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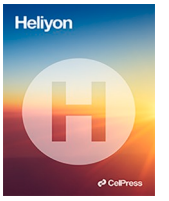

Research article

Unveiling the nutritional and antioxidant properties of brown algae resources (*Dictyota* J.V. Lamouroux) from the Bay of Bengal and Arabian Sea, Indian coast

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ABSTRACT

Brown algae are increasingly recognized as a promising alternative food source due to their nutritious and bioactive properties. This study investigates the biochemical constituents and antioxidant properties of eight *Dictyota* species collected from the East and West coast of India, providing insights into their nutritional status for fulfilling dietary requirements. The analysis revealed significant levels of protein (6.67–19.27 %), ash (16.48–52.55 %), lipids (1.37–4.55 %), carbohydrates (25.98–57.07 %), and digestible energy (186.43–311.88 Kcal/100 g), indicating their potential as functional foods. *Dictyota* species were enriched in mineral contents, including Na (113–1973 mg/100 g), K (71–1487 mg/100 g), Ca (1773–11,108 mg/100 g), Mg (515–1138 mg/100 g), Fe (248–887 mg/100 g), Zn (1.2–3.6 mg/100 g), Cu (0.89–7 mg/100 g), and Mn (1–38 mg/100 g). Among these, Ca, Fe, Mg, and Mn obtained from 5.2 g of *Dictyota* contributed significantly (>15 %) to the Recommended Dietary Allowance for Indians, highlighting their potential to address dietary mineral gaps. Similarly, chlorophyll *a* (1.351–3.478 mg g^{-1}), chlorophyll C1+C2 (0.664–1.720 mg g^{-1}), total carotenoids (0.427–1.763 mg g^{-1}), and fucoxanthin (0.058–1.741 mg g^{-1}) contents were notably high. Antioxidant properties were evaluated through total phenols and in-vitro antioxidant activities using different solvents, showing species-specific and solvent-specific variations ($p < 0.05$). These antioxidants can help reduce the risk of chronic diseases, improve immune function, and promote overall well-being. The findings of this study provide comprehensive insights into the nutritional and antioxidant potentials of *Dictyota*, facilitating future applications in nutrition and health promotion.

1. Introduction

In today's world, the profound impact of climate change and the imperative to ensure food security for a growing global population have become significant concerns [1]. By 2050, the world's population is projected to reach 9.8 billion, raising the food consumption rate by 70 % or 5.4 thousand million tons per year [2,3]. This increase underscores the challenge of meeting future nutritional needs through sustainable dietary resources. Additionally, fluctuating environmental conditions negatively impact metabolic processes by triggering excessive production of reactive oxygen species (ROS), leading to oxidative stress and chronic health issues in humans [4].

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Consequently, the regular consumption of antioxidant-rich foods is now recognized as essential for mitigating health risks. Reports of carcinogenic and adverse effects associated with synthetic antioxidants in animal models have spurred research interest in natural food sources with antioxidant properties, particularly from terrestrial and marine ecosystems [5].

Macroalgae, or seaweeds, widely consumed in several Southeast Asian countries, are rich in proteins, polyunsaturated fatty acids (PUFAs), dietary fibres, vitamins, minerals, pigments, and carotenoids, making them suitable as functional foods [6–8]. These marine algae produce secondary metabolites as part of their defence mechanisms under unstable environmental conditions, conferring them with bioactivities such as antibacterial, antioxidant, antiviral, anticancer, anti-inflammatory, anti-obesity, and anticoagulant properties [9–12]. Notably, compounds like chlorophyll-a, carotenoids (e.g., fucoxanthin), and polyphenols (e.g., phenols and flavonoids) enable seaweeds to scavenge free radicals efficiently, inhibit oxidation enzymes, and exhibit other beneficial biological properties [13, 14]. The variation in the primary and secondary metabolites of seaweeds is closely linked to abiotic factors and geographical distribution [15].

The chemical and medicinal properties of seaweeds have garnered significant attention across fields such as food, feed, phycocolloid production, biofertilizers, biofuel production, cosmetics, and neutraceuticals [16]. Despite approximately 9000 reported seaweed species worldwide, only 291 species from 43 countries are commercially important, with cultivation techniques developed for only a select few, indicating a vast untapped potential [17]. The overexploitation of specific species and the underutilization of many others threaten the sustainability of seaweed resources and ecosystem stability. Therefore, it is essential to identify the biochemical constituents of unexplored seaweeds regionally and their nutritional significance for future consumption.

Dictyota, one of the largest genera of brown algae, includes 96 species with a global distribution, and twelve species are found abundantly along the Indian coast [18,19]. While a few species, such as *Dictyota dichotoma, Dictyota bartayresiana, Dictyota acutiloba, Dictyota sandvicensis, Dictyota menstrualis*, and *Dictyota ceylanica*, have been studied for their biochemical properties, many species remain relatively unexplored [20–23]. This study aims to explore the nutritional aspects of eight *Dictyota* species collected from the east and west coasts of India by investigating their proximate composition (protein, lipid, carbohydrate, total minerals, and moisture content), digestible energy, macro and microelements (Na, K, Ca, Mg, Zn, Fe, Cu, and Mn), percentage of mineral contribution to Recommended Dietary Allowance for Indians, pigment profile (chlorophyll *a*, chlorophyll C1+C2, total chlorophyll, total carotenoids, and fucoxanthin), and determining the suitable solvent (i.e., water, 50 % methanol, and 100 % methanol) for extracting total phenols and assessing in-vitro antioxidant activities. This research will provide comprehensive insights into the nutritional characteristics and antioxidant properties of the genus *Dictyota*, contributing to developing healthy dietary options and advancing food science and human wellness.

