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Seaweeds, an aquatic plant-based protein for sustainable nutrition - A review

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A B S T R A C T

The eminent protein sources among the vegetarian population include cereals and pulses that do not satisfy the Recommended Dietary Allowance (RDA) level. The anti-nutrients such as protease inhibitors are responsible for the diminished bioavailability of plant protein. Consumption of a protein deficit diet severely impacts muscle health; hence, it becomes necessary to design an alternative source of complete protein. One such non-meat source with all essential amino acids in required quantity is seaweeds, an aquatic plant. The unique flavour and umami taste possessed by seaweeds notably enhance consumer acceptability. The principal focus of this review was on novel food products, digestibility, quality of protein, and consumer satisfactoriness of consuming seaweeds. The yield of seaweed obtained is based on the aquaculture system's type, location, season, and other environmental conditions, which is a significant challenge faced during extraction. This hurdle may prevail via unconventional extraction procedures summarized in this review. Subsequently, the consumers are becoming health conscious, seaweed-based food products are predicted to have excellent market potential. It is concluded that seaweeds can potentially contribute to future global security in functional foods and nutraceuticals.

1. Introduction

The consumption of more nutritious foods, especially the amount of protein consumed in developed countries, has increased rapidly. Approximately 1 billion people cannot afford healthy food (Salgado et al., 2020; Connor et al., 2020). The surge in the global demand for protein has been predicted to be doubled by 2050 (Pam et al., 2020). Domesticating animals and birds to suit present needs may not be an option for meeting future needs because of their significant environmental effect, including threats to biodiversity, greenhouse gas output, fragmentation of natural habitats, and damage to terrestrial ecosystems (Bleakley and Hayes, 2017). On the other hand, prominent plant-based protein sources such as cereals and pulses, widespread among the vegetarian and vegan population, do not meet the Recommended Dietary Allowance (RDA) level (FAO, 1994). The lag in nutritional potential may be due to allergens and anti-nutritional compounds. Anti-nutrients interfere with the absorption of nutrients and may be eliminated by processing the harvested grains. For example, lectins and protease inhibitors are anti-nutrients that have evolved within the seed as a protective mechanism. However, these compounds aid in promoting health and preventing certain diseases significantly lower the digestibility of proteins (Alonso-Miravalles et al., 2019; Roy et al., 2010; Anjali, 2020). Insects are another attractive substitute to conventional proteins that meet the essential amino acid requirements and improve digestibility than plant protein. The total protein level varies based on the life stage of insects and is approximately found to exist between 50 to 80 %. Due to relatively low consumer acceptance, incorporating insect protein into food products is still a significant challenge (Gravel and Doyen, 2019; De Castro et al., 2018). Given fulfilling the consumer demands, the growing food industry targets to design an equivalent source of complete protein compared to the existing alternatives. One such non-meat source of complete protein is seaweeds, an aquatic plant. Aquaculture is a rapidly growing sector specifically as a significant source of food, and the overall world vast aquaculture production has elevated from 31.1 in 2004 to 44.1% in 2014 (Raguraman et al., 2020). The annual global output of seaweeds specifically for human consumption is 2,000,000 tons of dry matter.

The Food and Agriculture Organization reports revealed that worldwide seaweed production has risen from 44 in 1996 to 51.3 % in 2018. Countries such as the United Kingdom, Spain, Norway, France, Philippines, Vietnam, China and Japan account for about 90% of the overall seaweed production. Other countries, including Ireland, Canada, the United States, and New Zealand, are also involved in producing seaweeds (Fleurence, 2016; Chopin and Tacon, 2020). Seaweeds have become an integral part of the coastal ecosystem, supporting aquatic life. In several Asian countries, seaweeds were eaten as food; however, in India, seaweeds are exclusively used to produce hydrocolloids

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(Ganesan et al., 2019a). Out of 10,000 seaweed species reported to exist, only a few seaweed species are aqua-cultured for human consumption (Mac Monagail et al., 2017). China, Japan, and the Republic of Korea predominantly consume seaweed. Recently, North America, South America, and Europe have adopted seaweeds in their cuisine (Černá, 2011).

A study on the amino acid composition of various seaweed species revealed that aspartic and glutamic acids were present in abundance, whereas methionine was scarcely present (Lafarga et al., 2020). Apart from high-quality protein, seaweeds represent an excellent collection of bioactive compounds such as essential fatty acids, dietary fibres, carotenoids, phenolic compounds, water-soluble and liposoluble vitamins (Nunes et al., 2017). The bioactive compounds possess antioxidant, antibacterial, anticancer, antidiabetic, antitumor, antiviral, anti-inflammatory, and anticoagulant properties that potentially contribute to functional food products development (Ganesan et al., 2019b). Seaweeds are employed as active prebiotic ingredients to improve the fermentability of gut microorganisms by limiting the proliferation of pathogenic organisms in the human gut (Vidhya Hindu et al., 2018). However, in vivo studies, metabolism, bioavailability, and clinical trials are necessary before direct human consumption (Wijesekara and Karunarathna, 2017). The mineral profile of seaweeds reports the presence of high calcium, magnesium, phosphorus, potassium, sodium, and iron contents (Serge and Joel, 1993). The quality and yield of protein extracted from seaweeds are based on the aquaculture system's location, season, and other environmental conditions. This hurdle can prevail via unconventional extraction procedures such as enzyme-assisted extraction, microwave, ultrasound, pulsed electric fields, accelerated solvent extraction, and membrane filtration (Pliego-Cortés et al., 2019). Consumer safety is another primary concern of consuming seaweeds. Several chemical hazards like contamination of toxic metals and microbiological hazards, including *Salmonella spp., Bacillus cereus,* were identified. Public and private Food Safety Organizations mandatorily adhere to the Hazard Analysis and Critical Control Point (HACCP) principles (Banach et al., 2020). Seaweeds' product diversification is essential to reach out to consumers belonging to different demographics and cultures.

Innovative snack products and ready-to-eat meals such as flavoured tidbits, noodles, health drinks, cookies, crackers, sweets, salad and condiments are manufactured in the European Union, USA, and South Asian countries (FAO, 2018). Seaweeds are known to possess the fifth basic taste, "umami". The presence of organic acids, amino acid salts and short peptides is a prominent feature of the umami taste of seaweeds. Globally, there is a considerable elevation in the consumption of seaweed-based food products because of the unique flavours (Milinovic et al., 2021). Drying is considered the best method of preserving seaweeds as it maintains the organoleptic quality and reduces the weight of the product, which in turn reduces the shipping cost. When soaked in water, the dried seaweeds tend to regain their original shape with minor loss of nutrients. Post-drying, the seaweed undergoes other unit operations such as size reduction, blending, and packaging based on the requirement (Ahmed et al., 2017). Seaweeds can be labelled as "alternative protein" as they can fulfil the drawbacks of existing protein and maintain a sustainable, nutritious diet. Including seaweeds as an everyday food source in functional foods and nutraceuticals may potentially contribute to future global food security.

