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REVIEW PAPER

Seaweed: a prominent source of protein and other nutrients

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Abstract

It is crucially important to provide a sufficient food supply to ensure food security in the context of an increasing global population, shrinking cropland, and changes in the environment. The availability of adequate nourishment is important for both human and animal health. A strong dietary protein source is animal products, particularly their proteins, however, because of the large carbon footprint associated with their production, efforts to find alternative protein sources have been made. This study sought to provide more information on the development of scientific research into the nutritional properties of seaweed as an alternative source of nutrients. When it comes to mariculture or controlled fisheries, seaweed has a clean, renewable supply that is natural, sustainable, and has a natural origin. Being a good source of protein, carbohydrates, vitamins, polyunsaturated fatty acids, and minerals, seaweed has a high nutritional value, derived from seawater based on environmental and seasonal factors. To increase seaweed production to a commercial level and win over consumers all over the world, efforts must be made to sustainable seaweed cultivation and better management. Furthermore, more study is required to optimize the process of seaweed protein extraction for applications in food and nutraceuticals.

Introduction

Humans generally rely on livestock and seeds of terrestrial plants for sources of high-quality protein. But the increased use of farmland and freshwater contributes to climate change and jeopardizes the viability of the world's food supply chain (Springmann et al., 2018). Food systems were responsible for 35 percent of all manmade greenhouse gas (GHG) production, with animal-based diets having a greater than 50 percent impact (Xu et al., 2021). As a result, one of the most viable methods to achieve global sustainability is to look for alternative sources of protein, and seaweed can be a notable substitute for livestock and terrestrial plants. This is because of the anticipated global food scarcity as well as other economic and environmental concerns.

Seaweeds are Thallophytes because they are autotrophic, simple in structure, and have little to no cellular differentiation. Since they lack a structured vascular system for receiving nutrients, seaweeds are not considered real plants. According to the taxonomy, they may be divided into three groups: Rhodophyta, Ochrophyta (or, Phaeophyta), and Chlorophyta, which correspond to red, brown, and green algae, respectively (Beetul et al., 2016; Ibáñez and Herrero, 2017; Ullah et al., 2023). Red algae, also known as Rhodophyta, are the most primitive group of algae, making up roughly 6000 species, and they may be found in a variety of environments (Lozano and Díaz, 2020). A vast family of marine algae known as brown algae or Ochrophyta (Phaeophyta), has over 1750 species (Lozano and Díaz, 2020). Its name comes from the coloring, which ranges from yellow to dark brown. Green algae or Chlorophyta are less prevalent, with 1836 species in around 285 genera (Wehr, 2015). Its coloration ranges from greenish yellow to dark green.

Seaweed is a significant nutrient source with potential uses in food and medicine (Rameshkumar et al., 2012). According to Rajapakse and Kim (2011), Asian countries like China, Japan, and Korea have consumed a lot of these marine algae during the past few decades; over 66% of the species are regularly utilized as ingredients in their cuisine. Seaweed is now consumed by numerous nations, including those in Europe, the Pacific Ocean, and other regions. Several varieties of seaweed, particularly protein-rich seaweeds, are used as food in many different countries worldwide (Haque et al., 2009). A number of edible seaweeds have high levels of proteins, fats, vitamins, and minerals (Norziah and Ching, 2000). Seaweed's nutritional content varies depending on the species, region, seasonality, temperature, and rainfall (Kaehler and Kennish, 1996). Being a source of sustenance for both humans and animals, seaweed plays a significant role in both nature and human existence. As fresh or dried veggies, salads, or as components in a broad range of prepared dishes, they are nutritiously useful (Robledo and Freile-Pelegrin, 1997). According to various reports (Pereira, 2011; Mohibbullah et al., 2022), there are 145 distinct types of seaweeds utilized for human consumption, of which 79 are red seaweed, 38 are brown seaweeds, and 28 are green seaweeds. Recently, 33 different seaweeds- 20 brown, 10 red, and 3 green, have been identified as the primary edible seaweeds (Pereira, 2016; Mohibbullah et al., 2022). In contrast to other aquatic resources, seaweed can be quite important in a variety of ways. Seaweed should receive a lot of attention in order to partially offset the food shortage and cover the nutritional gap necessary to boost the economies of various nations. They also have been utilized in the food industry as sources of phycocolloids, thickening agents, and gelling agents (Estevam et al., 2016; Scieszka and Klewicka, 2019). Seaweed is also a superb source of chemical compounds, including a wide range of physiologically active secondary metabolites, as well as polysaccharides, minerals, and vitamins (Villarreal-Gómez et al., 2010). These bioactive substances are molecules that may be created from either natural or synthetic sources and are physiologically tested for their potential medicinal effects. There has long been a connection between the activity of these bioactive compounds and health, and it now appears that bioactive food ingredients can change the genetic expression of a variety of cellular processes, potentially affecting health status or providing beneficial antioxidant or enzyme inhibitory activities (MacArtain et al., 2007). There may be antibacterial, antifungal, antioxidant, and antiviral properties in certain seaweeds (Venugoapl, 2009).

This review presents the nutritional composition of different species of seaweed around the world. We have extensively studied the information on seaweed with special reference to its nutritive value. We also consider their production volumes (FAO, 2022). The database contains more than 80 articles including research articles, reviews, case studies, Ph.D. research, annual reports, and much more current research. The findings might be compiled to give the scientific community the most recent knowledge and to encourage the appropriate use of seaweed with respect to their nutritional value.