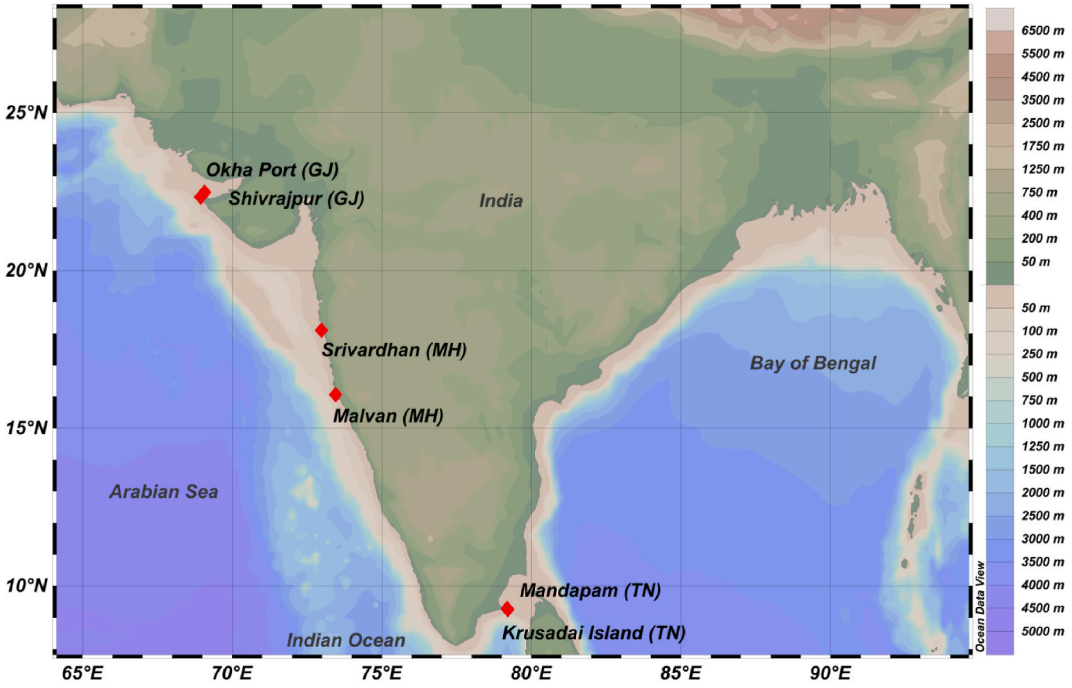

Fig. 1. Sampling sites along the East and West coast of India.

2. Materials and methods

2.1. Sample collection and preservation

Eight *Dictyota* species were collected on an abundance and availability basis from the different coastal regions of India's eastern and western states (Fig. 1). Collected species were identified by proper classical taxonomical tools concerning their morphological and anatomical characteristics. The details of sampling sites and voucher specimen numbers for herbaria submitted in the Aquatic Biodiversity Museum & Repository at ICAR-CIFE, Mumbai are provided in Table 1. The collected samples were promptly rinsed with seawater, placed in zip-lock plastic bags, and stored with long-lasting ice blocks in an insulated box for transportation. Upon arrival at the laboratory, the samples were washed multiple times with fresh water to eliminate sand particles and attached organisms. Special attention was given to sorting the samples before subjecting them to morphological and anatomical studies for accurate identification. Fresh samples were kept for pigment analysis. The remaining samples were dried overnight at $40 \pm 2\ ^{\circ}C$ in a cabinet tray dryer (Direct-On-Line, Motor Starter, RIC-1 type, REGAL company, Bangalore). Subsequently, the dried samples were powdered and stored in a desiccator until further analysis. The eight *Dictyota* species were evaluated in triplicate (n = 3) for their proximate composition, minerals, pigment profile, total phenols, and in-vitro antioxidant properties.

2.2. Biochemical composition

The proximate composition analysis, which included moisture content, crude protein, crude lipid, and total ash (minerals), was conducted following the AOAC Official method [24]. A conversion factor of 5.38 was applied to determine the total protein in brown algae [25]. The total carbohydrate content was calculated by subtracting the percentage of other nutrients from 100 [26].

2.3. Digestible energy calculation

The calorific values of protein (4 cal/g), carbohydrate (4 cal/g) and lipids (9 cal/g) were considered to calculate the digestible energy as kcal/100 g of dry algae [27].

2.4. Minerals composition and their contribution to RDA for indians

Macro-elements such as sodium (Na), potassium (K), magnesium (Mg), calcium (Ca) and trace-elements include zinc (Zn), copper (Cu), iron (Fe), manganese (Mn) were estimated by the Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES: Model Thermo Electron IRIS INTREPID II XSP DUO, Germany). The seaweed samples were homogenized with concentrated HNO_3 and digested using a microwave digester (Milestone, Shelton, Italy) for elemental analysis. The resulting sample was subjected to flame inhalation, and the absorption of distinctive radiation by each element was recorded. The mineral concentration was determined and expressed as mg/100 g. Regarding the Recommended Dietary Allowance (RDA), 5.2 g of seaweed meal in the daily diet was taken as the reference limit for calculating the percentage of minerals' contribution [28]. In this study, the ICMR report has been considered to estimate the RDA for Indians [29].

2.5. Pigment analysis

Seaweed extract was prepared using 80 % acetone, by following the Arnon's method [30]. The pigments, including chlorophyll *a*, chlorophyll C1+C2, carotenoids, and fucoxanthin, were quantified by measuring the absorbance at specific wavelengths (663, 645, 630, 664, 480, 510, 631, and 581 nm, respectively) [30–33]. The pigments were quantified in mg g^{-1} using the following formula:

$$Chlorophyll\ a = \frac{[12.7(A663) - 2.69(A645)V]}{1000*W} \quad (1)$$

$$Total\ Chlorophyll = \frac{[20.2(A645) + 8.02(A663)V]}{1000*W} \quad (2)$$

Table 1
Sampling site details of eight *Dictyota* species from the Indian coast.

Sampling sites	Geographical Co-ordinates	Species Collected
Mandapam, Tamil Nadu*	9°16′53.81″ N; 79°11′20.77″ E	*D. indica* (B202404), *D. ciliolata* (B202405)
Krusadai Island, Tamil Nadu*	9°15′05″ N; 79°12′56″ E	*D. maxima* (B202406)
Malvan, Maharashtra**	16°03′37.5″ N; 73°27′21.4″ E	*D. divaricata* (B202402), *D. friabilis* (B202401)
Srivardhan, Maharashtra**	18°06′12″ N; 72°59′07″ E	*D. flabellata* (B202407)
Shivrajpur, Gujarat**	22°19′58″ N; 68°57′07″ E	*D. bartayresiana* (B202409)
Okha coast, Gujarat**	22°28′48.2″ N; 69°04′50.9″ E	*D. dichotoma* (B202410)

Note: *Sampling sites from the East Coast; ** Sampling sites from the West Coast.

$$Chlorophyll\ C1 + C2 = [24.36(A630) - 3.73(A664)] \tag{3}$$

$$Total\ Carotenoids = \frac{[7.6(A480) - 1.49(A510)V]}{1000*W} \tag{4}$$

$$Fucoxanthin = \frac{[A470 - 1.239(A631 + A581 - 0.3*A664) - 0.0275*A664]}{141} \tag{5}$$

where,

A- Absorbance at the particular wavelength.
V- Total volume of the pigment extract.
W- Weight of the sample used for extraction.