This review outlines the classification of seaweeds followed by conventional and novel techniques used in the extraction of protein and the challenges faced. Furthermore, the determination of protein quality by digestibility of protein and amino acid composition were also discussed. The primary focus of this review is to provide a clear view and also to cover the gap in-between the extraction and the application part of the seaweed protein towards human consumption. Our purpose is to assess the role of seaweed protein in different food sectors such as fermented, bakery, diary, meat and meat based products in the context of providing knowledge over the efficacy of seaweed based food products. The risk assessments and consumer acceptability over the incorporation of seaweeds in food products were also discoursed.

2. Classification of seaweeds

The edible aquatic macroalgae are classified into three main groups based on the composition of photosynthetic pigments present, red seaweed (Rhodophyta), brown seaweed (Ochrophyta, Phaeophyceae), and green seaweed (Chlorophyta) (Ganesan et al., 2019b). Brown seaweeds are identified as the second-largest group of seaweeds with more than 2000 species. The four major brown seaweeds found in coastal areas of china are *Sargassum fusiforme* (formerly *Hizikia fusiformis), Undaria pinnatifida, Sargassum pallidum,* and *Ecklonia cava subsp. kurome* (Xie et al., 2021). The brown and the red colour of Phaeophyceae and Rhodophyceae were due to the colour pigments such as fucoxanthin, and phycoerythrin, respectively. Pigments such as phycoerythrin and phycocyanin show dominance over other pigments, for instance, xanthophylls, chlorophyll and carotene. The presence of chlorophyll and related compounds are responsible for the green colour of Chlorophyta, similar to that of higher plants (Khalid et al., 2018).

Brown seaweeds have a protein content of 5 to 15% and include all of the necessary amino acids in the amounts suggested by the FAO (Fauziee et al., 2020). The levels of the acidic amino acids, including aspartic and glutamic acid, were higher than red and green macroalgae. Brown seaweeds exhibit excellent solubility, foaming, and emulsifying properties, suggesting that they could be used to formulate a wide variety of food products such as sausages, bread, cakes, soups, and salad dressing (Garcia-Vaquero et al., 2016). A broad spectrum of anti-inflammatory and anti-allergic activities of brown seaweeds makes it suitable for designing pharmaceuticals (Barbosa et al., 2019). Red seaweeds contain essential amino acids in levels higher than the FAO/WHO requirement. It is also reported to lack methionine, cystine, and lysine (Wong and Cheung, 2001). The protein content of red seaweeds is determined to be around 10 to 40%, higher than green and brown ones (Barral-MartÃnez et al., 2020). Lectin and phycobiliprotein are the two most functionally active proteins in the seaweed. Lectins are glycoproteins that bind to carbohydrates and control biological functions such as intercellular communication and red blood cell agglutination. Phycobiliproteins are chromo-proteins present in a few species of red seaweeds responsible for anti-inflammatory, hepatoprotective, and antioxidant activities (Pina et al., 2014; Pooja, 2020). Due to a specific structure, red seaweeds possess water-soluble algal pigments. These pigments are isolated and are widely used as fluorescent probes and food colourants based on their purity (Dumay et al., 2014). The gelling properties of the polysaccharides such as agar, carrageenan, and alginates present in red seaweeds can be isolated and applied in food, biomedical, pharmaceutical, and biotechnological industries (Thiruchelvi et al., 2020). Green seaweeds are less abundant than red seaweeds (Rocio et al., 2020). The protein content of green seaweeds is estimated to be 30% higher than brown seaweeds, and the quality of mineral profile is low. The colour varies from greenish-yellow to dark green (Cardoso et al., 2015; Makkar et al., 2016). Seaweeds exhibit cation exchanging properties due to functional groups such as carboxylic and sulfonic groups on the cell wall matrix. There are ongoing studies on metal biosorption capacity, which may be effectively employed to treat wastewater (Arumugam et al., 2018). Green seaweeds produce complex and acidic polysaccharides that act as prebiotic functional ingredients in the food and medical industries (Laurens et al., 2020). Conversely, the excessive growth of green seaweeds leads to the deterioration of the environment and are commonly termed as "green tides" (Fletcher, 1996).

Consuming seaweeds as a whole plant may decrease protein accessibility and digestibility due to soluble fibres and polyphenols. Protein must be extracted from the non-protein components (Abdollahi et al., 2019). Seasonal trends are observed in both the chemical and nutritional composition of various seaweeds. The brown seaweed *Saccharina longicruris* is reported to have a significant rise in the quantity of pro-

Table 1
Significant growth season for a variety of seaweed species.

Classification of seaweed	Species	Significant season for growth	Reference
Chlorophyceae	*Ulva intestinalis*	Summer	(Cecilia et al. 2010)
	Ulvaria obscura	Summer	(Makarov and (Makarov and Makarov 1999))
	Ulva lactuca(as Ulva fasciata)	Late summer and early autumn	(Aguilar et al., 2005)
	Undaria pinnatifida	Spring and summer	(Food and Agriculture Organization (FAO) 2021)
Phaeophyceae	*Alaria esculenta*	Summer	(Makarov and Makarov 1999)
	Turbinaria ornata	Winter	(Stiger and Payri 1999)
	Dictyota dichotoma	Winter	(Tronholm et al. 2008)
	Saccharina latissimi (as *Laminaria saccharina)*	Summer	(Makarov and Makarov 1999)
Rhodophyta	Callophyllis microdonta	Summer	(Yoneshigue-Valentin 1992)
	Gracilaria corticata	Summer	(Joanna and Christophe 1995)
	Centroceros clavulatum	Summertime-monsoon	(Wynne 2003)
	Acanthophora nayadiformis (as *Acanthophora delilei)*	Winter	(Cecere and Perrone, 2002)

tein, lipid, and ash during the summer season while each of the components decreases by the end of summer (Rioux et al., 2009; Boulom et al., 2014). The investigation of the biochemical composition of red seaweeds, *Catenella caespitosa* (formerly *Catenella repens*) reveals that the protein content is highest during the monsoon season while the carbohydrate content is high during pre-monsoon season (Banerjee et al., 2009). The total protein content of green seaweed species, including *Ulva lactuca, Ulva flexuosa* (formerly *Enteromorpha flexuoca), Cladophora prolifera, Chaetomorpha linum* was higher in July and October and is identified to reduce in other months (Ansari and Ghanem, 2017). The significant aquaculture season of seaweeds belonging to various genera is discussed in Table 1.

