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REVIEW

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Global seaweed farming and processing in the past 20 years

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Abstract

Seaweed has emerged as one of the most promising resources due to its remarkable adaptability, short development period, and resource sustainability. It is an effective breakthrough to alleviate future resource crises. Algal resources have reached a high stage of growth in the past years due to the increased output and demand for seaweed worldwide. Several aspects global seaweed farming production and processing over the last 20 years are reviewed, such as the latest situation and approaches of seaweed farming. Research progress and production trend of various seaweed application are discussed. Besides, the challenges faced by seaweed farming and processing are also analyzed, and the related countermeasures are proposed, which can provide advice for seaweed farming and processing. The primary products, extraction and application, or waste utilization of seaweed would bring greater benefits with the continuous development and improvement of applications in various fields.

Keywords: Algal farming, Algal processing, Breeding technology, Extraction technology

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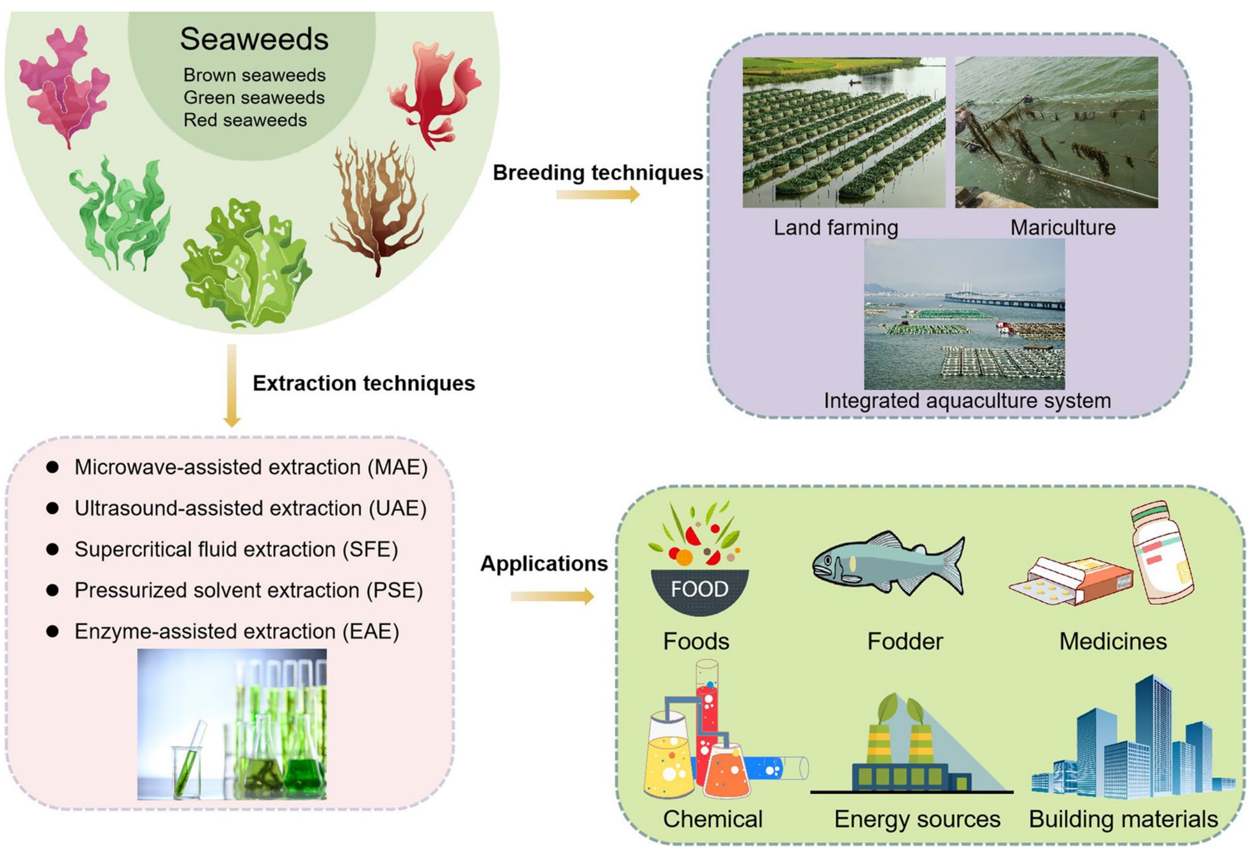
Graphical Abstract