2.6. Preparation of seaweed extracts

Seaweed extracts were prepared using three solvents: water, 50 % methanol (v/v), and 100 % methanol, to estimate the total phenolic content and antioxidant activities based on the solvents' polarity (high to low). Dried seaweed powder (1 g) was mixed with 25 ml of the respective solvent in a conical flask and shaken continuously for 1 h on an orbital shaker. The extracts were centrifuged at 2935×*g* for 10 min, and the supernatant was transferred to another container. The same pellet was used for a second extraction, following the repetition of the centrifugation step. The supernatants from both extractions were combined, adjusted to a total volume of 50 ml, and stored at −20 °C until further use [14].

2.7. Total phenols and in-vitro antioxidant activities

The total phenolic content was determined using the Folin–Ciocalteau method [34]. Gallic acid (25–1000 mg/l) served as a standard, and the phenolic content was expressed as mg GAE/100 g of dry seaweed. DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging assay was performed using the Trolox standard (25–1000 μmol/l) [35]. The DPPH radical scavenging activity (%) was calculated using the following formula:

$$Scavenging\ activity\ (\%) = \left\{1 - \left[A(Sample) - \frac{A(Blank)}{A(Control)}\right]\right\}*100 \tag{7}$$

The Ferric Reducing Antioxidant Power (FRAP) assay was conducted using Trolox (25–1000 μmol/l) as the standard and the results were expressed as μmol of TE/100 g of dry seaweed [35].

2.8. Statistical analysis

Variables are presented as mean ± standard deviation (n = 3). SPSS software package (version 26) was used to perform a one-way or two-way analysis of variance, the Duncan (post-doc) test, which describes the significant variation.

3. Results and discussion

3.1. Proximate composition

The chemical composition of *Dictyota* was incredibly varied depending on the species ($p < 0.05$). *D. maxima* showed the maximum moisture levels among eight *Dictyota* species collected during the present study (Table 2). The existing moisture content in *Dictyota* ranges from 58.83 to 84.02 % on a fresh weight basis, which is lower than findings for nine brown algae (92.21–96.97 %) from the Sri Lankan coast [36]. The study results were supported with statement that the genus *Dictyota* had lower moisture content when compared to other brown algae species [37]. Also, samples collected from India's East Coast, such as *D. maxima* (84.02 %) and

Table 2
Thallus description and moisture content of different *Dictyota* species.

Species	Moisture (FW %)	Thickness (μm)	Thallus nature
D. friabilis	77.60 ± 1.82^{b}	180–200	Short thallus, friable, creeping.
D. divaricata	58.83 ± 1.22^{f}	70–80	Short, very thin, tuft and entangled
D. indica	81.01 ± 2.24^{a}	80–110	Long, thin, and spirally twisted.
D. ciliolata	83.35 ± 1.35^{a}	100–140	Linearized with membranous texture
D. maxima	84.02 ± 1.96^{a}	250–330	Short, thick, linearized-broad thallus
D. flabellata	73.99 ± 6.71^{c}	120–180	Broad, short, thin and linearized thallus
D. bartayresiana	62.21 ± 1.25^{e}	150–220	Long linearized thallus; Broaden towards the base
D. dichotoma	68.35 ± 3.13^{d}	100–140	Short-linearized and membranous

Note: Moisture content in FW % (Mean ± SD) with different superscripts ($^{a\text{-}g}$) shows a significant difference between the species ($p < 0.05$).

D. ciliolata (83.35 %), were observed to have the highest moisture content which is consistent with the previous study's findings for *Dictyota acutiloba* (88.5 %) and *Dictyota sandvicensis* (86.4 %) from the Hawaiian coast [20]. In comparison, *D. divaricata* (58.83 %) from the West Coast had the lowest, which might be connected with salinity shift [38] and their morphological differences [38,39]. In this study, thallus thickness, texture and consistency were found to have a more significant influence on their water binding capacity (Table 2), as evidenced by the higher thickness values in *D. maxima* (250–330 μm) and *D. ciliolata* (100–140 μm) and the lower value in *D. divaricata* (70–80 μm).

Comparing those eight *Dictyota* species, *D. bartayresiana* contained the highest amount of protein and lipids. *D. divaricata* had more ash content. *D. flabellata* was rich in total carbohydrates (Fig. 2A–D). On a dry weight basis, protein content is typically higher in red and green algae (10–47 %) than in brown algae (3–15 %) [40]. In this study, protein content varied significantly, ranging from 6.67 % in *D. dichotoma* to 19.27 % in *D. barteyresiana* (Fig. 2A). These values are consistent with protein levels of several brown algal species (8.93–13.83 %) reported along the Indian coast. However, the protein content of *D. dichotoma* (6.67 %) was lower than that reported in the earlier study conducted on the Indian coast [1,41]. *D. ciliolata* had more protein (12.93 %) than previously reported from the Australian coast [42]. Protein content in seaweeds generally varies according to species, phylum, and environmental factors such as temperature, salinity, and nutrient levels in seawater [40,43]. Together, we identified the depth as another factor influencing protein content since samples collected at the supra littoral area (*D. bartayresiana*) had the maximum amount following the species from intertidal (*D. flabellata, D. indica, D. ciliolata, D. maxima, D. divaricata* and *D. friabilis*) and sublittoral zone (*D. dichotoma*). Seaweed exposure to sunlight in a semi-diurnal tidal cycle varies with the depth range, which might be responsible for protein variation [44].

Seaweeds typically have low lipid content (<4 %) [45]. The total lipid content of *Dictyota* species ranged from 1.37 % to 4.55 % of dry weight (Fig. 2B), which is lower than the lipid content reported for species in the order Dictyotales [20,46]. However, *D. barteyresiana* (4.55 %), *D. dichotoma* (3.82 %) and *D. divaricata* (3.21 %) showed higher lipid content compared to several brown seaweeds reported earlier from various parts of the Indian coast and the West Algerian coast [41,47–49]. *D. dichotoma* had higher lipid content (3.82 %) than previously reported along the Kachchh coast, India [1]. The interaction of abiotic factors, especially with temperature [50] and other nutritional complexes of seaweeds can be attributed to the variation in lipid content [51].

Ash content in seaweeds indicates the presence of minerals in their tissues [52]. In this study, the ash content of *Dictyota* species ranged from 16.48 % to 52.55 % of dry weight (Fig. 2C), surpassing the levels found in previously investigated brown seaweeds belonging to the genera of *Dictyota*, *Laminaria, Fucus, Saccharina, Chorda, Ascophyllum, Padina* and *Toania* from different countries [20,41,53,54]. *D. divaricata* had the highest ash content (52.55 %), followed by *D. friabilis* (43.50 %), *D. indica* (38.67 %), *D. maxima* (37.05 %), and *D. ciliolata* (34.44 %). The ash content of *D. dichotoma* showed significant variability compared to previous studies from India [1,41], which may be influenced by the ions uptake ability of seaweeds' cell wall or fluctuations in salt and inorganic components present in seawater [7,55].