3. The conventional technique for protein extraction

The conventional extraction method requires a large amount of solvent, is time-consuming, and has limited efficiency. Fig. 1 depicts the process of the traditional way of extraction.

4. Novel methods of protein extraction

Protein from seaweed may be extracted via various non-conventional extraction techniques apart from the conventional procedures. The ideal extraction method should be environment friendly, time-saving, and less expensive. Both the quality and quantity of the protein extracted should also be retained. However, every method has its advantages and disadvantages; therefore, the process parameters should be optimized to overcome the challenges faced during extraction. The novel protein extraction techniques, principles, advantages, and disadvantages are discussed.

4.1. Enzyme-assisted extraction

The presence of polysaccharides such as alginates, carrageenans in the cell wall of seaweed acts as physical barriers to limit the extraction efficiency of proteins. The degradation of cell wall polymers by enzymatic method had become an attractive alternative over mechanical and chemical processes (Wijesinghe and Jeon, 2012). Traditionally, acids, bases, organic solvent extracts, or hot water extracts were employed in chemical extraction methods. However, these conventional water and solvent extracts are limited due to low selectivity, low extraction efficiency, solvent residue, and environmental pollution (Tao et al., 2010). The addition of water causes gel formation and entraps the desired bioactive compound in the gel matrix, which leads to poor solubility and improper extraction (Siriwardhana et al., 2008). Enzymatic extraction was currently employed in various industries due to its safety, nontoxicity, and better properties of gel solubility. The yield obtained via this method is also promisingly high. The hydrolytic enzymes enhance the release of secondary plant metabolites, preserve the properties of bioactive compounds, and improve their extractability. The few generally employed enzymes include arabanase, celluiase, β-glucanase, hemicellulase, xyianase, α-amylase, exo-1,4-α-D-glucosidase, endoprotease, and exopeptidase. These enzymes can convert water-insoluble seaweeds into water-soluble materials (Hardouin et al., 2016; Soo-Jin et al., 2005).

4.2. Microwave-assisted extraction

Microwave-assisted extraction is a technique that involves the application of microwave radiation to transfer heat to the solvents via dipole rotation and ionic conduction. The hydrogen bonds are disintegrated, resulting in higher penetration of solvent into the matrix and extraction of desired compounds (Shen et al., 2018). Microwave-assisted extraction may be operated at an elevated temperature, increasing the diffusion of molecules from sample to solvent (Michalak et al., 2015). Microwave is a potential alternative input source of energy as it lessens the heating time and processing time by eliminating dewaxing, a preparation step for extraction of seaweeds (Singh et al., 2017). The yield obtained via microwave-assisted extraction is superior to solid-liquid extraction. The high yield is achieved by optimizing parameters such as time and temperature combination, selection of solvent, and solvent to biomass ratio (Magnusson et al., 2017). The time taken to reach the extraction temperature and holding time are statistically nonsignificant (Romarís-Hortas et al., 2009). The extraction is improved further by performing microwave-assisted enzymatic extraction. Combining both methods has a higher extraction yield than performed individually (Charoensiddhi et al., 2015). Since microwave-assisted extraction consumes a reduced amount of energy and solvent, generates a smaller quantity of wastes, and is eco-friendly and sustainable compared to conventional procedures, it is considered a "green technique" (Lim and Aida, 2017).

4.3. Ultrasound-assisted extraction

Ultrasound causes inter-particle collision at high velocity, a phenomenon described as bubble cavitation. The collision results in peeling, destruction, and particle breakdown of seaweed surface. The mechanical effect generated accelerates internal diffusion and mass transfer operation (Dumay, 2016). The two important categories of ultrasound equipment employed for extraction purposes are ultrasonic water bath that is reasonably inexpensive and is commonly used to sonicate seaweed and ultrasonic probe system fitted with horn transducers which are relatively effective as it induces vibrations directly into seaweeds (Kadam et al., 2015a). The simplicity of the setup apparatus makes ultrasound-assisted extraction suitable for industrial extraction of thermolabile compounds. It can be easily combined with other supercritical fluid extraction and other solvent extraction (Kadam et al., 2015b). Extraction via ultrasound does not affect the molar mass distribution and reduces the extraction period four times (Flórez-Fernándezet al., 2019). For obtain-