Global seaweed production

The technique of growing and producing seaweed has greatly expanded, and it is now essential to the fishery sector (Cai et al., 2021). Data from the Food and Agricultural Organization (FAO, 2022) show that between 1950 and 2020, the world's production of seaweed (both from farmed and wild) increased from 0.56 million tons to 36.23 million tons (Figure 1). In the past two decades, the yield of seaweed (from both farmed and natural sources) has about tripled (FAO, 2022).

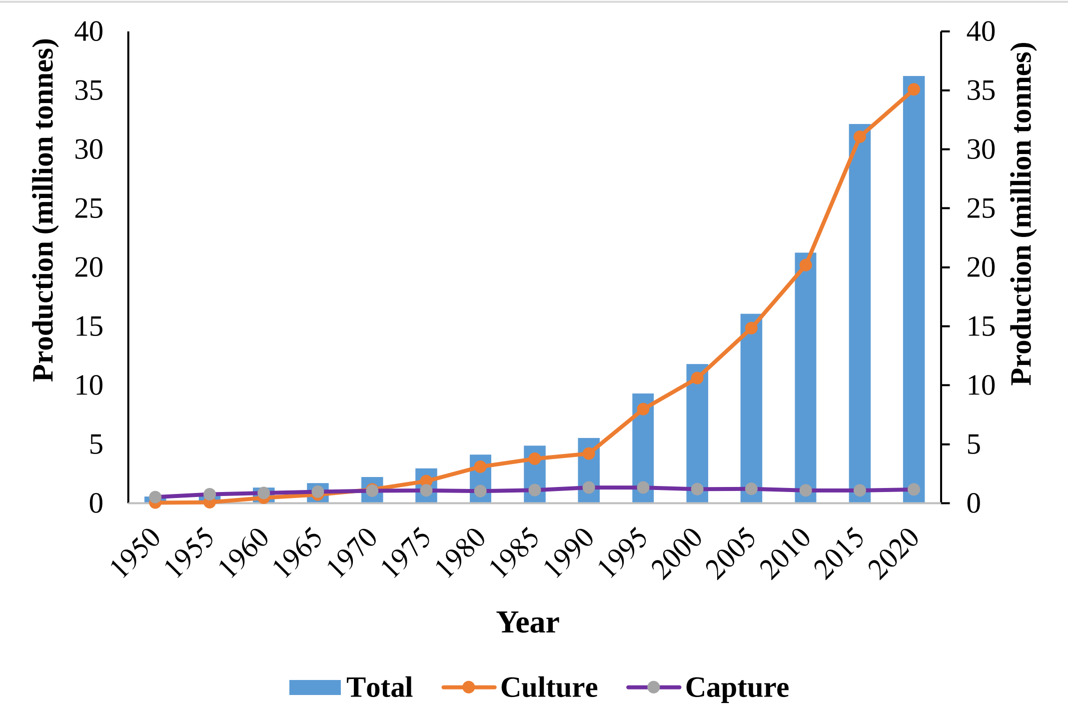

Figure 1. Status of world seaweed production (million tons) from 1950 to 2020 (FAO, 2022)

Around 97% of the world's seaweed production in 2020 came from marine farming. The 5 major continents produce the majority of the seaweed consumed worldwide. Ninety-nine percent of seaweed in Asia is cultured. China, which produces 58.18% of the world's seaweed, is at the top position in terms of production. The second is Indonesia, a significant producer of seaweed that accounts for 26.72% of world production. A large number of seaweed species, including red, brown and green seaweeds, are found in South Korea, which accounts for 4.89% of the world's total seaweed production. The Philippines holds 4.06% of the world market for seaweed culture. Japan produces 1.27% of the world's seaweed. Over 95% of the seaweed consumed in North America comes from natural resources, making up around 1.36% of the world's total seaweed production. Chile accounts for 1.19% of the world's seaweed production, making it the leading producer in America. Although brown seaweed has recently been cultivated, the majority of brown seaweeds (Ochrophyta) and red seaweeds (Rhodophyta) come from natural riverbeds. Algae are mostly collected from natural sources in Canada, the United States, and Peru. Ninety-six percent of the seaweed consumed in Europe comes from natural sources. Cultivation has only been tested in Europe since 2010. Around 0.41% of the seaweed in the world is found in Africa. Oceania makes up around 0.05% of world seaweed production (FAO, 2022).

In 2020, over 93% of the seaweed farmed around the globe came from eight different species. *Laminaria japonica* makes up roughly 35.5% of worldwide seaweed cultivation and is mostly used in salads, sauces, and other condiments. More than 27% of the carrageenan utilized for extraction came from the algae *Kappaphycus* and *Eucheuma* (FAO, 2022). According to FAO (2022), *Gracilaria*, *Undaria*, and *Porphyra* each contributed 14.8%, 8%, and 6.3% of the total seaweed production, respectively (Figure 2).

