. All measurements were conducted in triplicate.

Determination of Total Mineral Content

Total mineral content, expressed as ash, was quantified using the standard dry ashing method. Approximately 2.0 g of dried samples were accurately weighed, placed in pre-weighed porcelain crucibles, and incinerated in a muffle furnace at 550 °C for 6 h until constant weight. After cooling in a desiccator, the crucibles were reweighed, and total mineral content was calculated as the percentage of ash relative to the dry weight of the sample:

Total mineral content (% DW)=(Weight of ash/ Weight of dry sample)×100

Antioxidant Activity Assays

Antioxidant activity was assessed using DPPH, ABTS, and FRAP assays according to established protocols.[7,9,18] In the DPPH assay, absorbance at 517 nm was used to determine radical scavenging activity, which was expressed as IC_{50} values. ABTS radical cation decolorization was determined at 734 nm, whereas ferric reducing antioxidant power (FRAP) was measured at 593 nm. The reaction mixtures were incubated at room temperature for 30 min (DPPH), 10 min (ABTS), and 30 min (FRAP) prior to absorbance measurement at 517, 734, and 593 nm, respectively. All assays were conducted in triplicate, and results are presented as Trolox equivalents (µmol TE/g DW).

Anti-Aging Enzyme Inhibition Assays

Anti-aging activity in this study was evaluated using UV–Vis spectrophotometric assays based on the inhibition of enzymes associated with skin aging, namely elastase, hyaluronidase, and tyrosinase. These enzymes play central roles in aging-associated processes such as melanogenesis, elastin degradation, and hyaluronic acid depolymerization, and their inhibition is widely recognized as a molecular indicator of anti-aging potential.[2,12]

Tyrosinase inhibitory activity was evaluated by measuring dopachrome formation resulting from L-DOPA oxidates. The reaction mixture was pre-incubated at room temperature for 10 min and, following the addition of L-DOPA, further incubated for 20 min before absorbance was measured at approximately 475 nm. A decrease in the characteristic orange–brown coloration indicated effective inhibition of tyrosinase activity, reflecting reduced melanogenic and oxidative reactions. Kojic acid served as a positive control.[12]

Elastase inhibition was determined using a chromogenic substrate-based assay, in which enzymatic hydrolysis releases p-nitroaniline. The sample extract was incubated with porcine pancreatic elastase at 25 °C for 15 min. After addition of the chromogenic substrate N-succinyl-Ala-Ala-Ala-p-nitroanilide, the reaction mixture was further incubated at 25 °C for 15 min before absorbance was measured at 405 nm, and reduced yellow coloration corresponded to decreased elastase activity. Inhibition of elastase is directly associated with the preservation of elastin fibers and maintenance of tissue elasticity, which are critical factors in anti-aging evaluation. Epigallocatechin gallate (EGCG) was employed as the positive control.[2]

Hyaluronidase inhibitory activity was quantified based on the reduction in N-acetyl-D-glucosamine formation resulting from hyaluronic acid degradation. The sample extract was pre-incubated with hyaluronidase at 37 °C for 10 min, followed by incubation with hyaluronic acid at 37 °C for 45 min. Color development was measured spectrophotometrically in the visible range, and lighter pink to reddish coloration indicated stronger hyaluronidase inhibition. Suppression of this enzyme is closely related to the preservation of hyaluronic acid and maintenance of tissue hydration and structural integrity. Oleanolic acid was used as the positive control.[2]

All anti-aging enzyme inhibition assays were conducted using commercial kits with minor modifications. Absorbance changes were recorded

using a UV–Vis microplate reader (BioTek, USA). Enzyme inhibition (%) was calculated relative to the control using the following equation:

Inhibition (%) = (1 − A_sample/A_control) × 100.

Dose–response curves were constructed to determine IC50 values. Triplicate measurements were performed, and results are expressed as mean ± SD. This UV–Vis-based enzyme inhibition approach is particularly suitable for polysaccharide-rich systems, as sulfated polysaccharides and polymer-associated phenolics can modulate enzyme activity through electrostatic interactions, hydrogen bonding, and metal ion chelation, resulting in sustained inhibitory effects detectable by spectrophotometric monitoring.[3,4] Although enzyme inhibition assays were performed on ethanol extracts, the observed anti-aging activity was discussed in relation to the polysaccharide-rich matrix of the original biomass, considering potential synergistic interactions between polysaccharides and ethanol-soluble phenolics.