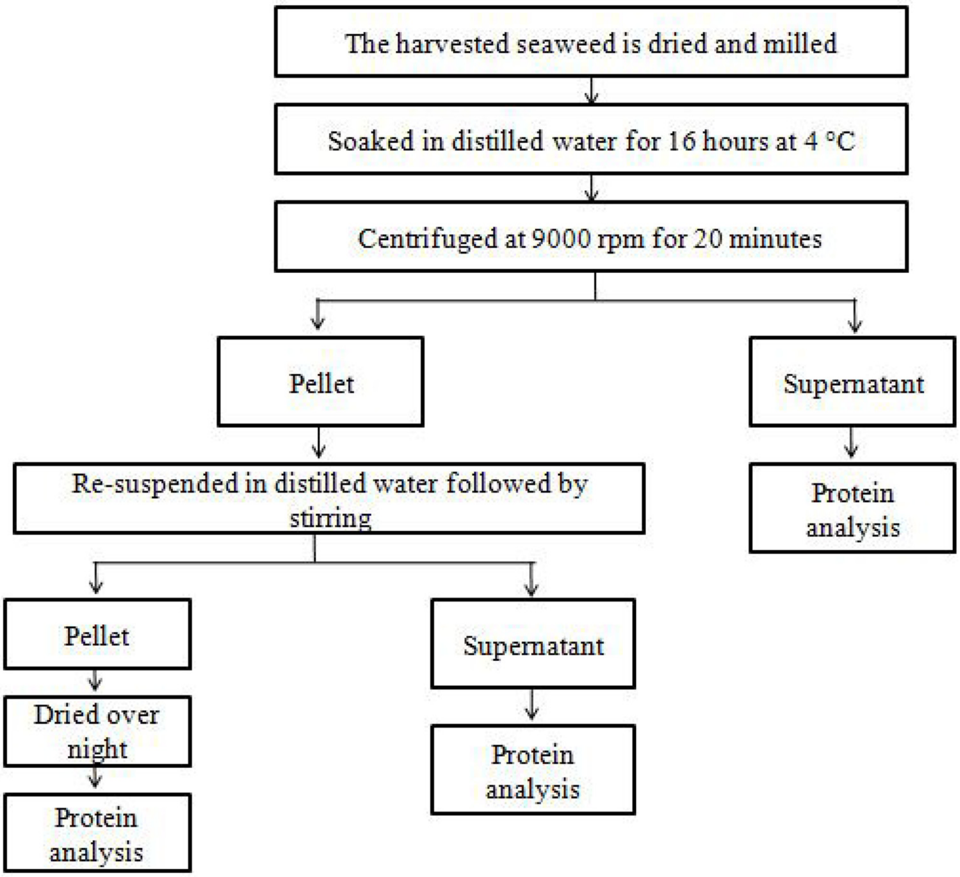

Fig. 1. Traditional method of protein extraction from seaweed.

ing a maximum yield, parameters such as pH, temperature, extraction time, ultrasound power, and algae to water ratio should be optimized (Youssouf et al., 2017). Ultrasound-assisted technology is demonstrated to be economically feasible technology as it is both quick and straightforward (Zhu et al., 2017). However, the heat generated by ultrasound may denature the heat-liable compounds, which is a significant limitation of this method (Terme et al., 2020).

4.4. Pulsed electric field extraction

The pulsed electric field is an emerging, energy-efficient method applied for selective protein extraction from seaweeds that involves the passage of high electric current to perforate cell wall and cell membrane of seaweed which in turn leads to reversible or irreversible electroporation (Hayes, 2018; Polikovsky et al., 2018). The electric field reduces the ratio between cell surfaces to pore area, leading to better penetration of solvent and improving the yield (Parniakov et al., 2020). Parameters such as the strength of field must be optimized for each seaweed species as it varies concerning the radius of the cell wall (Rego et al., 2013). The time for disruption of cell membrane ranges from microseconds to milliseconds; therefore is known to have almost no thermal effects on the extracted protein (Pliego-Cortés et al., 2019). The pulsed electric field can enhance the extraction of valuable bioactive compounds and hence, may also be utilized as a preliminary treatment followed by traditional pH-assisted aqueous extraction (Parniakov et al., 2015). This technology does not require toxic chemical additives and is known to consume less energy and water than other cell permeabilization processes. Conversely, the protein yield obtained via this method is lesser than enzyme-assisted extraction and similar to that of ultrasound-assisted extraction (Najafpour, 2015).

4.5. Supercritical fluid extraction

Supercritical fluid extraction has been identified as a non-conventional technique that uses fluids with pressure and temperature above the threshold limit as a solvent for extraction. This technology involves heating fluid above its critical point, making it supercritical. Under this condition, the supercritical fluid density is similar to liquids. The low viscosity and high diffusivity of supercritical fluids make it a relatively better solvent than liquids (Pangestuti and Siahaan, 2018; Miguel Herrero et al., 2006). The commonly employed solvent in supercritical fluid extraction is Carbon dioxide as it is non-toxic, non-flammable, readily available, and inexpensive. Carbon dioxide becomes supercritical fluid at 304 K temperature and 74 bar pressure and a gas at room temperature that decompression can eliminate to obtain solvent-free extracts. It also prevents the degradation of desired compounds present in the section by providing non-oxidizing atmospheres (López et al., 2019; Herrero et al., 2015). The low polarity of Carbon dioxide reduces the extraction efficiency and is overcome by the aid of co-solvent (Gallego et al., 2019). Xenon, hexane, ethane, ethane, ammonia, nitrous oxide and water are a few other supercritical fluids however are not employed in industrial applications (Williams et al., 2000). At optimal conditions, supercritical fluid extraction offered reproducible, effective, and quick extraction equivalent or better than ultrasound-assisted extraction and accelerated solvent extraction techniques (Punín Crespo and LageYusty, 2005). The advantages and regulations of the novel extraction techniques are elaborated in Table 2.

The yield of protein obtained, the efficiency of the technique, and the less processing time required via novel methods of extraction are significantly better than the conventional technique. However, the overall disadvantage of new techniques is the initial cost requirement for the

Table 2
Advantages and disadvantages of extraction methods.

S. no	Extraction methods	Advantages	Disadvantages	Reference
1.	Enzyme-assisted extraction	Increased yield extract, Non-toxic, Non-inflammable	Cost of enzymes is relatively high Difficult to scale up	(Munish et al., 2012; Rehman Maqsood, 2020)
2.	Microwave-assisted extraction	Less use of solvent, High extraction efficiency	Filtration step is required Time consuming process	(Veggi et al. 2012; Li et al. 2012)
3.	Ultrasound-assisted extraction	Reduced use of solvent, Lower extraction temperatures, Shorter extraction time	Cannot be combined with other instrument and automation	(Duarte, 2014; SilveiraVasconcelos et al., 2020)
4.	Pulsed electric field extraction	Low energy consumption, Non-destructive Less expensive	Lack of selectivity, time consuming	(Chahardoli et al., 2020; Puértolas et al., 2012)
5.	Supercritical fluid extraction	Easy separation of solvent and desired compound, The supercritical fluid is inert to humans	High capital cost	(Lo, 2003; Meireles, 2013;)

set up, this can prevail once the industry begins production on a large scale.

5. Challenges faced in protein extraction

The protein molecules are located at various parts of the seaweed including the cell wall, cytoplasm, and organelles. The cell wall of seaweeds is complex due to the presence of anionic or neutral polysaccharides, and polyphenols which in turn lowers the protein yield. The total protein content in seaweeds varies based on the species, season, and geographical location. The physiological and biochemical characteristics especially the type of protein influences the extraction efficacy. The protein extraction also involves the elimination of non-protein nitrogenous compounds to obtain pure protein. For that reason, seaweed protein extraction requires an additional purification process. Purification of proteins refers to the fractionation of protein with the aid of fractionation apparatus and chemicals. Column chromatography and centrifugation are the generally adopted laboratory techniques to purify proteins. All the freshly harvested seaweed species become inedible due to the development of off-flavor and slime on the surface after an average of 4 days of harvest. This short post-harvest life of seaweeds greatly affects their export. Therefore several post-harvest treatments are being adopted to preserve the quality and enhance the shelf-life of seaweeds. The seaweed biomass post-harvest can be preserved by various techniques such as freeze-drying, vacuum drying, solar drying, and convective drying to prevent protein denaturation. The total protein and amino acid content also vary based on the temperature and the drying technique adopted. A study was conducted to extend the shelf life of *Gracilaria salicornia* by submerging the seaweed in seawater and storing it in a dark environment. The results revealed that the quality of seaweed remained to be stable with a shelf-life of about 30 days (Pliego-Cortes et al., 2019; Cermeno et al., 2020). In conclusion, the extraction of protein from seaweeds requires a preservation technique to extend their shelf-life along with a purification technique to maintain the purity of the extracted protein. The combination of these additional processes must be designed in a way such that there is no negative impact on the quality and quantity of protein extracted from seaweeds.