Introduction

In the past 20 years, the seaweed farming and production process have increased significantly, and play the important role in the fishing industry by country (Cai et al. 2021). According to the Food and Agriculture Organization (FAO) data, the global seaweed output (both aquaculture and wild) has increased nearly threefold from 118,000 tons to 358,200 tons from 2000 to 2019 (FAO 2021) (Fig. 1). In 2019, 97% of the global aquaculture output came from artificial farming. The world's seaweed production mostly comes from the five major continents with Asia accounting for 97.38%. In Asia, 99% of seaweed is cultured artificially. In particular, China ranks first in the world in terms of aquaculture production, accounting for 56.82% of the global aquaculture. The main algae are Japanese kelp (*Laminaria japonica*), *Gracilaria* seaweeds *(Gracilaria* spp.) and nori Nei (*Porphyra* spp.). The second is Indonesia, another major seaweed farming country, which accounts for 28.6% of the global breeding. *Eucheuma* seaweeds nei (*Eucheuma* spp.) and *Gracilaria* seaweeds (*Gracilaria* spp.) are the main species. South Korea has a developed seaweed culture industry and many seaweed species, accounting for 5.09% of the world, including brown, red, and green seaweeds (excluding microalgae). Among them, Japanese kelp (*Laminaria japonica*) is the most cultured, followed by laver (*Porphyra tenera*) and wakame (*Undaria pinnatifida*). The aquaculture in the Philippines accounts for 4.19% of the global market, mainly planting Elkhorn Sea moss (*Kappaphycus alvarezii*), accounting for more than 90% of the country. North Korea accounts for 1.6% of the global aquaculture and mainly grows Japanese kelp (*Laminaria japonica*). Japan accounts for 1.15% of the global seaweed production, mainly planting laver (*nori, Porphyra tenera)*, wakame (*Undaria pinnatifida*), and Japanese kelp (*Laminaria japonica*). Malaysia accounts for 0.53% of the global aquaculture, mainly planting Elkhorn Sea moss (*Kappaphycus alvarezii*). North America accounts for 1.36% of the world's seaweed, and 95% of the seaweed in North America is obtained from natural resources. In terms of seaweed cultivation, Chile is the main producer, accounting for 0.3% of the global