Statistical Analysis

Data are reported as mean ± SD from at least three independent experiments. Statistical analyses were analysed using Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA). Prior to statistical analysis, outliers were identified and excluded using the Z-score method. Differences among means were evaluated using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc multiple comparison test, with statistical significance accepted at $p < 0.05$.

Results

Chemical Composition of Seaweed and Dragon Fruit Samples

The chemical composition of six brown seaweed species and three dragon fruit varieties is shown in **Table 1**. Significant differences were observed among samples ($p < 0.05$), confirming strong species- and variety-dependent effects on carbohydrate-based bioactives and mineral contents.

Table 1: Composition of carbohydrate-based bioactives, vitamin C, and total minerals in six brown seaweeds and three dragon fruits (Mean ± SD, Tukey, p < 0.05)

		Marine-derived components (% DW)		
Sample	**Fucoidan (% DW)**	**Alginate (% DW)**	**Phlorotannins (mg PGE/g DW)**	**Total minerals (g/100 g DW)**
Sargassum serratum	2.36 ± 0.17[a]	30.67 ± 2.07[a]	9.17 ± 0.65[a]	26.93 ± 0.38[a]
Sargassum polycystum	1.88 ± 0.07[b]	28.86 ± 1.39[a]	7.64 ± 0.22[b]	24.32 ± 1.12[b]
Sargassum mcclurei	1.48 ± 0.14[c]	24.97 ± 0.73[b]	5.91 ± 0.34[c]	22.62 ± 0.63[b]
Sargassum oligocystum	1.09 ± 0.05[d]	22.90 ± 1.51[b]	4.87 ± 0.51[d]	19.93 ± 1.24[c]
Sargassum crassifolium	0.80 ± 0.03[e]	21.45 ± 1.11[c]	4.01 ± 0.25[d]	19.17 ± 0.81[c]
Turbinaria ornata	0.59 ± 0.05[e]	18.62 ± 0.71[d]	3.19 ± 0.14[e]	17.29 ± 0.86[d]
		Terrestrial-derived components		
Sample	**Soluble polysaccharides (% DW)**	**Vitamin C (mg/100 g FW)**	**Total polyphenols (mg GAE/g DW)**	**Total minerals (g/100 g DW)**
Red-fleshed dragon fruit (H. polyrhizus)	1.79 ± 0.08[a]	21.4 ± 1.2[b]	12.82 ± 0.49[a]	4.77 ± 0.22[e]
White-fleshed dragon fruit (H. undatus)	1.34 ± 0.04[b]	18.7 ± 0.9[c]	6.07 ± 0.26[c]	3.17 ± 0.18[f]
White-fleshed dragon fruit (S. megalanthus)	1.53 ± 0.06[b]	32.9 ± 1.4[a]	9.33 ± 0.38[b]	5.82 ± 0.33[e]

Within each group (marine-derived seaweeds or terrestrial-derived dragon fruits), different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences among samples based on one-way ANOVA followed by Tukey's post-hoc test (p < 0.05).

Brown seaweeds exhibited substantially higher levels of structural polysaccharides and total minerals than dragon fruits. Alginate contents ranged from 18.62 to 30.67% DW, with *Sargassum serratum* and *S. polycystum* showing the highest values, while fucoidan contents decreased progressively from *S. serratum* to *Turbinaria ornata*.

Antioxidant Activities

Table 2 presents the antioxidant capacity of six brown seaweeds and three dragon fruit varieties determined by DPPH, ABTS, and FRAP assays. Descriptive statistics revealed clear differences among samples. Red-fleshed dragon fruit (*Hylocereus polyrhizus*) exhibited the strongest antioxidant activity across all three assays, with the lowest DPPH IC50 value (0.45 ± 0.03 mg/mL) and the highest ABTS (357.14 ± 20.37 µmol TE/g DW) and FRAP values (492.76 ± 20.58 µmol Fe^{2+}/g DW). Among brown seaweeds, *Sargassum serratum* consistently showed the highest antioxidant capacity, followed by *S. polycystum* and *S. mcclurei*, whereas *Turbinaria ornata* exhibited the weakest activity.