6. Determination of protein quality in seaweeds

The protein composition in each food is unique which influences the physiological functions performed by the protein upon consumption. The quality of any source of protein is determined by protein digestibility and amino acid profile.

6.1. Protein digestibility

Protein digestibility is defined as the difference between nitrogen intake and faecal nitrogen output (Mišurcová, 2011). A source containing a perfect amino acid profile may have reduced nutritive value due to low protein digestibility. The protein fraction was subjected to digestion with enzymatic mixture or enzymes such as pancreatin, pepsin and pronase for a period of 5h. The digestibility of the seaweed protein is then compared to the relative digestibility of ceasin (100%) (Fujiwara-Arasaki et al., 1984). The protein digestibility of seaweed is determined by both *in-vitro* and *in-vivo* studies. The former method is a rapid and straightforward technique, while the next is more accurate and laborious (Fleurence et al., 2018; Raminet et al., 2019). The total protein content is estimated by multiplying the total nitrogen content and nitrogen conversion factor 6.25. However, seaweeds also contain non-protein nitrogenous material such as chlorophyll, nitrate and nitrite nitrogen, ammonium ions, and nucleic acids. Therefore the total protein available in the diet is calculated by the formula digestibility factor X amino acid score (Černá, 2011). The majority of the seaweeds contain up to 30-50% protein, and it is found that 75% of that is digestible.

6.2. Amino acid composition of seaweeds

The amino acid profile of seaweeds satisfies the requirement of FAO and WHO. Amino acids such as glycine, arginine, alanine, and glutamic acid are found in abundance, while lysine, threonine, tryptophan, cysteine, and methionine are limited (Pangestuti and Kim, 2015). Identification of amino acid profile is made by systematic techniques such as high-performance liquid chromatography (HPLC), Gas chromatography (GC) and combined gas chromatography-mass spectrometry (GC-MS) (Walker and Mills 1995). The requirement of amino acid protein varies from person to person based on age, gender, body weight, everyday activity, and physiological states. Table 3 compares and discusses certain seaweeds' essential amino acid composition and the minimum amino acid intake per day for adults and infants recommended by the World Health Organization.

The amino acid composition of seaweeds is often compared with egg to estimate the nutritional value (Mahadevan, 2015). The overall amino acid composition of several seaweed species resembles the ovalbumin. The isoleucine and threonine content of seaweeds is similar to that of leguminous protein, while histidine, an essential amino acid, is equivalent to leguminous and egg proteins (Joël Fleurence, 1999). The total concentration of glutamic acid and aspartic acid in numerous seaweed species sums up to 40% (Sergio et al., 2002). Glutamic acid and aspartic acid give seaweeds a unique flavour and taste. The majority of the seaweed species are a rich source of phenylalanine, tyrosine, and threonine, also known to be the common limiting amino acids in plant proteins. Seaweeds possess a significant quantity of essential amino acids except

Table 3
A comparison between essential amino acid composition of seaweeds and recommended amino acid intake per day for adults and infants (World Health Organization 2002).

Amino acid protein (mg/Kg)		Phe + Tyr	Val	Thr	Met + Cys	Leu	Ile	Lys	His	Reference
Ulva lactuca (C)		70	55	50.6	29	67.1	38.2	65.8	4.82	(Wong and Cheung 2000)
Hypnea charoides (R)		56.3	56.3	45.9	47.6	97.9	44.8	63.3	6.89	
Hypnea japonica (R)		61.4	61.4	51.3	44.9	72.3	48.5	64.9	6.58	
Colpomenia sinuosa (P)		46.1	32.9	22.5	4.1	48	24.5	33.4	16.7	(Tabarsa et al. 2012)
Dictyota dichotoma (P)		32.6	24.6	10.5	29.9	33.4	10.9	7.4	15.8	
Padina pavonica (P)		87.2	69.6	56.6	10.5	86.2	43.2	45.5	31.2	
Gracilaria changgi (R)		38.4	31.7	39.8	24.2	36.5	29.4	16.6	19.1	(Norziah and Ching 2000)
Osmundea pinnatifida (R)		32.4	25.9	27.3	56	25.2	21.5	30.7	36.9	(Vieira et al. 2018)
Ascophyllum nodosum (P)		88.8	20.9	19.3	40	22.8	16	42.4	10.5	
WHO/FAO/UNU recommended quantity	For adults (in mg/kg/day)	25	26	15	15	39	20	30	10	(World Health Organization 2002)
	For infants (in mg/kg/day)	59	49	37	27	73	31	64	22	

C- Chlorophyta; P- Phaeophyceae; R- Rhodophyta

methionine and lysine. On the contrary, seaweeds such as *Amansia multifida, Alsidium seaforthii* (formerly *Bryothamnion seaforthii*), *Alsidium triquetrum* (formerly *Bryothamnion triquetrum, Corallina ofticinalis, Digenea simplex* and *Enantiocladia duperrey* (Rhodophyta) are rich in lysine and deficit in methionine. Therefore these seaweed species may be combined with cereal proteins that lack lysine and are rich in methionine. Certain seaweed species are known to have lesser concentrations of cysteine, a sulfur-containing amino acid. However, the required quantity of sulfur may be held in glutathione (Ramos et al., 2000; Paul et al., 2007). The green seaweeds contain the highest total amino acid content, followed by red and brown seaweeds. However, the essential amino acid levels in all three seaweed varieties were comparable to that requirement pattern of the FAO/WHO/UNU (Patricia et al., 2009).