Seaweeds are rich in carbohydrates, providing significant energy during metabolism [49]. The total carbohydrate content of *Dictyota* species ranged from 25.98 % in *D. divaricata* to 57.07 % of dry weight in *D. flabellata* (Fig. 2D). The carbohydrate levels in *Dictyota* were comparable to those found in many commercially critical edible species reported earlier [1,41,47,49,54]. Brown algae rich in carbohydrates have a significant amount of bioactive polysaccharides and oligosaccharides including alginate, fucoidans and dietary fibre which support several physiological processes in humans [56]. The earliest report stated that a range of dietary fibre in *Dictyota* species varied from 10.2 % to 14.1 % DW [23,64]. The major health benefit of dietary fibre is improving gastrointestinal health by reduction in the risks of diverticular disease, obesity, constipation, duodenal ulcers, hypertension, gallstones, appendicitis,

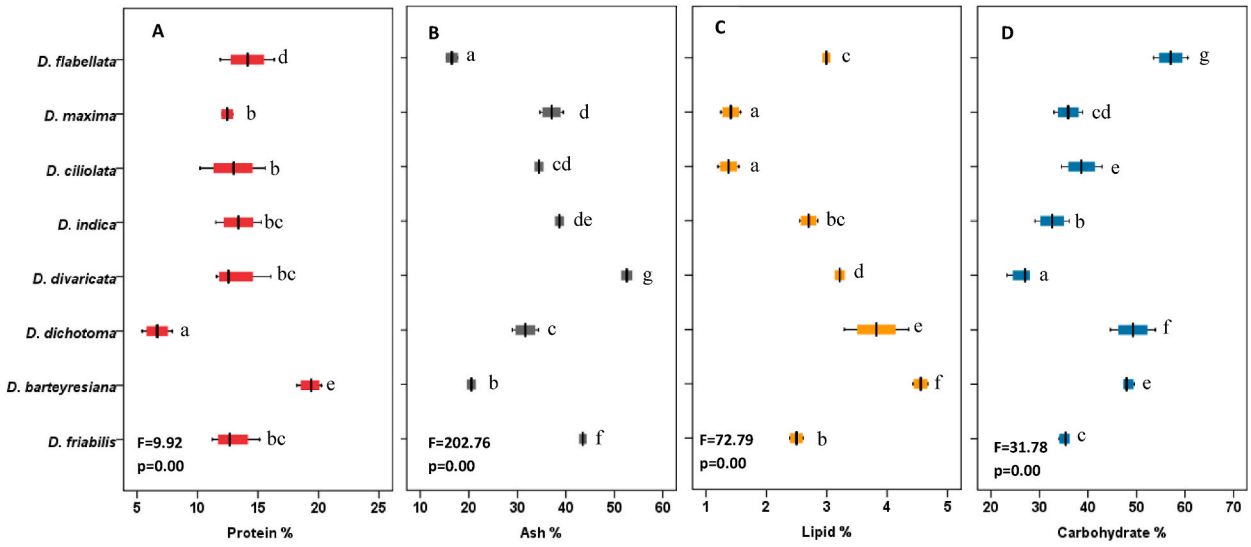

Fig. 2. Biochemical composition of eight *Dictyota* species collected from the Indian coast (% of dry weight); a). Total protein; b). Total (Minerals) ash; c). Total lipid; d). Total carbohydrate content. Each variable's F-value and p-value significantly differ among eight *Dictyota* species.

hyperlipidaemia and colorectal & breast cancer [57]. These polysaccharides can be utilized for bioethanol production through fermentation processes. The present study showed that carbohydrate levels (25.98–49.25 %) found in *Dictyota* were similar to those of brown algae used for bioethanol production, including *Laminaria japonica, Sargassum fulvellum, Sargassum polycystum, Sargassum vulgare*, and *Saccharina latissima* [58].

3.2. Digestible energy value

Variation in the digestive energy (DE) of different food sources purely depends on the existence of protein, lipid, and carbohydrate content in them. The highest DE value was observed in *D. flabellata* (311.68 Kcal 100 g^{-1}), followed by *D. barteyresiana* (271.88 Kcal 100 g^{-1}) and *D. dichotoma* (258.05 Kcal 100 g^{-1}). *D. divaricata* had the lowest energy value of 186.43 Kcal 100 g^{-1} (Fig. 3). The energy values obtained from *Dictyota* (186.43–311.68 Kcal 100 g^{-1}) were relatively higher compared to other edible seaweeds [14,59]. Similar energy values (210.6–247.9 Kcal 100 g^{-1}) were found in *Cystoseira stricta, Cystoseira compressa, Enteromorpha compressa,* and *Ulva lactuca* [49].

3.3. Minerals composition and its contribution (%) to Recommended Dietary Allowances

The mineral content of seaweeds is significantly higher than other food products derived from land plants and animals [60]. Seaweeds absorb inorganic elements from the surrounding seawater, producing enriched mineral content [8,61]. The nutritional aspects of minerals play a crucial role in human health by helping prevent chronic degenerative diseases such as cancer, obesity, and cardiovascular diseases [62]. The present study investigated the macro and microelements in different *Dictyota* species collected from sites free of pollution and their contribution to RDA for Indians (Tables 3 and 4). In this study, the abundance of calcium (1773–11108 mg 100 g^{-1}), sodium (113–1973 mg 100 g^{-1}), magnesium (515–1138 mg 100 g^{-1}), potassium (71–1487 mg 100 g^{-1}), and iron (248–887 mg 100 g^{-1}) in *Dictyota* was found to be significantly high (Table 3).

The seaweed species *D. divaricata* (11,108 mg 100 g^{-1}), *D. friabilis* (9602 mg 100 g^{-1}), *D. barteyresiana* (9139 mg 100 g^{-1}), *D. dichotoma* (6278 mg 100 g^{-1}), and *D. flabellata* (5693 mg 100 g^{-1}) collected from the west coast of India had the highest calcium content, while *D. maxima* (1973 mg 100 g^{-1}), *D. ciliolata* (1870 mg 100 g^{-1}), and *D. indica* (1607 mg 100 g^{-1}) from the East coast had higher sodium content (Table 3). These findings support previous studies indicating that the mineral content of seaweeds varies depending on species, geographic range, wave exposure, seasonal and annual variations, and environmental and physiological factors [63]. This study showed similarities in mineral ratios (Ca > Na) with those reported for *Colpomenia sinuosa, D. dichotoma*, and *Padina pavonica* from the Iran coast [64]. Calcium was more abundant than sodium in several brown algae samples collected from Pakistan [65]. Regarding the Recommended Dietary Allowance for Indians, Na contribution was notably high in *Dictyota* species collected from the eastern coastal states of India [28]. Similarly, eight *Dictyota* species examined in this study contributed significantly to RDA for calcium (15.37–96.27 %) (Table 4).