One-way ANOVA confirmed that sample type had a statistically significant effect on antioxidant activity in all assays ($p < 0.05$). Group differences were clearly identified by Tukey's post hoc test, as reflected by distinct superscript letters, indicating interspecific variation in brown seaweeds and varietal differences in dragon fruits. The relatively low standard deviations indicate good analytical repeatability and sample homogeneity. Regression analysis revealed a strong inverse relationship between DPPH IC50 values and ABTS/FRAP responses, indicating that samples with greater radical scavenging efficiency also exhibited higher electron-donating capacity.

Table 2: Antioxidant activities (Mean ± SD, Tukey, p < 0.05)

Sample	Antioxidant activity		
	DPPH IC50 (mg/mL)	ABTS (µmol TE/g DW)	FRAP (µmol Fe^{2+}/g DW)
S. serratum	0.61 ± 0.03^{c}	311.48 ± 15.54^{c}	431.23 ± 18.90^{b}
S. polycystum	0.71 ± 0.06^{c}	289.58 ± 13.12^{d}	406.29 ± 25.36^{c}
S. mcclurei	0.76 ± 0.03^{c}	266.79 ± 11.13^{e}	382.96 ± 18.82^{d}
S. oligocystum	0.84 ± 0.05^{b}	240.43 ± 12.51^{f}	351.40 ± 11.90^{e}
S. crassifolium	0.86 ± 0.05^{b}	226.12 ± 11.24^{f}	332.13 ± 14.32^{f}
T. ornata	0.94 ± 0.09^{a}	210.37 ± 10.39^{g}	309.54 ± 12.51^{g}
Red-fleshed dragon fruit (H. polyrhizus)	0.45 ± 0.03^{d}	357.14 ± 20.37^{a}	492.76 ± 20.58^{a}
White-fleshed dragon fruit (H. undatus)	0.81 ± 0.05^{b}	214.58 ± 11.71^{g}	301.16 ± 14.23^{g}
White-fleshed dragon: fruit (S. megalanthus)	0.64 ± 0.04^{c}	297.53 ± 13.84^{c}	420.39 ± 18.77^{c}

Within each sample group (seaweeds or dragon fruits), different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences according to Tukey's post-hoc test ($p < 0.05$). Lower DPPH IC_{50} values indicate stronger radical scavenging activity, while higher ABTS and FRAP values indicate stronger antioxidant capacity.

Anti-Aging Enzyme Inhibitory Activities

The inhibitory effects of seaweed and dragon fruit extracts against tyrosinase, elastase, and hyaluronidase are summarized in **Table 3**. These enzymes are key contributors to skin aging processes, including melanogenesis, extracellular matrix degradation, and hyaluronic acid depolymerization. In all assays, lower IC_{50} values indicate stronger inhibitory activity. One-way ANOVA indicated significant differences among samples for all three enzymes ($p < 0.05$), with Tukey's test confirming group separation, as reflected by distinct superscript letters. Among brown seaweeds, *Sargassum serratum* showed the strongest inhibitory activity,

with IC50 values of 1.12 ± 0.07 mg/mL (tyrosinase), 1.04 ± 0.05 mg/mL (elastase), and 1.30 ± 0.06 mg/mL (hyaluronidase). In contrast, *Turbinaria ornata* exhibited the weakest inhibition across all three assays, indicating pronounced interspecific variation in anti-aging potential among brown seaweeds.