Even though the consumption of seaweeds is predicted to satisfy the essential amino acid requirement, the protein quality is not equal to animal-based sources. On the contrary, seaweeds are identified as a protein-rich source over terrestrial plant-based protein for human consumption (Cerna, 2011). Since seaweeds are harvested in large quantities, they can be employed in the production of inexpensive high-protein foods for everyone including the economically weaker sections of the society.

7. Value-added food products from seaweed

Seaweeds provide positive health effects such as immune regulation, protection against radiation, skin whitening effect, reduction of blood pressure, fat, sugar, impairing and delaying Alzheimer's disease, promoting gut health, reducing the risk of osteoporosis and cardiovascular diseases (Déléris et al., 2016; Qin, 2020). Seaweed-derived hydrocolloids possess unique biophysical properties such as thickening, gelling and emulsifying that are necessary for developing functional foods (Qin and Yimin, 2018b). Th componenets of the seaweed, properties and applications in food sectoe were illustrated in Fig 2. Seaweed-based novel food products were designed and developed in consideration of the protein quality and health benefits associated with it. "Itzu", a UK-based company, has successfully launched a low-calorie healthy snack ", Itzu Crispy Seaweed Thins". The seaweed snack has now entered the mainstream supermarket (Nielsen, 2016).

The organoleptic and nutritional quality of the product produced depends on the characteristics of seaweeds employed. Therefore, different seaweeds are utilized to produce a variety of functional food products summarized in Table 4.

7.1. Fermented food product

The water content present in seaweeds is relatively more than terrestrial biomass, making it a better source for microbial fermentation. The usage of seaweeds in the brewing process in China dates back to 2700 BCE. Research works are being carried out by fermenting seaweeds with lactic acid bacteria to design functional food products. Seaweed species like *Saccharina latissima* and *Laminaria digitata* (Phaeophyceae) act as the sole source of nutrition for the fermentation of *Lactobacillus rhamnosus* probiotic bacterium to develop a product with health-promoting properties. The seaweed liquor is known to take up the taste of sour wine. Though seaweeds are a potential source for lactic acid fermentation, they have not been commercially explored (Ojha et al., 2016; Kraan, 2016). Seaweeds such as bladderwrack, dulse, and sea tangle are employed to prepare a type of herbal seaweed tea. In countries like Japan, the extract of seaweeds obtained by steaming or boiling is infused in tea as a flavour-giver instead of direct incorporation of seaweed (Mouritsen et al., 2018).

7.2. Bakery and dough products

Bakery and dough products are widely consumed around the globe and are expected to deliver good aquatic-based functional food. The incorporation of seaweed powder in bread helps in improving the nutritional properties without affecting the sensory attributes and overall acceptability. By using seaweeds in noodles, the textural properties such as firmness, elasticity, resistance to cooking loss, water absorption, and cooking yield are elevated. However, too much addition of seaweed diminishes the textural properties (Roohinejad et al., 2017). The addition of seaweeds in pasta is a good choice as it is popular among consumers. In addition, it enhances the formation of a gluten network and nutritional properties, including protein and dietary fibre (Kadam and Prabhasankar, 2010).

7.3. Dairy products

The calcium in cheese, a dairy product, is present in casein, which cannot be reabsorbed by people lacking casein-degrading enzymes. The addition of seaweeds elevates the concentration of calcium. Incorporating seaweeds in various cheese, including smoked cheese, cottage cheese, processed cheese, Quarg Fresh cheese, and Appenzeller cheese, is known to improve nutritional and sensory characteristics. Yoghurt and fermented milk products are often used as a matrix to deliver

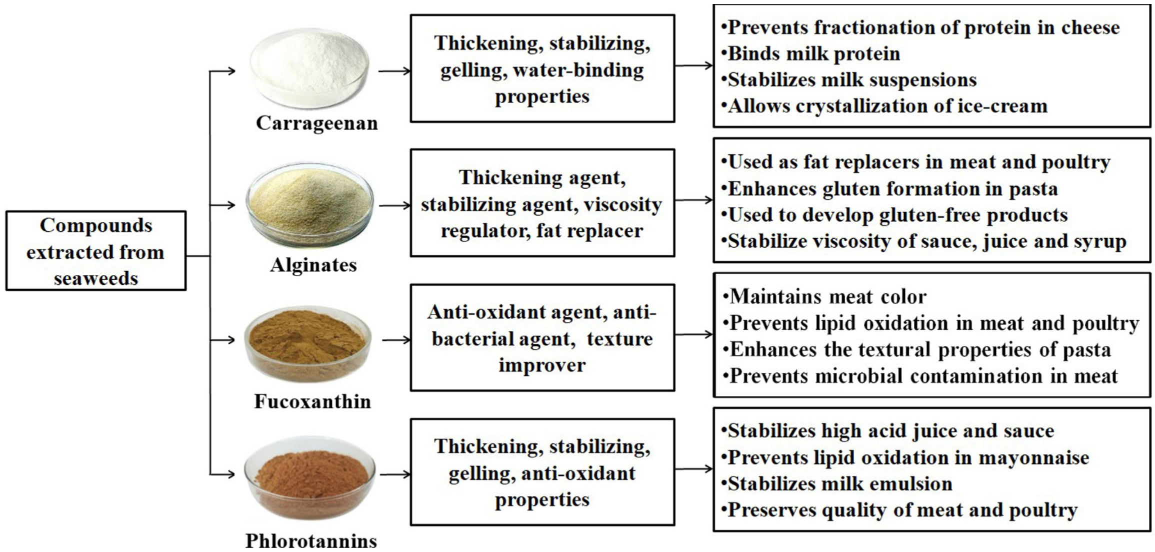

Fig. 2. Compounds extracted from seaweeds, their properties and application in food industry.

Table 4
The scientific and common name of seaweed along with the type of food product manufactured (Food and Agriculture Organization (FAO) 2018; Food and Agriculture Organization 2003).