The Na/K ratio is essential in nutrition as a high Na/K ratio is associated with hypertension [60]. In this study, the Na/K ratio of *D. ciliolata* (9.44) was very high, while the other species had ratios ranging from 1.56 to 2.35, which is similar to Na/K ratio of *Caulerpa* sp., *Codium fragile*, and *Undaria pinnatifida* [62]. The Na/K ratio is entirely dependent on the elemental absorption ability of brown seaweeds from their surrounding environment due to the presence of cellulose (polysaccharides) and alginic acid in their cells [61]. Iron accumulation in *Dictyota* (248–887 mg 100 g^{-1}) was more remarkable than other trace elements, similar to tropical seaweeds [66]. Among the eight species studied, *D. flabellata* had the highest Fe content (887 mg 100 g^{-1}). Likewise, high magnesium levels were recorded in *D. divaricata* (1138 mg 100 g^{-1}) and *D. maxima* (1054 mg 100 g^{-1}). The outstanding contribution of Fe (75.03–271.32 %) and the considerable percentage of Mg, i.e. 7.88–19.09 % in adults and 26.78–118.35 % in children, to RDA were observed in eight

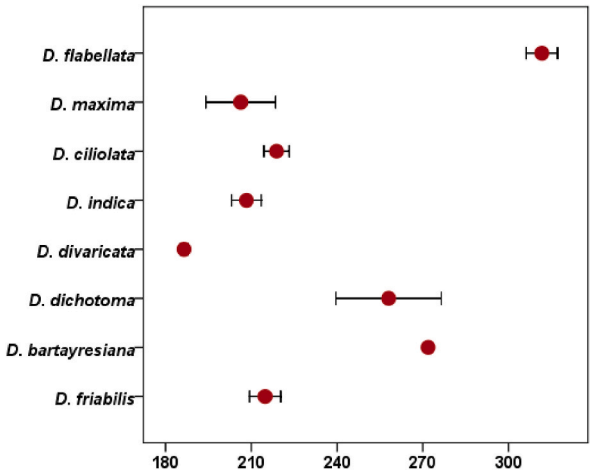

Fig. 3. Range of digestible energy (kcal/100 g) obtained from genus *Dictyota*.

Table 3
Macro and micro elements of *Dictyota* (mg/100 g) and Recommended Daily Allowances (mg/day) of minerals for Indians, provided by ICMR, (2010).

Species	The concentration of macro and microelements in *Dictyota* (mg/100 g)							
	Macro-minerals (mg/100 g)				Micro-minerals (mg/100 g)			
	Na	K	Mg	Ca	Zn	Cu	Fe	Mn
D. friabilis	156	89	958	9602	3.3	0.9	551	34
D. divaricata	162	81	1138	11,108	3.6	0.89	665	38
D. indica	1607	1487	889	2137	1.4	0.98	303	2
D. ciliolata	1870	198	1009	2676	1.8	1.37	470	4
D. maxima	1973	840	1054	1773	1.2	0.95	248	1
D. flabellata	113	71	880	5693	4.5	2.32	887	10
D. bartayresiana	527	260	761	9139	3	3.6	400	7
D. dichotoma	184	118	515	6278	3.2	7	461	14
	Recommended Daily Allowances (mg/day) for Indians by ICMR, (2010)							
Men	2100	3750	340	600	12	1.7	17	4.0
Women	1900	3225	310	600	10	1.7	21	4.0
Children	590–1010	1100–1550	50–100	600	5–8	1.7	9–16	4.0

Note: Concentration of minerals is given as mean of duplicate samples (n = 2).

Table 4
Percentage contribution of minerals in 5.2 g of seaweeds to Recommended Daily Allowances (RDA) for Indians.

	Percentage contribution of *Dictyota* (5.2 g) to RDA of macro minerals									
	Sodium (Na)			Potassium (K)			Magnesium (Mg)			Calcium (Ca)
	M	W	Children	M	W	Children	M	W	Children	Children-Adult
D. friabilis	0.39	0.43	0.80–1.37	0.12	0.14	0.30–0.42	14.65	16.07	49.82–99.63	83.22
D. divaricata	0.40	0.44	0.83–1.43	0.11	0.13	0.27–0.38	17.40	19.09	59.18–118.35	96.27
D. indica	3.98	4.40	8.27–14.16	2.06	2.40	4.99–7.03	13.60	14.91	46.23–92.46	18.52
D. ciliolata	4.63	5.12	9.63–16.48	0.27	0.32	0.66–0.94	15.43	16.93	52.47–104.94	23.19
D. maxima	4.89	5.40	10.16–17.39	1.16	1.35	2.82–3.97	16.12	17.68	54.81–109.62	15.37
D. flabellata	0.28	0.31	0.58–1.00	0.10	0.11	0.24–0.34	13.46	14.76	45.76–91.52	49.34
D. bartayresiana	1.30	1.44	2.71–4.64	0.36	0.42	0.87–1.23	11.64	12.77	39.57–79.14	79.20
D. dichotoma	0.46	0.50	0.95–1.62	0.16	0.19	0.40–0.56	7.88	8.64	26.78–53.56	54.41
	Percentage contribution of *Dictyota* (5.2 g) to RDA of micro minerals									
	Zinc (Zn)			Copper (Cu)			Iron (Fe)			Manganese (Mn)
	M	W	Children	Children-Adult			M	W	Children	Children-Adult
D. friabilis	1.43	1.72	2.15–3.43	2.75			168.54	136.44	179.08–318.36	44.20
D. divaricata	1.56	1.87	2.34–3.74	2.72			203.41	164.67	216.13–384.22	49.40
D. indica	0.61	0.73	0.91–1.46	3.00			92.68	75.03	98.48–175.07	2.60
D. ciliolata	0.78	0.94	1.17–1.87	4.19			143.76	116.38	152.75–271.56	5.20
D. maxima	0.52	0.62	0.78–1.25	2.91			75.86	61.41	80.60–143.29	1.30
D. flabellata	1.95	2.34	2.93–4.68	7.10			271.32	219.64	288.28–512.49	13.00
D. bartayresiana	1.30	1.56	1.95–3.12	11.01			122.35	99.05	130–231.11	9.10
D. dichotoma	1.39	1.66	2.08–3.33	21.41			141.01	114.15	149.83–266.36	18.20

Dictyota species (Table 4).