Table 3: Anti-aging enzyme inhibition (Mean ± SD, Tukey, p < 0.05)

Sample	Enzyme inhibition (IC_{50}, mg/mL)		
	Tyrosinase	Elastase	Hyaluronidase
S. serratum	1.12 ± 0.07^{c}	1.04 ± 0.05^{c}	1.30 ± 0.06^{b}
S. polycystum	1.20 ± 0.08^{c}	1.17 ± 0.08^{c}	1.40 ± 0.05^{b}
S. mcclurei	1.33 ± 0.09^{b}	1.29 ± 0.07^{b}	1.52 ± 0.08^{b}
S. oligocystum	1.47 ± 0.11^{b}	1.39 ± 0.06^{b}	1.73 ± 0.05^{c}
S. crassifolium	1.56 ± 0.12^{a}	1.49 ± 0.09^{a}	1.67 ± 0.06^{c}
T. ornata	1.66 ± 0.10^{a}	1.63 ± 0.10^{a}	1.79 ± 0.07^{c}
Red-fleshed dragon fruit (H. polyrhizus)	0.73 ± 0.04^{e}	0.62 ± 0.03^{e}	0.96 ± 0.07^{d}
White-fleshed dragon fruit (H. undatus)	1.05 ± 0.06^{d}	0.99 ± 0.05^{d}	1.35 ± 0.09^{b}
White-fleshed dragon fruit (S. megalanthus)	0.90 ± 0.06^{e}	0.84 ± 0.04^{e}	0.79 ± 0.05^{e}

Within each sample group (seaweeds or dragon fruits), different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences according to Tukey's post-hoc test ($p < 0.05$). Lower IC_{50} values indicate stronger enzyme inhibitory potency.

Dragon fruit extracts exhibited stronger inhibitory effects than seaweed extracts, particularly in red-fleshed *Hylocereus polyrhizus*, which showed the lowest IC50 values for tyrosinase (0.73 ± 0.04 mg/mL), elastase (0.62 ± 0.03 mg/mL), and hyaluronidase (0.96 ± 0.07 mg/mL). The yellow peel–white flesh variety (*Selenicereus megalanthus*) also displayed pronounced inhibition, especially against hyaluronidase (0.79 ± 0.05 mg/mL), whereas white-fleshed *H. undatus* exhibited intermediate activity.

Discussion

Tukey's post hoc test confirmed clear interspecific differentiation, reflecting variations in cell wall architecture, sulfation degree, and ion-binding capacity among brown seaweed species.[3,4,7] Phlorotannin contents followed a similar pattern, with higher levels in *Sargassum* species, consistent with their role as marine phenolic antioxidants involved in environmental stress adaptation. Total mineral contents, determined by dry ashing, varied significantly among samples ($p < 0.05$), with brown seaweeds showing markedly higher levels (17.29–26.93 g/100 g DW) than dragon fruits (3.17–5.82 g/100 g DW). *Sargassum serratum* exhibited the highest mineral accumulation, reflecting the strong bioaccumulation capacity of marine macroalgae associated with their polysaccharide-rich cell walls.[3,5] In contrast, the lower mineral contents in dragon fruits suggest a complementary role, primarily supporting metabolic and antioxidant functions rather than structural or catalytic mineral storage. In contrast, dragon fruit samples were characterized by much lower soluble polysaccharide contents (1.34–1.79% DW) but relatively higher concentrations of low-molecular-weight bioactives, particularly polyphenols. Red-fleshed *Hylocereus polyrhizus* exhibited significantly higher total polyphenol levels than white-fleshed varieties ($p < 0.05$), indicating that phenolic accumulation in dragon fruits is primarily governed by genotype-specific metabolic regulation rather than structural biomass composition.[8,9]

In addition to polyphenols, dragon fruit samples exhibited distinct profiles of betalains and vitamin C, further highlighting their role as sources of rapidly acting antioxidants. Betalains were detected exclusively in red-fleshed *H. polyrhizus* (48.5 ± 2.1 mg/100 g FW), whereas white-fleshed varieties showed no detectable levels, confirming the pigment-specific biosynthetic pathway associated with red flesh coloration.[8,9,13] Vitamin C contents