S.no	Scientific name	Common name	Food product
1.	*Porphyra spp.* (R)	Nori or purple laver	Wrapped with rice in sushi
2.	*Monostroma spp. Ulva* (as *Enteromorpha*) *spp.* (C)	Aonori or green laver	Preparing jam boiled with sugar, soy sauce and other ingredients
3.	*Saccharina japonica* (as *Laminaria japonica*) (P)	Kombu or haidai	Added to sauces, soups and rice
4.	*Undaria pinnatifida* (P)	Wakame, quandai-cai	Added to noodles and soups
5.	*Sargassum fusiforme* (as *Hizikia fusiformis*) (P)	Hiziki	Cooked with curd and vegetables like bean and carrot.
6.	*Cladosiphon okamuranus* (P)	Mozuku	Freshly consumed with soy sauce in salad
7.	*Caulerpa lentillifera* (C)	Sea grapes or green caviar	Used in fresh salads
8.	*Palmaria palmate* (R)	Dulse	Used as seasoning and salty cock-tail snack
9.	*Chondrus crispus* (R)	Irish moss or carrageenan moss	Added to salads, soup and sashimi garnishes
10.	*Gracilaria spp.* (R)	Ogo, ogonori or sea moss	Added to vegetable salad and non-alcoholic drink
11.	*Gelidium spp.* (R)	-	Processed into jelly and cold food
12.	*Saccharina japonica* (P)	Japanese kelp	Seasoned snacks, jam and fermented beverages
13.	Gracilaria *spp.* (R)	-	Crackers, cookies and pasta
14.	*Kappaphycus alvarezii* (as *Eucheuma* cottonii) (R)	Kappaphycus	Sweets, beverages and tidbits
15.	*Durvillaea Antarctica* (P)	Cochayuyo	Seasoning in Asian cuisines and salad

C- Chlorophyta; P- Phaeophyceae; R- Rhodophyta.

the functionality of nutraceuticals. The addition of seaweeds to probiotic yoghurt products contains relatively higher calcium and potassium, sodium, magnesium and iron (Cofrades, 2013; Champagne, 2013). The inclusion of powdered seaweed extracts in whole milk is associated with shelf-life and quality attributes. The colour of the milk varied based on the species of seaweed used and the solvent used to prepare the extract, while the texture and flavour of milk were reasonably high. The overall acceptability of seaweed fortified fresh milk is reported to be high for a few days and deteriorates over storage (O'Sullivan et al., 2014). The addition of seaweed powder in ice cream significantly increases the quantity of protein and no change in the level of fat content, making it suitable to claim as a "low-fat diet". The seaweed infused increases the viscosity, melting point, and texture of ice cream. The seaweed incorporated also helps raise the foam volume during overrun, making the ice cream creamier and palatable (WinarniAgustini et al., 2016).

7.4. Meat and poultry-based products

Meat and poultry play a vital role in the fast-food diet of consumers, especially in developed countries. The consumption of red meat is declining gradually as the consumption pattern of consumers is moving towards processed meat such as bacon, sausage, hamburgers, salami, and tinned meat. The regular consumption of meat is associated with health risks such as cardiovascular disorder and colon cancer. Therefore, meat-based functional foods are being manufactured to reduce the negative health effects associated with the consumption of meat products and enhance nutrition. A wide spectrum of ingredients such as soy, walnut, oils, oats, rice, wheat, carrot has been employed in producing functional plant-based meat products. Seaweeds possess a remarkable nutritional profile that includes high protein, dietary fiber, vitamin, mineral, and low lipid content. The incorporation of whole seaweeds or seaweed extract into meat products enhances the nutritional, sensorial, and physicochemical properties of meat. For instance, seaweeds are known to improve the water and fat binding properties that enhance the chewiness and firmness of the meat structure. Conversely, the incorporation of seaweeds with strong flavor and color is limited due to the negative effect on the sensorial properties such as appearance, taste, and flavor. The color of the seaweed employed greatly influences the color of the final product. A study conducted on preparing sausages using sea tangle powder had a very low acceptance of color with a high acceptance of flavor, juiciness, and tenderness (Cofrades et al., 2017; Roohinejad et al., 2017). Another research work demonstrated that the incorporation of seaweed extract in pork patties significantly improved the protein stability and lessened the lipid oxidation than the control patties prepared with synthetic antioxidants during storage at 4°C for 180 days. The formulation of chicken nuggets using seaweed extract as a fat-replacer relatively improved the cooking yield, fat, and water retention properties due to the presence of carrageenan compared to the regular chicken nuggets (Gagaoua et al., 2020). Considering the nutritional and technological benefits of incorporating seaweeds into meat, it is concluded that seaweeds have the potential to convert the negative effects of meat and poultry products. The growing awareness about the risk involved in the consumption of meat and poultry products has paved way for meat replacers and meat-based functional foods.

7.5. Other products

The excessive consumption of salt is associated with health risks such as hypertension and cardiovascular diseases. Consequently, food industry focuses on manufacturing low-salt products. Several research works have been conducted to understand the influence of seaweeds as salt replacers in meat products. The results of the studies revealed that there is a significant reduction in cooking loss and improvement in the organoleptic properties in comparison with normal salted meat products (Gullon et al., 2020). Seaweed-derived hydrocolloids are used to prepare jellies containing a large quantity of water with low energy and provide detoxicating effects. Mothers traditionally consume seaweed soup after the child's birth as it is known to provide protein, vitamin A, minerals, and other essential nutrients required for both mother and child (Qin and Yimin, 2018a). Currently, the need for an alternate protein-rich plant-based source to satisfy the daily requirement of vegetarian/vegan athletes is elevating. Seaweeds being a potential source of protein as well as containing all essential amino acids, can be consumed by vegetarian/vegan athletes (Bleakley et al., 2017).

Rather than the consumption of seaweeds as a whole, the incorporation of seaweed extract or seaweed powder into food products that are a part of people's everyday diet would benefit the consumers in terms of overall acceptability and not switching from their cultural diet. Therefore, it is concluded that the value-added products have the potential to satisfy both the nutritional and sensorial requirements of the consumers.