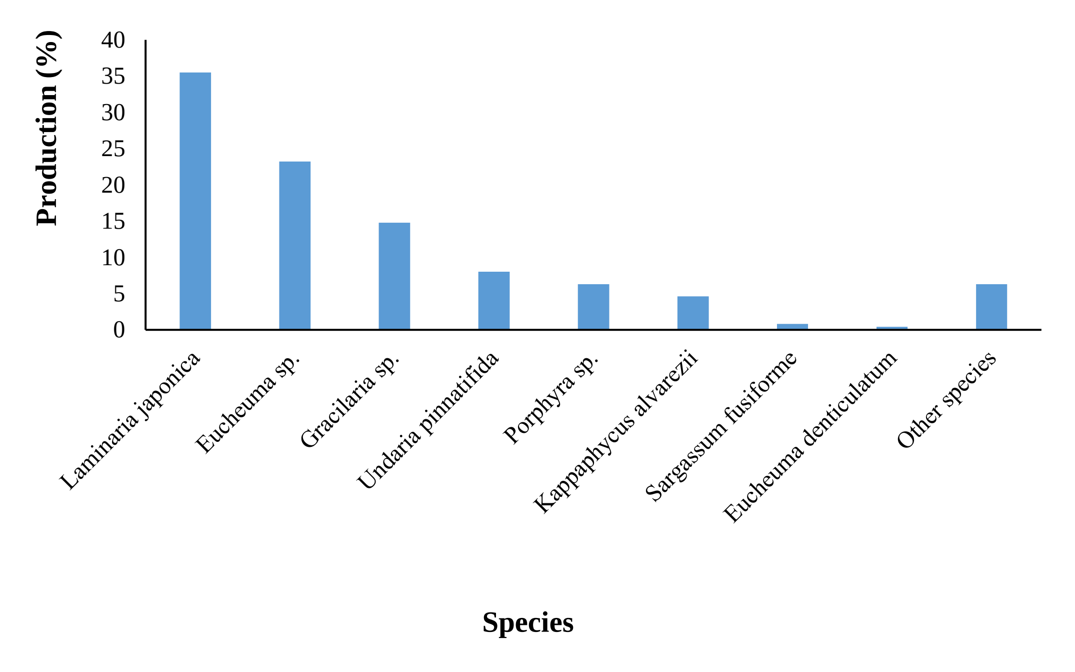

Figure 2. Seaweed aquaculture production (%) per species in the year 2020 (FAO, 2022).

Nutritional components of seaweeds

Red seaweeds

The group of seaweeds existing with the greatest diversity, dominance, and economic value is red seaweeds. They contain phycobilin (phycoerythrin and phycocyanin), a photosynthetic pigment that gives them their color in addition to carotene and xanthophyll (Salamanca et al., 2005). They mostly grow on dark ocean bottoms and may be seen in the intertidal and subtidal zones at depths of up to 40-250 m (Pineiro, 2012). *Porphyra* sp., *Eucheuma* sp., *Gracilaria* sp., and *Kappaphycus* sp. are the most common types of red seaweeds (Cotas et al., 2020).

The protein, lipid, ash, moisture, carbohydrate, and fiber content of different red seaweed species in the world is shown in Table 1. The range of red seaweeds' mean protein content is 4.07 to 36.88%. Since they contain more protein than the green and brown seaweed species, the red seaweed species are of great interest (Cerna, 2011; Rohani-Ghadikolaei et al., 2012). Lipid content ranged from 0.02 to 5.0%. Ash content ranged from 4.1 to 51.16%. Moisture content ranged from 2.4 to 89.78%. Carbohydrate content ranged from 1.8 to 63.12%. Fiber content ranged from 2.02 to 53.2%.

Table 1. Proximate composition of red seaweeds from different regions of the world.

Seaweed	Protein	Lipid	Ash	Moisture	Carbohydrate	Fibre	Location	Reference
Hypnea sp.	23.64	1.46	7.05	15.43	46.71	5.72	St. Martin's Island, Bangladesh	Chowdhury et al., 2022
Gracilaria verrucosa	16.51	0.20	46.72	79.78			Kilinochchi and Kalpitiya, Sri Lanka	Premadasa and Edirisinghe, 2022
Gracilaria corticate	21.66	0.24	44.34	89.78			Kilinochchi and Kalpitiya, Sri Lanka	Premadasa and Edirisinghe, 2022
Ahnfeltia plicata	20.1		23.2		30.2		Swedish west coast	Olsson et al., 2020
Brogniartella byssoides	15.8		41.9		24.0		Swedish west coast	Olsson et al., 2020
Ceramium sp.	15.8		32.8		35.2		Swedish west coast	Olsson et al., 2020
Chondrus crispus	10.3		27.2		52.6		Swedish west coast	Olsson et al., 2020
Delesseria sanguinea	18.3		31.2		25.9		Swedish west coast	Olsson et al., 2020
Dilsea carnosa	15.2		24.0		47.7		Swedish west coast	Olsson et al., 2020
Furcellaria lumbricalis	17.1		32.9		29.7		Swedish west coast	Olsson et al., 2020
Rhodomela confervoides	14.8		32.2		34.0		Swedish west coast	Olsson et al., 2020
Digenea simplex	21.14	2.3			42.4	10.55	Hurghada Red Sea coast, Egypt	Alwaleed, 2019
Acanthophora spicifera	5.07	0.55	28.38	18.84	44.76	2.42	Salinas Bay, Ecuador	D'Armas et al., 2019
Centroceras clavulatum	4.78	0.75	36.69	23.54	32.24	2.02	Salinas Bay, Ecuador	D'Armas et al., 2019
Hypnea spinella	8.02	1.44	33.07	18.61	34.46	4.41	Salinas Bay, Ecuador	D'Armas et al., 2019
Kappaphycus alvarezii	4.86	0.57	27.49	22.77	41.15	3.18	Salinas Bay, Ecuador	D'Armas et al., 2019
Digenea simplex	5.3	0.8	24.7	2.4	35.7	28.4	Red Sea coast, Egypt	El-Manawy et al., 2019
Porphyra sp.	21.14	0.19	5.4	14.30	20.59	38.24	Sri Lanka	Jayakody et al., 2019
Tricleocarpa fragilis	4.07	0.84	42.29	24.05	28.76	12.05	Andaman Sea, India	Banu and Mishra, 2018
Gracilaria corticate	12.18	0.20	51.16		23.53	4.37	Red sea coast, Eritrea	Kasimala et al., 2017
Aghardhiella subulate	8.8	2.0			4.5		Southeast Coast of India	Roy and Anantharaman, 2017
Amphiroa anceps	9.5	1.0			4.8		Southeast Coast of India	Roy and Anantharaman, 2017
Amphiroa fragilissima	8.6	4.8			4.4		Southeast Coast of India	Roy and Anantharaman, 2017
Digenea simplex	8.4	4.8			4.6		Southeast Coast of India	Roy and Anantharaman, 2017
Gelidium acerosa	8.2	0.8			10.0		Southeast Coast of India	Roy and Anantharaman, 2017
Gracilaria edulis	8.6	4.2			10.4		Southeast Coast of India	Roy and Anantharaman, 2017
Gracilaria foliifera	8.6	2.2			1.8		Southeast Coast of India	Roy and Anantharaman, 2017
Gracilaria opuntia	8.5	5.0			7.6		Southeast Coast of India	Roy and Anantharaman, 2017