Calcium and magnesium are responsible for strengthening bones and teeth, regulating heartbeat, facilitating muscle contraction, aiding blood coagulation, and activating insulin and calcitonin [67]. The copper (0.89–7 mg 100 g^{-1}) and zinc (1.2–4.5 mg 100 g^{-1}) present in *Dictyota* fell within the permissible levels (73.3 mg/kg of Cu and 99.4 mg/kg of Zn) recommended by FAO/WHO [68]. Similarly, Cu's (2.72–21.41 %) and Zn's (0.52–1.87 %) contributions to RDA for Indians were considerably less, which denotes that *Dictyota* had a safe amount of heavy metal Cu content. The manganese content in *Dictyota* ranged from 1 to 38 mg 100 g^{-1}, contributing 1.30–49.40 % to RDA. Magnesium may provide several health benefits because of its significant role in protein, carbohydrate and lipid metabolism, immune system function, blood sugar regulation, and skeletal and reproductive systems [69,70].

3.4. Pigment composition

Chlorophylls, carotenoids, and phycobiliproteins are natural pigments in seaweeds that play an essential role in photosynthesis and contribute to distinct colours. Chlorophyll-*a* is common in all three types of seaweeds, accompanied by varying proportions of chlorophyll *b, c, and d*. Fucoxanthin, a kind of carotenoid, shares a significant proportion of brown seaweeds [71]. Pigments are becoming popular in biomedical applications for their antioxidant, antimicrobial, anticancer, anti-inflammatory, and anti-obesity properties [72,73]. The present study reported a significant amount of chlorophylls and carotenoids from *Dictyota* extracted using

80 % acetone (Figs. 4–5). *D. flabellata* showed high levels of chlorophyll *a*, chlorophyll *C1+C2*, total carotenoids and fucoxanthin (3.478 mg g^{-1}, 1.720 mg g^{-1}, 1.763 mg g^{-1}, and 1.741 mg g^{-1}, respectively). *D. barteyresiana* (2.100 mg g^{-1}, 1.263 mg g^{-1}, and 0.830 mg $g^{-1,}$ respectively) and *D. dichotoma* (2.036 mg g^{-1}, 1.117 mg g^{-1} and 0.852 mg g^{-1} respectively) were found to have considerable amount of chlorophyll *a*, chlorophyll *C1+C2*, and total carotenoids. *D. maxima* (0.408 mg g^{-1}), followed by *D. dichotoma* (0.371 mg g^{-1}), had the maximum fucoxanthin content.

Chlorophylls consist of a tetrapyrrole ring with a magnesium ion in the centre, which helps improve human metabolism. Chlorophyll *a* content obtained from *Dictyota* (1.351–3.478 mg g^{-1}) using acetone was higher than the values reported for brown seaweeds of economic importance investigated earlier at various localities [14,74,75]. The range was similar to *D. dichotoma, Lobophora variegata, Iyengaria stellata, Sargassum linearifolium*, and *Turbinaria* species, while lower than that of their sister taxa *Stoechospermum marginatum, Spatoglossum asperum*, and *Dictyopteris australis* studied from the Indian waters [41]. The proportion of chlorophyll *C1+C2* in *Dictyota* (0.664–1.720 mg g^{-1}) is consistent with other Phaeophyceaen algae [41,76]. Carotenoids are tetraterpenes of 40 carbon atoms with 15 conjugated double bonds. Carotene, xanthophylls, and lutein are their three major groups. The present study reported total carotenoids and fucoxanthin with similar concentrations observed in several brown algal species in previous studies [14,41,75,76]. The inclusion of natural pigments in a regular diet helps humans prevent several health disorders like cancer (breast, ovarian, colorectal and cervical) and cardiovascular disease [77].

3.5. Total phenolic content

The phenolic compounds in brown seaweeds are known for their various bioactivities, including antioxidant, anti-ageing, anticancer, and antibacterial properties [13,78]. The present study showed significant variability in the total phenolic content (TPC) of eight *Dictyota* species extracted using solvents with different polarities. Total phenols obtained for these species were within the range reported for the water extract of *Fucus serratus, Fucus vesiculosus, Fucus distichus, Fucus spiralis, Sargassum muticum, Saccharina latissima, D. dichotoma*, and *Laminaria digitata* harvested from the Danish coast [79]. The TPC ranged from 375.77 to 623.20 mg GAE 100 g^{-1} in water extract (WE), 374.49–483.46 mg GAE 100 g^{-1} in 50 % methanol extract (MWE), and 477.05–591.15 mg GAE 100 g^{-1} in 100 % methanol extract (ME) (Fig. 6), which is consistent with previous findings in brown and red seaweeds from the Iceland, Indonesia, Philipines, Chile and Canada [80,81]. Among all, *D. ciliolata* exhibited the highest TPC in the water extract (623.20 mg GAE 100 g^{-1}), while *D. indica* (591.15 mg GAE 100 g^{-1}) showed higher TPC in the methanol extract. Most *Dictyota* species yielded a maximum of TPC in methanol extract except for *D. ciliolata* and *D. barteyresiana*. The TPC of *Dictyota* species was higher than the values reported earlier