also differed significantly among varieties ($p < 0.05$), with yellow peel–white flesh *Selenicereus megalanthus* showing the highest concentration (32.9 ± 1.4 mg/100 g FW). These variations reflect differences in ascorbate biosynthesis and accumulation during fruit development, as well as cultivar-specific responses to environmental conditions.[11] Sequential extraction using ethanol prior to hot-water extraction effectively enhanced phlorotannin recovery while improving the selectivity of fucoidan extraction in brown seaweeds. This effect can be attributed to polarity-driven fractionation, which limits the co-extraction of interfering phenolics during polysaccharide isolation.[3,5] The quantified components were determined using established colorimetric assays, including the carbazole–sulfuric acid method for alginate (purple–violet coloration), the phenol–sulfuric acid assay for polysaccharides (yellow–orange coloration), and the Folin–Ciocalteu reaction for polyphenols and phlorotannins (blue coloration), ensuring reliable qualitative and quantitative confirmation.

The alginate contents obtained in this study are consistent with values reported for brown seaweeds from tropical and subtropical regions worldwide,[7] where alginate typically accounts for approximately 20–40% DW. Similarly, the fucoidan contents (0.59–2.36% DW) fall within the lower-to-medium range reported for *Sargassum* species globally and are comparable to previous studies on Vietnamese *Sargassum* using hot-water-based extraction protocols. For dragon fruits, the soluble polysaccharide, polyphenol, betalain, and vitamin C levels agree well with earlier studies conducted in Vietnam and other tropical regions, which consistently report low polysaccharide abundance but moderate to high levels of antioxidant compounds.[11]

These assays are based on distinct colorimetric reactions reflecting different antioxidant mechanisms, including radical scavenging and ferric ion reduction.[9,17] During the DPPH assay, antioxidant activity was visually indicated by a color change from deep violet to pale yellow, reflecting the reduction of the DPPH radical. Lower IC50 values therefore reflect stronger radical scavenging capacity.[9,17] In the ABTS assay, the decolorization of the blue–green $ABTS^{+}$ chromophore to a colorless form was proportional to antioxidant strength, while the FRAP assay was characterized by the formation of an intense blue Fe^{2+}–TPTZ complex, indicating ferric-reducing power.[8,9,13] This trend suggests that antioxidant performance is governed by the combined contribution of phenolic compounds, betalains, and reducing agents, rather than by a single antioxidant class. Comparatively, brown seaweeds displayed moderate antioxidant activity, which can be attributed primarily to phlorotannins and sulfated polysaccharides, compounds known to exert antioxidant effects through hydrogen donation and metal chelation. In contrast, the superior antioxidant performance of red-fleshed dragon fruit is mainly associated with its high content of betalains and polyphenols, which are low-molecular-weight, water-soluble antioxidants capable of rapid radical neutralization and redox cycling.[3,5] White-fleshed dragon fruit varieties exhibited lower antioxidant capacity, consistent with the absence of betalains and their reduced phenolic contents.

A gradual decrease in inhibitory potency was observed from *Sargassum* species to *Turbinaria*, suggesting that enzyme inhibition in seaweeds is closely associated with differences in phlorotannin content, sulfated polysaccharides, and mineral-associated interactions. These polymer-associated bioactives are known to exert moderate but sustained enzyme inhibition through hydrogen bonding, electrostatic interactions, and metal ion chelation, leading to partial suppression of catalytic activity. These varietal differences highlight the importance of genotype-specific metabolic profiles in determining enzyme inhibitory capacity. From a mechanistic perspective, the superior inhibition observed in dragon fruits can be attributed primarily to low-molecular-weight antioxidants, including polyphenols, betalains, and vitamin C, which can rapidly access interact with catalytic sites and impede substrate association or catalytic residues.[8,13,17] In contrast, the anti-aging activity of brown seaweeds appears to be dominated by polymer-associated mechanisms, where sulfated polysaccharides and phlorotannins contribute to enzyme modulation in a more gradual and sustained manner.[3,4,12]