Hypnea valentiae	9.0	3.0			3.2		Southeast Coast of India	Roy and Anantharaman, 2017
Kappaphycus alvarezii	8.8	3.8			5.0		Southeast Coast of India	Roy and Anantharaman, 2017
Laurencia papillosa	8.6	4.5			9.4		Southeast Coast of India	Roy and Anantharaman, 2017
Gracilaria changii	12.57	0.30	40.30	5.32	41.52	29.44	Malaysia	Chan and Matanjun, 2017
Hypnea musciformis	13.73	0.34	9.76	24.31	46.26	5.6	St. Martin’s Island	Khan et al., 2016
Jania rubens	5.7	0.41	16.27	8.58	63.14	5.9	St. Martin’s Island	Khan et al., 2016
Gracilaria gracilis	20.2	0.60	24.8	7.99	46.6		West Coast of Portugal	Rodrigues et al., 2015
Osmundea pinnatifida	23.8	0.9	30.62	11.77	32.4		West Coast of Portugal	Rodrigues et al., 2015
Grateloupia turuturu	22.5	2.2	20.52	11.68	43.2		West Coast of Portugal	Rodrigues et al., 2015
Laurencia capsica	22.22	0.30	26.82		25.50		Southern Caspian Sea	Neda et al., 2014
Porphyra tenera	36.88	2.25	9.07	3.66			Wando, Korea and Jiangsu, China	Hwang et al., 2013
Porphyra haitanensis	32.16	1.96	8.78	6.74			Wando, Korea and Jiangsu, China	Hwang et al., 2013
Acanthophora spicifera	7.1	2.1	29.0		27.1		Northern Persian Gulf	Mohammadi et al., 2013
Champia parvula	10.0	4.6	38.5		34.0		Northern Persian Gulf	Mohammadi et al., 2013
Hypnea cervicornis	11.1	3.7	33.0		25.2		Northern Persian Gulf	Mohammadi et al., 2013
Gracillaria corticate	10.6	5.0	40.1		43.4		Northern Persian Gulf	Mohammadi et al., 2013
Jania rubens	9.8	1.7	44.5		29.8		Northern Persian Gulf	Mohammadi et al., 2013
Laurencia papillosa	11.7	3.5	34.0		24.6		Northern Persian Gulf	Mohammadi et al., 2013
Hypnea pannosa	16.31	1.56	18.65	12.35	22.89	40.59	St. Martin’s Island, Bangladesh	Siddique et al., 2013
Hypnea musciformis	18.64	1.27	21.57	11.54	20.60	21.57	St. Martin’s Island, Bangladesh	Siddique et al., 2013
Gelidiella acerosa	6.1	2.8	10.3	12.15	10.5	13.45	Gulf of Mannar	Syad et al., 2013
Hypnea valentiae	16.5	2.8	21.8	10.8	31.8		Persian Gulf of Iran	Rohani-Ghadikolaei et al., 2012
Gracilaria corticate	19.3	1.8	23.1	9.2	43.0		Persian Gulf of Iran	Rohani-Ghadikolaei et al., 2012
Gelidiella acerosa	31.9	1.9			16.4		Southeast Coast of India	Manivannan et al., 2009
Gracilaria crassa	15.0	2.0			16.9		Southeast Coast of India	Manivannan et al., 2009
Hypnea musciformis	14.8	1.2					Southeast Coast of India	Manivannan et al., 2009
Gracilaria folifera	6.98	3.23			22.32		Southeast Coast of India	Manivannan et al., 2008
Hypnea valentiae	8.34	1.5			23.60		Southeast Coast of India	Manivannan et al., 2008
Acanthophora spicifera	11.96	1.7			23.54		Southeast Coast of India	Manivannan et al., 2008
Eucheuma cottonii	9.76	1.10	46.19	10.55	26.49	5.91	North Borneo, Malaysia	Matanjun et al., 2009
Gracilaria cervicornis	19.7	0.43	7.72	14.66	63.12	5.65	Northwest of Brazil	Marinho-Soriano et al., 2006

Gracilaria changgi	6.90	3.30	22.70			24.7	West coast of Malaysia	Norziah and Ching, 2000
Hypnea japonica	19.00	1.42	22.10	9.95	4.28	53.2	Northeast of Hong Kong	Wong and Cheung, 2000
Hypnea charoides	18.40	1.48	22.80	10.90	7.02	50.3	Northeast of Hong Kong	Wong and Cheung, 2000
Asparagopsis taxiformis	10.56	0.02	4.1	61.64	23.68		St. Martin’s Island, Bangladesh	Mehedi et al., 1999
Gelidium pristoides	11.80	0.90	14.00		43.10			Foster and Hodgson, 1998
Gracilaria cornea	5.47		29.06		36.29	5.21	Yucatan	Robledo and Freile-Pelegrin, 1997
Eucheuma isiforme	12.10		34.00		25.89	3.21	Yucatan	Robledo and Freile-Pelegrin, 1997

Brown seaweeds

Brown seaweeds or Ochrophyta (Phaeophyta) are multicellular, highly evolved algae that are usually exclusively found in cold coastal waters and very rarely in freshwater. *Laminaria* sp., *Sargassum* sp., *Ascophyllum* sp., and *Undaria* sp. are the principal species of brown seaweed (Li et al., 2021). Fucoxanthin and other xanthophyll pigments, which conceal chlorophyll *a* and *c*, β-carotene, and other xanthophyll pigments, predominate in brown seaweeds, giving them their color. Alginic acid and cellulose make up their cells. Brown seaweeds are often found along coastal cold-water bodies and have stores of polysaccharides and alcohol. Brown seaweeds have an extremely flexible body that enables them to bend or orient in response to wave motion. These are the biggest seaweeds and may grow to a length of 35 meters (Pineiro, 2012).