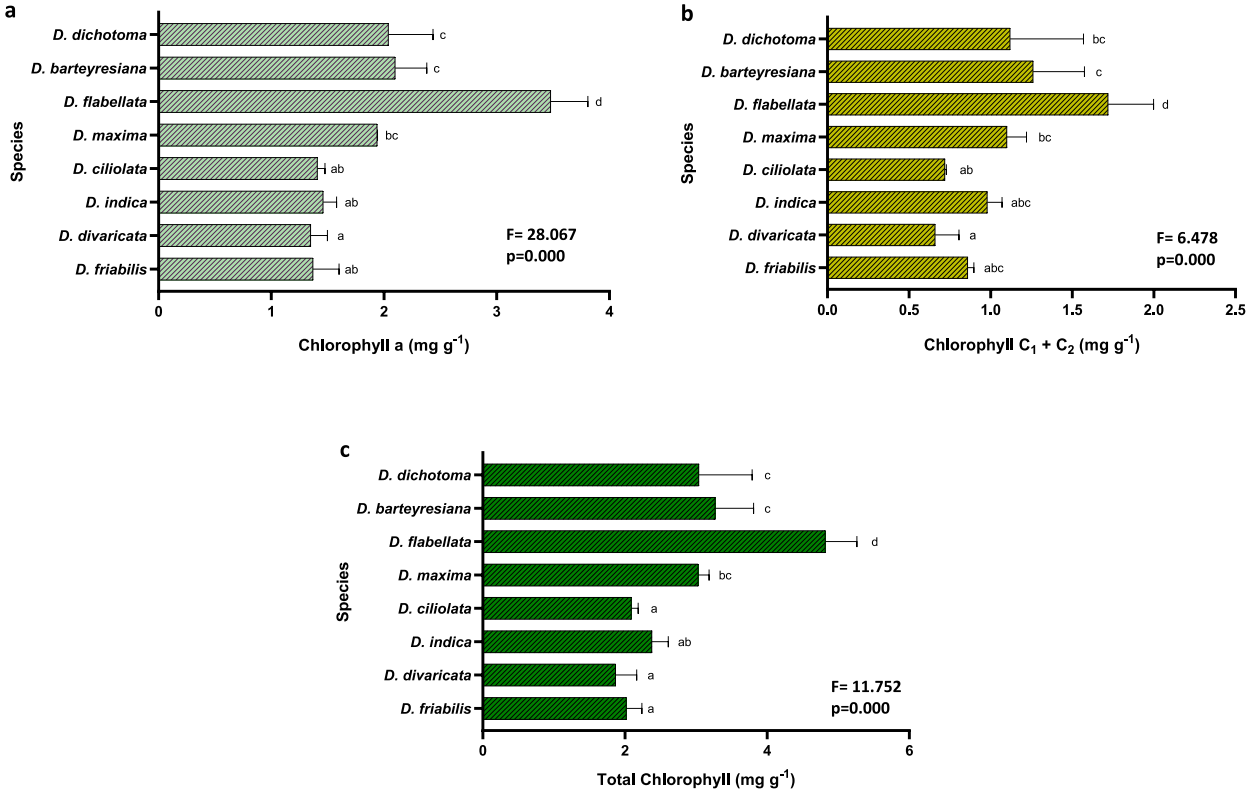

Fig. 4. Composition of chlorophyll contents (mg g^{-1}) in genus *Dictyota*: a). Chlorophyll-a, b). Chlorophyll C1+C2, c). Total chlorophyll: The F-value and p-value represent a significant difference between species.

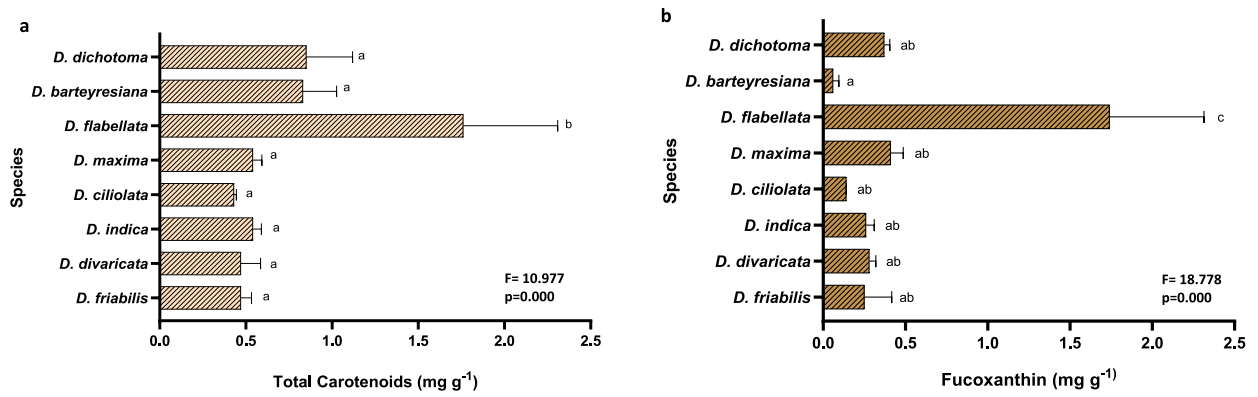

Fig. 5. Total carotenoids and fucoxanthin contents (mg g^{-1}) in genus *Dictyota;* The F-value and p-value represent a significant difference between species.

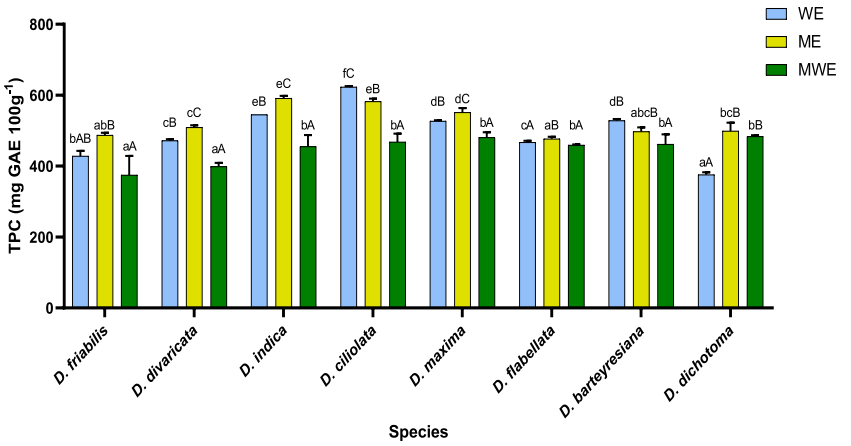

Fig. 6. Comparison of total phenolic content (mg GAE/100 g) of different *Dictyota* species using three solvents. WE-Water extract, MWE-Methanol 50 % v/v extract, ME-Methanol 100 % extract. Different superscripts (a–g) and (A–C) are given for each extract, showing a significant difference between the species and the solvents, respectively ($p < 0.05$).

[14,80]. The solubility of phenolic compounds depends on the polarity or dielectric constant of the solvents used for extraction, as well as the degree of phenol polymerization and its interaction with other biochemical components present in seaweeds, such as carbohydrates and proteins [82]. The phenolic composition of seaweeds can vary depending on environmental factors such as salinity, nutrients, depth, and sunlight intensity [83].

3.6. In-vitro antioxidant activities

Significant variations were observed ($p < 0.05$) among the eight species studied for evaluating their in-vitro antioxidant activities using three solvents (Fig. 7A–B). The DPPH radical scavenging method is commonly used to assess the antioxidant potential of natural resources. In this method, the 2,2-diphenyl-1-picrylhydrazyl radicals are neutralized through reduction or quenching via single electron transfer (SET) or hydrogen atom transfer (HAT) [84]. The drop in purple colour intensity, which indicates the proportion of DPPH radical reduction, often shows concentration dependency. The effectiveness of DPPH scavenging activity is influenced by the characteristics and phenolic arrangement of the antioxidants being extracted from the seaweeds when solvents with varying polarity are used [85]. In this study, six *Dictyota* species in the water extract (21.47–30.21 %) and two in the 50 % methanolic extract (13.80–16.34 %) exhibited significantly higher DPPH scavenging activity (Fig. 7A). All eight species showed the lowest DPPH activity in methanolic extract, indicating the influence of solvent polarity on the phenolic extraction. The DPPH scavenging capability of *Dictyota* species was comparatively lower than that reported for several seaweeds [86,87].