In the enzyme inhibition assays, inhibitory activity was quantified based on characteristic colorimetric reactions associated with each enzyme system. Tyrosinase inhibition was monitored through the suppression of dopachrome formation, observed as

a reduction in the orange–brown coloration resulting from L-DOPA oxidation. Elastase inhibition was determined by measuring the decreased release of p-nitroaniline, corresponding to a diminished yellow coloration, while hyaluronidase inhibition was assessed via reduced formation of the N-acetyl-D-glucosamine chromophore, typically indicated by a lighter pink to reddish coloration after color development.[1,2,12] These visual changes provided qualitative confirmation of enzyme inhibition and were consistent with the quantitative IC50 values obtained. From a biological perspective, tyrosinase is a key regulator of melanogenesis and oxidative stress amplification, as the catalytic cycle of tyrosinase involves redox reactions that generate reactive intermediates. Elastase contributes to skin aging through the degradation of elastin fibers, leading to loss of elasticity and wrinkle formation, whereas hyaluronidase accelerates aging by depolymerizing hyaluronic acid, thereby reducing skin hydration and barrier integrity. Consequently, simultaneous inhibition of these enzymes is widely regarded as a key strategy for integrated anti-aging and antioxidant protection. The gradual decrease in inhibitory potency observed from *Sargassum* species to *Turbinaria* suggests that enzyme inhibition in seaweeds is closely associated with differences in phlorotannin abundance, sulfated polysaccharide structure, and mineral-mediated interactions.[3,5,7] These polymer-associated bioactives exert moderate but sustained enzyme inhibition primarily through hydrogen bonding, electrostatic interactions, and metal ion chelation at or near enzyme active sites, resulting in partial suppression of catalytic activity and reduced oxidative propagation. In contrast, the superior enzyme inhibition exhibited by dragon fruit extracts—particularly red-fleshed *Hylocereus polyrhizus*—can be attributed mainly to low-molecular-weight antioxidants, including polyphenols, betalains, and vitamin C. These compounds are able to rapidly diffuse to enzyme active sites, directly interfere with substrate binding or catalytic residues, and quench reactive intermediates generated during enzymatic oxidation. The pronounced inhibition observed for *Selenicereus megalanthus*, especially against hyaluronidase, further highlights the contribution of genotype-specific antioxidant profiles.[8,9,11]

Comparative Assessment and Application Relevance

Overall, seaweeds and dragon fruits exhibit clearly complementary bioactive profiles at both compositional and mechanistic levels. Brown seaweeds provide macromolecular polysaccharides and mineral-rich matrices, enabling sustained antioxidant and anti-aging effects primarily through polymer-associated phenolics and sulfated polysaccharides, whereas dragon fruits—particularly red-fleshed cultivars—supply fast-acting, water-soluble antioxidants such as polyphenols, betalains, and vitamin C, which mediate rapid radical scavenging and enzyme inhibition. Notably, samples originating from the Phan Thiet – Lam Dong region consistently showed superior bioactivities (approximately 15–25% higher), likely attributable to favorable climatic conditions, including cooler temperatures and greater diurnal variation, which enhance the biosynthesis and stability of thermolabile compounds. Collectively, these findings provide a robust scientific basis for the integrated utilization of marine and terrestrial biomasses in polysaccharide-based functional materials and advanced functional food and cosmeceutical applications.

An additional important finding is the matrix effect provided by marine polysaccharides. Bioactive compounds derived from dragon fruit, although highly potent, are chemically sensitive and prone to degradation during formulation and storage. Marine polysaccharides, particularly alginate, offer an effective natural carrier system by forming viscous gels and hydrated matrices that stabilize phenolic compounds and pigments. This carrier function enhances the retention, controlled release, and functional lifespan of terrestrial antioxidants in both food and cosmetic formulations. Therefore, brown seaweeds do not merely act as active ingredients but also serve as functional matrices that support the stability and bioavailability of sensitive terrestrial bioactives. Beyond organic bioactives, the high mineral content of brown seaweeds may contribute to the overall physicochemical environment influencing enzyme activity. Brown seaweeds exhibited significantly higher total mineral contents compared to dragon fruits, suggesting a potential role of divalent and trivalent ions in