The nutrient content of different brown seaweed species in the world is shown in Table 2. The average protein content of red seaweeds ranges from 3.78 to 17.80%. Lipid content ranges from 0.15 to 8.0%. Ash content ranges from 4.08 to 76.42%. Moisture content ranges from 8.71 to 80.25%. Carbohydrate content ranges from 1.5 to 90.01%. Fiber content ranges from 0.83 to 51.77%.

Table 2. Proximate composition of brown seaweeds from different regions of the world.

Seaweed	Protein	Lipid	Ash	Moisture	Carbohydrate	Fibre	Location	Reference
Nizamuddinia zanardinii	3.86	0.24	16.34	8.71	65.05	5.23	Southern Oman	Al-Souti et al., 2022
Sargassum sp.	13.36	0.39	19.44	20.29	38.75	7.78	St. Martin’s Island, Bangladesh	Chowdhury et al., 2022
Hydroclathrus clathratus	7.20	0.15	61.98	17.79	10.70	2.19	St. Martin’s Island, Bangladesh	Chowdhury et al., 2022
Padina pavonica	7.64	0.23	54.51	12.09	24.72	0.83	St. Martin’s Island, Bangladesh	Chowdhury et al., 2022
Colpomenia sinuosa	7.15	0.20	57.21	12.74	17.04	5.68	St. Martin’s Island, Bangladesh	Chowdhury et al., 2022
Petalonia fascia	7.24	2.75	18.51	17.80	43.63	10.08	St. Martin’s Island, Bangladesh	Chowdhury et al., 2022
Dictyota ciliolata	7.69	1.68	44.49	29.65	14.74	1.76	St. Martin’s Island, Bangladesh	Chowdhury et al., 2022
Turbinaria ornata	16.79	0.37	26.11	76.33			Kilinochchi and Kalpitiya, Sri Lanka	Premadasa and Edirisinghe, 2022
Sargassum polycystum	17.80	1.94	29.45	80.25			Kilinochchi and Kalpitiya, Sri Lanka	Premadasa and Edirisinghe, 2022
Sargassum wightii	6.43	3.09	19.87	21.33	45.66	24.93	Indian Coast	Kumar et al., 2021
Cystoseira compressa	8.91	1.83	32.04		39.62		West Algerian coast	Oucif et al., 2020
Cystoseira stricta	14.14	2.71	24.61		35.45		West Algerian coast	Oucif et al., 2020
Cystoseira elongata	5.85	0.64	76.42		13.40		West Algerian coast	Oucif et al., 2020
Ascophyllum nodosum	5.9		20.2		31.7		Swedish west coast	Olsson et al., 2020
Chorda filum	6.3		39.0		29.2		Swedish west coast	Olsson et al., 2020
Desmarestia aculeata	11.5		25.4		30.1		Swedish west coast	Olsson et al., 2020
Fucus serratus	7.1		20.3		28.7		Swedish west coast	Olsson et al., 2020
Fucus vesiculosus	7.1		24.4		26.6		Swedish west coast	Olsson et al., 2020
Halidrys siliquosa	7.9		17.6		23.7		Swedish west coast	Olsson et al., 2020
Laminaria digitata	6.6		16.8		51.9		Swedish west coast	Olsson et al., 2020
Saccharina latissimi	6.9		11.8		55.7		Swedish west coast	Olsson et al., 2020
Sphacelaria cirrosa	12.0		28.8		26.7		Swedish west coast	Olsson et al., 2020
Sargassum polycystum	5.85	0.45			90.01	33.95	Hurghada Red Sea coast, Egypt	Alwaleed, 2019
Cystoseria myrica	10.0	2.2			48.0	38.24	Hurghada Red Sea coast, Egypt	Alwaleed, 2019
Padina pavonica	5.53	0.83	24.85	20.47	43.39	4.94	Salinas Bay, Ecuador	D’Armas et al., 2019
Spatoglossum schroederi	5.21	3.07	34.58	12.84	40.04	4.28	Salinas Bay, Ecuador	D’Armas et al., 2019
Hormophysa cuneiformis	4.8	0.92	27.5	10.8	23.4	27.6	Red Sea coast, Egypt	El-Manawy et al., 2019
Padina boergesenii	5.9	3.8	35.8	9	24.7	36.2	Red Sea coast, Egypt	El-Manawy et al., 2019
Polycladia myrica	7.1	1.3	27.8	9.7	30.4	34.7	Red Sea coast, Egypt	El-Manawy et al., 2019