8. Risk assessment of seaweeds

Seaweeds do not produce endogenous toxins; however, there is a possibility of accumulation of toxins, especially heavy metals cadmium, lead and mercury, and arsenic. The characteristic cell wall of seaweeds allows the transmission of heavy metals from the aquaculture environment (Lähteenmäki-Uutela et al., 2021). The accumulation of metal also depends on the period of seaweed immersed in water, age, and position of seaweed were the quantity of nitrogen in seaweed controls the absorption of metals such as zinc and iron. It is necessary to incorporate seaweeds at required levels to achieve desired functional effect, as well as the safety at this level must be monitored. Despite the high concentration of non-essential metals, the risk assessment reveals a low hazard index. The nutritional and health benefits of consuming seaweeds are more likely to outweigh the unanticipated negative consequences (Forster and John, 2015; Anbazhagan et al., 2021; Hurd et al., 2014; Domínguez 2013**)**. Seaweeds are a rich in iodine; however, excessive consumption may cause ill effects to health. Dietary-induced iodine caused hyperthyroidism in a Japanese 20-year-old female due to the consumption of iodine-rich seaweed confectionery and similar symptoms were examined in a Japanese 71-year-old female after the consumption of cooked seaweed has been documented. The symptoms subsided immediately after the removal of seaweed from the diet. For example, kombu, a seaweed that exceeds the RDI value of 0.14mg/day for iodine The excessive consumption of seaweeds may be prevented by creating awareness about the iodine content present in various seaweed groups among consumers (Yeh et al., 2014; Müssig, 2009). Among the vegan population, the sources of iodine include iodized salt and dietary supplements; however, supplements may cause adverse health effects. Seaweeds being a good source of iodine, can balance the iodine intake in vegans. The high concentration of iodine in seaweed is relatively low when consumed in a vegan diet (Lightowler, 2009). The occurrence of seaweed poisoning is majorly due to the consumption of raw seaweed without any pretreatment. Many toxic compounds have been identified and isolated from natural seaweeds, including aplysiatoxin, debromoaplysiatoxin, prostaglandins, polycavernosides, and diethyl peroxides caulerpin and caulerpicin (Cheney, 2016).

The risk involved in the consumption of seaweeds can be reduced drastically by adopting appropriate processing techniques to eliminate the seaweeds contaminated with heavy metals. The contamination of seaweeds with heavy metals and toxins may be prevented at an industrial level by harvesting the seaweeds in an unpolluted aquaculture system. The consumption of large quantity seaweeds on an everyday basis may cause the accumulation of heavy metals and iodine in the body. This risk can be reduced at the consumer level by creating awareness among about the quantity of intake.

9. Consumer acceptability of seaweeds

Globally, there has been an elevation in research, development, and commercialization of functional components and nutraceuticals due to consumer responsiveness of the relationship between diet, health, and disease (Thakur et al., 2020). Some groups of consumers around the globe are interested in healthier products that include seaweeds. On the other hand, the idea of consuming seaweeds and seaweed derivatives at undetectable levels may be unpalatable to a few consumers. In western countries, seaweeds are rarely a part of the diet as seaweed taste is often misunderstood to be "fishy" and "sea taste". Seaweeds in western countries are not considered "luxurious foods", whereas seaweeds became a valuable commodity in countries like France, Ireland, Norway, Chile, and Canada. Seaweeds have become a staple diet in China, Japan, and Korea (Gupta et al., 2017; Delaney, 2016). The survey report infers that young males preferred to consume seaweed incorporated snacks and fast food over young females. Adult consumers showed an overall positive attitude towards the same (Wendin and Undeland, 2020). Consumers have realized the benefits of consuming nutritionally balanced food via published research, empirical knowledge, and media channels. With this increase in demand for organic products and alternative protein, seaweeds seem to have excellent market potential (Pereira et al., 2014). In today's world, seaweeds are also commercially employed to produce pharmaceuticals since they are known to contain medicinal properties that promote health. Fig. 3 represents a few health benefits obtained by consuming seaweeds.

The overall acceptability of seaweeds as a potential source of proteins is significantly high due to the skyrocketing awareness regarding the superior nutritional properties of seaweeds. However, during the initial stages of seaweed-based food marketing, a collaborative plan must be devised between the manufacturers and suppliers based on the demand. The consumption of seaweeds may be promoted by either manufacturing seaweed-based functional foods or concentrating isolates of extracted protein.

10. Conclusion

The quality of protein in marine macroalgae edible seaweeds is much more excellent than other aquatic plants and traditional plant-based protein sources. The seaweeds are known to promote health and provide nutrition and therefore are claimed to be a promising alternative source of complete plant protein. The high essential amino acid concentration and the low calorific value of seaweeds are suitable for health-conscious consumers. In order to maintain the sensory attributes and palatability, fine selection of seaweed with desired characteristics and the dosage used must be standardized while designing functional food products. The proposed extraction techniques are efficient enough to maintain protein quality present in seaweeds and eco-friendly. Seaweed-derived proteins, peptides, amino acids may be marketed in functional foods,

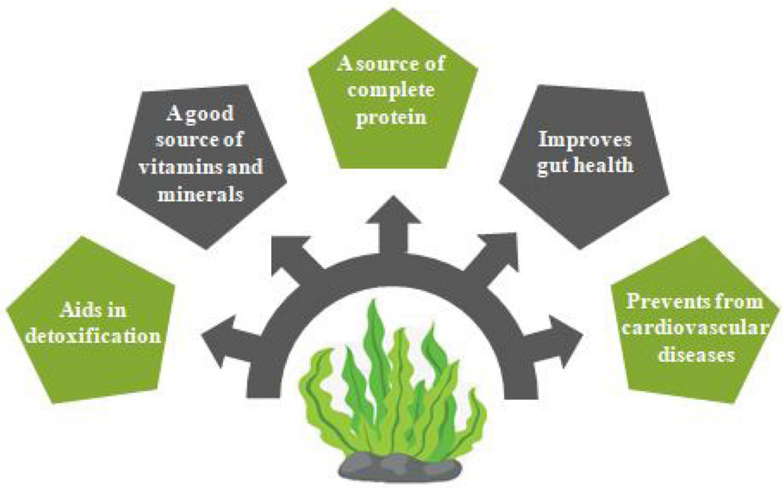

Fig. 3. Health promoting properties of seaweed.

therapeutics, and nutraceuticals for human health applications since the consumers are moving towards using nutritious products. Future research is required to overcome the challenges faced during industrial production of protein extraction and also to obtain maximum benefits and improved extraction yield. This review may be a stepping stone for processing seaweeds on an industrial scale and entering the food and nutrition market.

11. Future prespective

The worldwide production of seaweeds has been tremendously growing in the last decade and is expected to continue to grow at a steady rate. However, the seaweeds are majorly cultivated for their valuable components such as carrageenan, agar-agar, and alginic acid and have limited impact on food-based industries in countries other than China, Japan, and the Republic of Korea. The harvesting of seaweeds essentially for manufacturing protein-based food products and the replacement of other plant-based sources of protein is forecasted to be the future of seaweeds. As the demand for plant-based protein-rich sources has been amplified along with the growing populations, the production of seaweed-based functional food at an industrial scale is predicted to surpass the limitations and challenges faced by the manufacturer. Apart from providing a protein-rich diet for humans, harvesting seaweed also offers job opportunities to people residing in coastal areas. Therefore, seaweeds are predicted to be the future food.

Decleration of Competing Interest

The authors declare no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fufo.2022.100142.

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