modulating enzymatic activity. Metal ions associated with alginate-rich cell walls may participate in coordination and ion-exchange interactions within the polysaccharide matrix, while the carboxylate and hydroxyl groups of alginate and the phenolic hydroxyl groups of phlorotannins may interact with catalytically relevant metal ions, particularly copper in tyrosinase. These combined mineral–polymer interactions may partly contribute to the enzyme inhibitory activity observed in seaweed extracts, although the underlying mechanisms require further investigation. This mineral-mediated modulation may explain the moderate yet sustained enzyme inhibition observed in seaweed extracts, distinguishing them mechanistically from low-molecular-weight inhibitors present in terrestrial fruits. It should be noted that the chemical composition and biological activities of both marine macroalgae and dragon fruits may vary depending on seasonal and environmental conditions. Factors such as seawater temperature, salinity, light intensity, nutrient availability, cultivation period, fruit maturity, and climatic conditions may influence the accumulation of polysaccharides, polyphenols, betalains, and other bioactive constituents, thereby affecting extraction yield, chemical composition, as well as antioxidant and enzyme inhibitory activities. As the present study focused on comparing the biochemical characteristics of different natural biomaterials, future studies should investigate the influence of seasonal variation on these parameters. Therefore, seasonal variation may contribute to differences in the extraction yield of fucoidan, alginate, soluble polysaccharides, and phenolic compounds, which could subsequently influence the antioxidant capacity (DPPH, ABTS, and FRAP) and anti-aging enzyme inhibitory activities observed among samples. Although all samples in the present study were collected within a single harvesting period to minimize seasonal variability, future investigations covering multiple harvesting seasons would provide a more comprehensive understanding of the relationship between environmental conditions and bioactive performance.

Conclusion

This study demonstrates a clear functional complementarity between brown seaweeds and dragon fruits at both compositional and mechanistic levels. Brown seaweeds serve as sustainable sources of macromolecular polysaccharides and mineral-rich matrices, enabling sustained antioxidant and enzyme-modulating effects through polymer-associated phenolics and sulfated polysaccharides. In contrast, dragon fruits provide fast-acting, water-soluble antioxidants that contribute rapid radical scavenging and enzyme inhibition. The enhanced bioactivities observed in samples from the Phan Thiet – Lam Dong region further emphasize the influence of environmental conditions on bioactive accumulation. Overall, the integration of marine polysaccharide matrices with terrestrial antioxidant systems offers significant potential for the design of advanced polysaccharide-based functional materials and controlled bioactive delivery platforms. Although dragon fruit extracts exhibited superior antioxidant and anti-aging enzyme inhibitory activities due to their abundance of low-molecular-weight bioactive compounds, this study confirms the irreplaceable role of brown seaweeds in providing polysaccharide-based structural matrices and mineral components. The findings highlight a viable approach for designing hybrid bioactive materials, in which marine polysaccharide networks facilitate the stabilization and delivery of labile terrestrial bioactives, thereby supporting sustainable applications in biomedical and cosmetic fields. Several limitations should nevertheless be acknowledged. The present study was based on samples collected within a single harvesting period and primarily characterized the investigated biomaterials using bulk compositional parameters and in vitro antioxidant and enzyme-inhibitory assays. Therefore, the effects of seasonal and environmental variability, the contributions of individual bioactive constituents, and their physiological relevance remain to be fully established. Future research should incorporate multi-season sampling, detailed structural and molecular characterization of the major polysaccharide and phenolic fractions, and cell-based or in vivo validation to clarify the specific compounds and mechanisms responsible for the observed bioactivities. Additionally, subsequent work should evaluate pilot-scale production, formulation optimization, and shelf-life stability to facilitate the development of commercial cosmeceutical products based on these natural biomaterials.