Sargassum aquifolium	5.4	3.1	30.8	9.1	29.3	33.1	Red Sea coast, Egypt	El-Manawy et al., 2019
Chnoospora minima	13.70	0.21	17.20	13.24	3.87	51.77	Sri Lanka	Jayakody et al., 2019
Sargassum linearifolium	6.93	1.42	26.86		27.82	19.97	Red sea coast, Eritrea	Kasimala et al., 2017
Ascophyllum nodosum	8.70	3.62	30.89	11.08			Atlantic Ocean	Lorenzo et al., 2017
Fucus vesiculosus	12.99	3.75	20.71	11.23			Atlantic Ocean	Lorenzo et al., 2017
Bifurcaria bifurcata	8.92	6.54	31.68	7.95			Atlantic Ocean	Lorenzo et al., 2017
Cystoseira indica	7.5	3.1			4.0		Southeast Coast of India	Roy and Anantharaman, 2017
Fucus vesiculosus	8.5	5.4			4.2		Southeast Coast of India	Roy and Anantharaman, 2017
Hydroclathrus clathratus	8.2	2.1			2.5		Southeast Coast of India	Roy and Anantharaman, 2017
Padina boergesenii	8.6	8.0			1.5		Southeast Coast of India	Roy and Anantharaman, 2017
Padina tetrastromatica	8.9	7.4			3.4		Southeast Coast of India	Roy and Anantharaman, 2017
Sargassum cinereum	8.8	3.0			3.9		Southeast Coast of India	Roy and Anantharaman, 2017
Sargassum cinctum	8.6	3.0			3.5		Southeast Coast of India	Roy and Anantharaman, 2017
Sargassum cristaefolium	8.0	2.3			4.2		Southeast Coast of India	Roy and Anantharaman, 2017
Turbinaria conoides	8.8	3.2			3.2		Southeast Coast of India	Roy and Anantharaman, 2017
Turbinaria decurrens	8.4	6.8			1.5		Southeast Coast of India	Roy and Anantharaman, 2017
Turbinaria ornata	8.3	6.6			3.2		Southeast Coast of India	Roy and Anantharaman, 2017
Padina tetrastromatica	12.29	0.98	27.95	15.68	36.30	6.8	St. Martin's Island, Bangladesh	Khan et al., 2016
Sargassum oligocystum	8.19	0.83	12.94	21.09	51.75	5.2	St. Martin's Island, Bangladesh	Khan et al., 2016
Sargassum muticum	16.9	1.45	22.94	9.64	49.3		West Coast of Portugal	Rodrigues et al., 2015
Saccorhiza polyschides	14.44	1.1	28.15	10.88	45.6		West Coast of Portugal	Rodrigues et al., 2015
Colpomenia sinuosa	11.0	3.5	25.5		22.3		Northern Persian Gulf	Mohammadi et al., 2013
Sargassum wightii	14.82	2.72	25	22.4	9.5	17	Gulf of Mannar	Syad et al., 2013
Sargassum polycystum	7.78	0.71	21.87		34.93	34.71	Malaysia	Ahmad et al., 2012
Padina gymnospora	5.93	0.51	45.04		26.86	21.66	Malaysia	Ahmad et al., 2012
Sargassum ilicifolium	8.9	2.0	29.9	10.4	32.9		Persian Gulf of Iran	Rohani-Ghadikolaei et al., 2012
Colpomenia sinuosa	9.2	1.5	28.1	11.5	32.1		Persian Gulf of Iran	Rohani-Ghadikolaei et al., 2012
Dictyota dichotoma	9.9	1.5			16.8		Southeast Coast of India	Manivannan et al., 2009
Padina pavonica	13.8	1.4			15.0		Southeast Coast of India	Manivannan et al., 2009
Turbinaria ornate	14.0	1.7			17.2		Southeast Coast of India	Manivannan et al., 2009
Padina gymnospora	17.08	1.4			21.88		Southeast Coast of India	Manivannan et al., 2008

Sargassum tenerimum	12.42	1.46			23.55		Southeast Coast of India	Manivannan et al., 2008
Tubunaria conoides	12.01	2.4			23.9		Southeast Coast of India	Manivannan et al., 2008
Sargassum wightii	11.7	2.33			23.50		Southeast Coast of India	Manivannan et al., 2008
Colpomenia sinuosa	10.7	2.33			22.46		Southeast Coast of India	Manivannan et al., 2008
Sargassum vulgare	13.6	0.4	19.4	14.33	61.6	7.7	Northwest of Brazil	Marinho-Soriano et al., 2006
Hydroclathrus clathratus	4.24	1.67	5.22	70.40	18.47		St. Martin’s Island, Bangladesh	Mehedi et al., 1999
Colpomenia sinuosa	3.78	1.10	4.08	68.44	22.61		St. Martin’s Island, Bangladesh	Mehedi et al., 1999
Sargassum filipendula	8.72		44.29		3.73	6.57	Yucatan	Robledo and Freile-Pelegrin, 1997
Padina gymnospora	9.86		36.61		1.86	9.07	Yucatan	Robledo and Freile-Pelegrin, 1997

Green seaweeds

Chlorophyll *a* and chlorophyll *b*, found in chloroplasts, are the primary components that give green seaweed their distinctive color. Similar amounts of these pigments are present in higher plants. In littoral zones, green seaweed is the most prevalent. The most prevalent green seaweed seen in various settings are sea lettuce (*Ulva* sp.) (Pineiro, 2012). Often used as food sources include green seaweeds, i.e., *Ulva* sp., *Monostroma* sp., *Caulerpa* sp., and *Codium* sp. (Kılınç et al., 2013).

Table 3 presents the composition of several green seaweed species from across the world in terms of protein, lipids, ash, moisture, carbohydrates, and fibers. The range of green seaweeds' mean protein content is 3.25 to 29.5%. Because of changes in geography and species, various species may have variable protein contents (Dhargalkar et al., 1980; Haroon et al., 2000). Seaweed has very few lipids (Burtin, 2003). Green seaweed has a lipid content that varies from 0.08 to 8.2% of dry weight. Because their anionic carboxyl, sulfate, and phosphate groups are excellent binding sites for holding metals, seaweed often has a high ash content (Davis et al., 2003). This characteristic consistently leads to the accumulation of various mineral elements in substantial quantities (Matanjun et al., 2009).