The Ferric Reducing Antioxidant Power assay measures compounds' reducing ability, which terminates free radicals' chain reaction through electron or hydrogen transfer. This assay indicates the antioxidant potential of seaweeds [88,89]. In this present study, *D. ciliolata* (450.88 μM TE 100 g^{-1}), followed by *D. maxima* (377.19 μM TE 100 g^{-1}) and *D. indica* (377.19 μM TE 100 g^{-1}) exhibited the maximum activity in water. The extracts prepared using low-polarity solvents such as 50 % methanol (25.44–48.23 μM Trolox equivalent 100 g^{-1}) and 100 % methanol (1.68–14.85 μM Trolox equivalent 100 g^{-1}) were exhibited the lowest FRAP activity

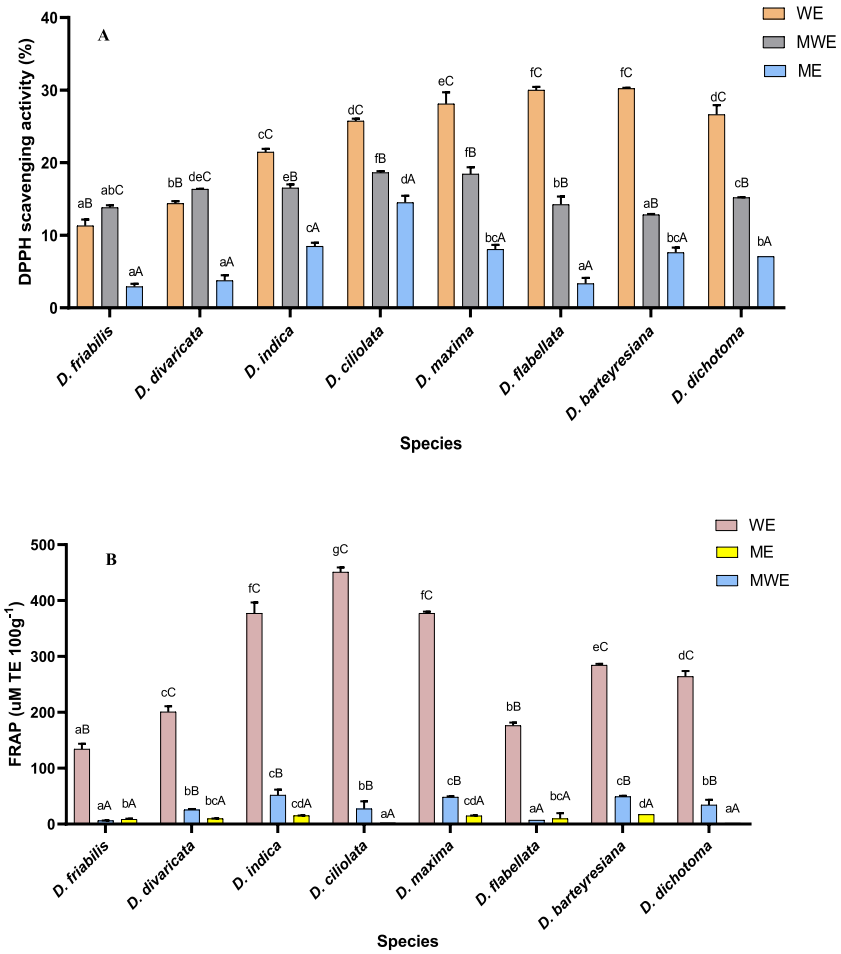

Fig. 7. Comparison of In-vitro antioxidant activities in different *Dictyota* species using three solvents: A). DPPH radical scavenging activity (%), B). Ferric Reducing Antioxidant Power activity (mg TE/100 g). WE-Water extract, MWE-Methanol 50 % v/v extract, ME-Methanol 100 % extract. Different superscripts (a–g) and (A–C) are given for each extract, showing a significant difference between the species and the solvents, respectively ($p < 0.05$).

(Fig. 7B). The results suggest that compounds from *Dictyota* dissolved in highly polar solvents exhibited the highest reducing capacity. The water extract of *Dictyota* (134.21–450.88 μM Trolox equivalent 100 g^{-1}) showed high FRAP activity, similar to the methanolic and water extracts of many seaweeds [90].

4. Conclusion

The comprehensive nutritional profile of *Dictyota* underscores its potential for significant levels of protein, total minerals, crude carbohydrates, and low-fat diets, which make it suitable for addressing various dietary needs and enhancing health. *D. bartayresiana* exhibited the highest protein and lipid levels, whereas *D. divaricata* and *D. flabellata* showed the highest total minerals and carbohydrate content. A significant quantity of macro and micro elements was noticed, and *Dictyota* species collected from the west coast had a rich amount of Ca, Fe, Zn, and Mn; the species collected from the east coast were enriched in Na and K contents. Therefore, calcium, iron, magnesium and manganese obtained from 5.2 g (Dry weight) of *Dictyota* efficiently fulfilled the Recommended Dietary Allowance for Indians. Including *Dictyota* species in the diet can contribute to fulfilling the daily nutritional requirements, particularly in regions with mineral deficiencies. Bioactive compounds such as chlorophylls, total carotenoids, and fucoxanthin added value to *D. flabellata* followed by *D. bartayresiana, D. dichotoma* and *D. maxima* that may help reduce oxidative stress. Methanol extraction successfully yielded significant phenol content in six species, with *D. ciliolata* and *D. bartayresiana* showing the highest amount in water extract. Solvent polarity was vital in the species-specific variations observed in In-vitro antioxidant activities. These findings offer comprehensive insights into the nutritional and antioxidant potentials of *Dictyota* species help fulfil the objectives of Pradhan Mantri Matsya Sampada Yojana (PMMSY) scheme of India, and hold the key to compelling prospects in food, feed, biomedical, pharmaceutical, and neutraceuticals wonders.

CRediT authorship contribution statement

P. Chellamanimegalai: Writing – original draft, Formal analysis. **Geetanjali Deshmukhe:** Supervision. **Amjad K. Balange:** Validation, Investigation. **P. Layana:** Writing – review & editing, Conceptualization.

Data availability

Data will be made available on request.

Funding statement

There is no finding source for conducting this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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