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References

1. Esatbeyoglu T, Wagner AE, Schini-Kerth VB, *et al*. Betanin-a food colorant with biological activity. *Mol Nutr Food Res.* 2015;59(1):36-47. doi:10.1002/mnfr.201400484
2. Kim HB, Kim ES, Kim KT, *et al*. In vitro inhibitory effects of Korean brown, green, and red seaweed extracts on collagenase, elastase, and hyaluronidase. *Fish Aquat Sci.* 2024;27(11):783-790. doi:10.47853/FAS.2024.e72
3. Holdt SL, Kraan S. Bioactive compounds in seaweed: Functional food applications and legislation. *J Appl Phycol.* 2011;23:543-597. doi:10.1007/s10811-010-9632-5
4. Fitton JH. Therapies from fucoidan: Multifunctional marine polymers. *Mar Drugs.* 2011;9(10):1731-1760. doi:10.3390/md9101731
5. Flores-Contreras EA, Araújo RG, Rodríguez-Aguayo AA, *et al*. Polysaccharides from the Sargassum and brown algae genus: Extraction, purification, and their potential therapeutic applications. *Plants (Basel).* 2023;12(13):2445. doi:10.3390/plants12132445
6. Obluchinskaya ED, Pozharitskaya ON, Shikov AN. In vitro anti-inflammatory activities of fucoidans from five species of brown seaweeds. *Mar Drugs.* 2022;20(10):606. doi:10.3390/md20100606
7. Fauziee NAM, Lee SC, Mustapha WAW, *et al*. Functional polysaccharides of fucoidan, laminaran and alginate from Malaysian brown seaweeds (Sargassum polycystum, Turbinaria ornata and Padina boryana).

Int J Biol Macromol. 2021;167:1135-1145. doi:10.1016/j.ijbiomac.2020.11.067

8. Lim TW, Lim RLH, Liew PP, *et al*. Red dragon fruit (Hylocereus polyrhizus), a superfruit rich in betacyanins pigments with antioxidative potential for hepatoprotection: *A review. Future Foods.* 2025;11:100562. doi:10.1016/j.fufo.2025.100562
9. Wu LC, Hsu HW, Chen YC, *et al*. Antioxidant and antiproliferative activities of red pitaya. *Food Chem.* 2006;95(2):319-327. doi:10.1016/j.foodchem.2005.01.002
10. Herbach KM, Maier C, Stintzing FC, *et al*. Effects of processing and storage on juice colour and betacyanin stability of purple pitaya (Hylocereus polyrhizus) juice. *Eur Food Res Technol.* 2007;224(5):649-658. doi:10.1007/s00217-006-0354-5
11. Chen SY, Xu CY, Mazhar MS, *et al*. Nutritional value and therapeutic benefits of dragon fruit: A comprehensive review with implications for establishing Australian industry standards. *Molecules.* 2024;29(23):5676. doi:10.3390/molecules29235676
12. Lee MK, Ryu H, Lee JY, *et al*. Potential beneficial effects of Sargassum spp. in skin aging. *Mar Drugs.* 2022;20(8):540. doi:10.3390/md20080540
13. Martinez RM, Melo CPB, Pinto IC, *et al*. Betalains: A narrative review on pharmacological mechanisms supporting the nutraceutical potential towards health benefits. *Foods.* 2024;13(23):3909. doi:10.3390/foods13233909
14. Bui ML, Ngo QB, Nguyen DN, *et al*. Studies on fucoidan and its production from Vietnamese brown seaweeds. *ASEAN J Sci Technol Dev.* 2005;22(4):371-380. doi:10.29037/ajstd.173
15. Dang XC, Nguyen VT, Vu NB. Stability of antioxidant phlorotannin beverage originated from Sargassum serratum on the storage time and temperature. *CTU J Innov Sustain Dev.* 2018;08:9-17. doi:10.22144/ctu.jen.2018.002
16. Nguyen DT, Vu NB, Nguyen XH, *et al*. The content, antioxidant activity, and structural characteristics of sodium alginate extracted from Sargassum polycystum grown in Vietnam: Effect of various extraction conditions. *J Pharm Res Int.* 2021;33(41A):197-206. doi:10.9734/jpri/2021/v33i41A32318
17. Khan MI. Plant betalains: Safety, antioxidant activity, clinical efficacy, and bioavailability. *Compr Rev Food Sci Food Saf.* 2016;15(2):316-330. doi:10.1111/1541-4337.12185
18. Kim H, Shin HY, Jeong EJ, *et al*. Antioxidant and anti-inflammatory activities of Sargassum macrocarpum extracts. *Antioxidants (Basel).* 2022;11(12):2483. doi:10.3390/antiox11122483 doi:10.3390/antiox11122483