Green seaweed has an ash concentration that ranges from 9.9% to 55.11%, and a moisture content that ranges from 6.1% to 24.6% of its dry weight. The primary element in the proximate makeup of seaweeds is carbohydrates (Rohani-Ghadikolaei et al., 2012). The percentage of carbohydrates varies from 2.8% to 67.4%. Green seaweed has between 0.23% and 54.9% of its weight in fibers. Seaweed species differ in terms of developmental stages, seasonal environmental conditions, and photosynthetic capacity, and this may explain the large variation in their crude fiber content (Wong and Cheung, 2000; Siddique et al., 2013).

Table 3. Proximate composition of green seaweeds from different regions of the world.

Seaweed	Protein	Lipid	Ash	Moisture	Carbohydrate	Fibre	Location	Reference
Ulva fasciata	13.92	0.08	24.22	8.22	51.31	5.45	Southern Oman	Al-Souti et al., 2022
Ulva sp.	18.35	0.59	32.40	15.79	32.65	0.23	St. Martin's Island, Bangladesh	Chowdhury et al., 2022
Ulva rigida	27.11	2.71	19.63	22.61	31.87	18.65	Indian Coast	Kumar et al., 2021
Cladophora rupestris	18.4		20.7		39.9		Swedish west coast	Olsson et al., 2020
Cladophora sp.	13.9		36.5		34.8		Swedish west coast	Olsson et al., 2020
Ulva intestinalis	9.0		31.9		36.7		Swedish west coast	Olsson et al., 2020
Ulva lactuca	9.3		32.2		34.7		Swedish west coast	Olsson et al., 2020
Ulva compressa	13.61	1.00	26.36		46.11		West Algerian coast	Oucif et al., 2020
Ulva lactuca	12.54	0.98	27.13		42.81		West Algerian coast	Oucif et al., 2020
Caulerpa racemosa	16.5	4.0			49.0	5.93	Hurghada Red Sea coast, Egypt	Alwaleed, 2019
Ulva lactuca	5.54	0.33	26.99	20.67	45.52	0.96	Salinas Bay, Ecuador	D'Armas et al., 2019
Caulerpa racemosa	4.8	5.2	31.5	6.1	35.5	31.9	Red Sea coast, Egypt	El-Manawy et al., 2019
Ulva fasciata	11.84	0.28	18.05	18.11	7.68	44.04	Sri Lanka	Jayakody et al., 2019
Ulva clathrata	13.64	0.80	39.42		28.97	17.17	Red sea coast, Eritrea	Kasimala et al., 2017
Caulerpa racemosa	8.8	8.0			3.0		Southeast Coast of India	Roy and Anantharaman, 2017
Caulerpa racemosa var. *macrophysa*	8.8	0.4			4.4		Southeast Coast of India	Roy and Anantharaman, 2017
Caulerpa scalpelliformis	8.6	3.6			6.4		Southeast Coast of India	Roy and Anantharaman, 2017
Chaetomorpha antennina	9.0	8.0			4.6		Southeast Coast of India	Roy and Anantharaman, 2017
Chlorodesmis hildebrandtii	8.7	2.5			3.2		Southeast Coast of India	Roy and Anantharaman, 2017
Cladophora vagabunda	9.0	2.0			4.2		Southeast Coast of India	Roy and Anantharaman, 2017
Halimeda gracilis	9.0	4.2			3.0		Southeast Coast of India	Roy and Anantharaman, 2017
Ulva fasciata	8.8	3.0			3.0		Southeast Coast of India	Roy and Anantharaman, 2017
Ulva lactuca	8.6	3.0			2.8		Southeast Coast of India	Roy and Anantharaman, 2017
Valoniopsis pachynema	8.9	8.2			3.2		Southeast Coast of India	Roy and Anantharaman, 2017
Caulerpa racemosa	22.25	2.65	9.9	16.36	44.04	4.8	St. Martin's Island, Bangladesh	Khan et al., 2016
Ulva intestinalis	19.5	0.3	15.2	24.6	35.5	4.9	St. Martin's Island, Bangladesh	Khan et al., 2016
Codium tomentosum	18.8	3.6	35.9	9.0	32.8		West Coast of Portugal	Rodrigues et al., 2015
Cladophora glomerata	20.82	0.20	17.87		24.00		Southern Caspian Sea	Neda et al., 2014

Ulva intestinalis	28.08	1.62	25.08		21.70		Southern Caspian Sea	Neda et al., 2014
Caulerpa sertulariodes	11.9	2.7	42.5		23.5		Northern Persian Gulf	Mohammadi et al., 2013
Caulerpa lentillifera	13.24	0.17	14.10		53.08	19.40	Malaysia	Ahmad et al., 2012
Caulerpa racemosa	10.52	0.15	10.64		67.40	11.29	Malaysia	Ahmad et al., 2012
Ulva lactuca	17.1	3.6	12.4	6.8	59.1		Persian Gulf of Iran	Rohani-Ghadikolaei et al., 2012
Ulva intestinalis	10.5	2.9	22.4	10.6	35.5		Persian Gulf of Iran	Rohani-Ghadikolaei et al., 2012
Ulva lactuca	8.46	7.87	19.59	14.95		54.90	Tunisia	Yaich et al., 2011
Ulva compressa	13.1	0.85			16.9		Southeast Coast of India	Manivannan et al., 2009
Ulva reticulata	14.0	1.5			15.1		Southeast Coast of India	Manivannan et al., 2009
Cladophora glomerata	20.8	1.2			14.8		Southeast Coast of India	Manivannan et al., 2009
Halimeda macroloba	29.5	0.3			17.1		Southeast Coast of India	Manivannan et al., 2009
Halimeda tuna	23.0	3.5			17.0		Southeast Coast of India	Manivannan et al., 2009
Ulva intestinalis	16.38	1.33			23.84		Southeast Coast of India	Manivannan et al., 2008
Ulva lactuca	3.25	1.6			23.6		Southeast Coast of India	Manivannan et al., 2008
Codium tomentosum	6.13	2.53			20.47		Southeast Coast of India	Manivannan et al., 2008
Ulva clathrata	11.1	4.6			23.55		Southeast Coast of India	Manivannan et al., 2008
Caulerpa racemosa	3.98		55.11		3.60	1.36	Yucatan	Robledo and Freile-Pelegrin, 1997

Other nutritional components of seaweeds

Seaweed, which is renowned for its high amount of minerals (between 8 and 40% of the dry weight), obtains a large amount of minerals from the marine environment. These include micronutrients like iron, iodine, zinc, copper, molybdenum, selenium, fluoride, manganese, boron, nickel, cobalt, etc. as well as important minerals like sodium, calcium, magnesium, potassium, phosphorus, chloride, and sulfate (Lorenzo et al., 2017; Peñalver et al., 2020). The method of processing and mineralization methods used (Rupérez et al., 2002) as well as the taxonomic group, regional, seasonal, and physiological variables may all affect the mineral composition (Mabeau and Fleurence, 1993). Consuming seaweed enables individuals to meet their daily dietary iodine requirements, as seaweed serves as a substantial source of this essential element (Rajapakse and Kim, 2011). Seaweed can be used as a dietary supplement to assist in meeting the daily requirements for several macro minerals and trace elements due to their high mineral content.

According to Matanjun et al. (2009), seaweed contains almost all amino acids. A large number of seaweed species are regarded as excellent sources of protein since they contain a lot of essential amino acids (EAAs). Several seaweed species with high valine, phenylalanine, and threonine content have comparable EAA patterns in their proteins. Of all EAAs, methionine and cysteine levels in seaweed are due to their sulfur content (Artemisia et al., 2019). Seaweed may be a rich functional component since sulfur-containing amino acids are essential for human protein synthesis and development. The total of these amino acids was much greater than many terrestrial plants. seaweedmino acids (such as glutamic and aspartic acids) may make up to 30% of the non-EAAs' total amino acid content, greatly enhancing the distinct umami flavor of seaweed (Harrysson et al., 2018).

Due to their abundance in essential fatty acids, seaweed may be more effective as a nutritional supplement or as a component of a healthy diet (Admassu et al., 2015). Several seaweed species' fatty acids exhibit anti-inflammatory and antibacterial properties and their fatty acid content changes according to the season (Belattmania et al., 2016).

Vitamins are crucial nutrients for carrying out certain necessary bodily tasks as well as for ensuring wellness (Bellows et al., 2012). All vitamins, both essential and non-essential, are abundant in seaweeds (Ganesan et al., 2019). Certain seaweeds include vitamins with several health benefits and antioxidant activity, which helps to lower a number of health issues like high blood pressure, cardiovascular disease, and cancer risk (Gupta et al., 2020). Diverse seaweeds have been shown to include the water-soluble vitamins B1, B2, B12, and vitamin C, as well as the fat-soluble vitamins, such as vitamin E and β-carotene which is the precursor of vitamin A (Škrovánková, 2011).

Natural pigments are fat-soluble polyenes that have a variety of biological roles in addition to serving as colorants (Li and Kim, 2011). Seaweeds, plants, mammals, and invertebrates all have pigments in varying amounts. A possible source of distinctive natural pigments is seaweed (Pangestuti and Kim, 2015). The three kinds of pigments found in seaweeds are carotenoids, phycobiliproteins, and chlorophylls (Pereira et al., 2014). Since chlorophyll cannot be absorbed by the human body, it is converted into the easily absorbed compounds pyropheophytin, pheophorbide, and pheophytin in processed vegetable meals. Chlorophylls have an antimutagenic action and may be essential in preventing cancer (Ferruzzi and Blakeslee, 2007). Red seaweed contains large amounts of water-soluble pigments called phycobiliproteins

(Mihova et al., 1996). Phycobilins have neuroprotective, antiviral, anti-inflammatory, and antioxidant effects (Holdt and Kraan, 2011). The xanthophylls (zeaxanthin, violaxanthin, lutein, fucoxanthin, neoxanthin, antheraxanthin, and astaxanthin) and carotenes are carotenoids found in seaweeds (Manivasagan et al., 2018). Pigment-rich seaweed might be utilized as nutritional supplements.

5. Conclusion

A growing alternative source of nutrients is seaweed. Seaweed has the potential as a source of dietary supplements for both human and animal nutrition as well as a sustainable functional food. They could potentially provide a solution to the global human nutritional crisis. If ingested consistently, the nutritional value of seaweed, which has a high concentration of protein, lipids, vitamins, and fatty acids, could further contribute to the enhancement of human life and the growth of a balanced diet. Additionally, seaweed would be a more sustainable product given the rising need for plant-based nutrients, and industrial development is anticipated to be financially feasible. In this context, more research and development are needed to scale up seaweed cultivation and processing operations while taking into account factors such as acceptance by consumers, safety, and compliance with food regulations such as innovative foods or protein sources.

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The author declares that this study complies with research and publication ethics.

Informed consent

Not available.

Conflicts of interest

There is no conflict of interests for publishing of this study.

Data availability statement

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Author contribution

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