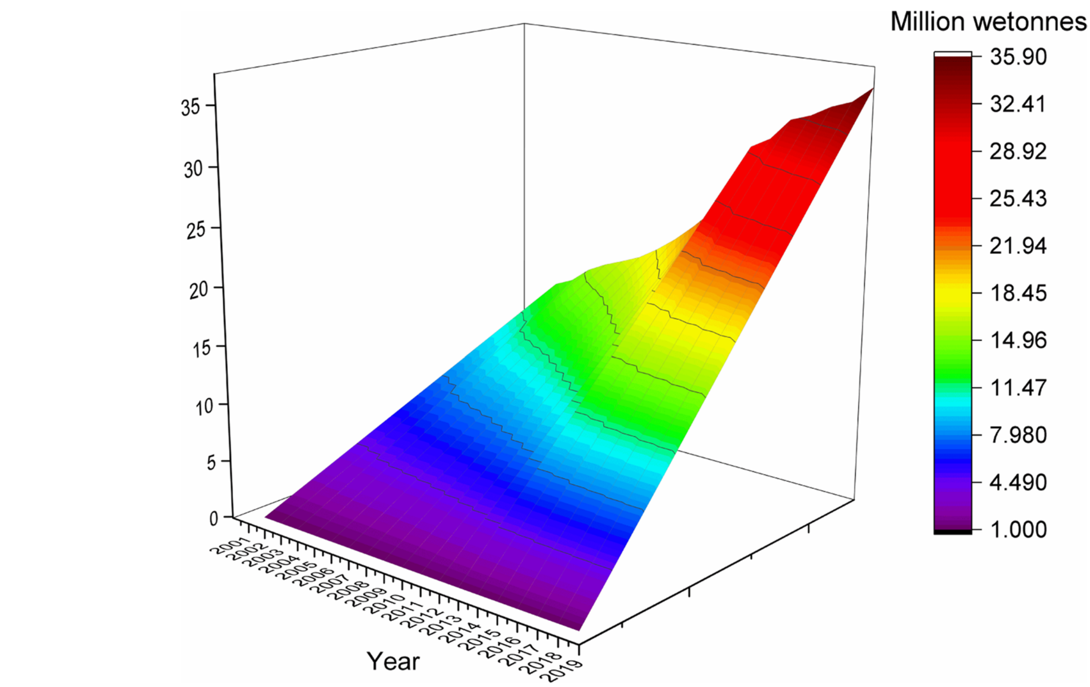


Fig. 1 Status and trends of world algal production from 2001 to 2019 (FAO 2021)

production, and it mainly grows *Gracilaria* seaweeds and *Spirulina maxima*, but 99% of them comes from natural riverbeds. Mexico accounts for 0.02% of the global output of raw seaweed. Brown seaweeds has been planted in recent years, but currently, 99% of brown seaweeds (*Phaeophyceae*) and red seaweeds Nei (*Rhodophyceae*) come from natural riverbeds. Algae are largely obtained from natural resources in the United States, Peru, and Canada. Europe accounts for 0.8% of global seaweed production. In Europe, 96% of the seaweed is obtained from natural resources. Only since 2010, artificial cultivation has been experimenting in Europe. Africa accounts for 0.41% of the world's seaweed. By 2019, the percentage of 81% of seaweed came from seaweed farming. Zanzibar accounts for 0.5% of the global aquaculture, mainly spiny *Eucheuma* (*Eucheuma denticulatum*). Oceania accounts for 0.05% of the world. 99% come from cultured seaweed. It mainly produces miscellaneous brown seaweeds (Fig. 2).

In general, the following five kinds of seaweeds accounted for more than 95% of world's seaweed culture production in 2019. *Laminaria* and *Saccharina* account for 34.65% of the global cultivation for human consumption, mainly as salads, condiments, and sauces. Carageen from tropical algae *Kappaphycus* and *Eucheuma* accounted for 32.62% and was mostly used for carrageenan extraction. *Gracilaria*, *Porphyra*, and *Undaria* accounted for 10.32%, 8.33%, and 7.16%, respectively. In Asia and South Africa countries, seaweeds (such as brown algae, leafy algae, and kelp) are often used as fish feed like *Laminaria* and *Sargassum* in China, *Kappaphycus* are used as seaweed fertilizer in India, and made into livestock feed in most European countries (Fig. 3).

Excepted for commercially important brown algae species, research on green algae have so far focused on *Ulva lactuca*, *Enteromorpha prolifera*, *Monostroma nitidum*, *Chlorella pyrenoidosa*, and *Ulva conglobata*, with the bioeffects of regulating intestinal flora and improving immune function (Lee et al. 2013; Zheng et al. 2020a, 2020b). In contrast, the development of edible green algae resources is not enough. More nutrients in seaweed are discovered now, and the potential demand for algal compounds and other chemicals generated by biotechnology is growing In the future, it is expected that research and utilization of edible green algae will attract increasing attention.

Seaweed contains a wide range of bioactive compounds as well as nutritional benefits. Furthermore, algae can produce far more biomass than terrestrial plants and may be cultured successfully in fresh or seawater without the use of antibiotics or pesticides, which lead to an increase in consumer demand and economic interest over the last two decades. In this review, the development of global seaweed cultivation production and processing in the past 20 years was reviewed, and the latest situation and technology of seaweed farming

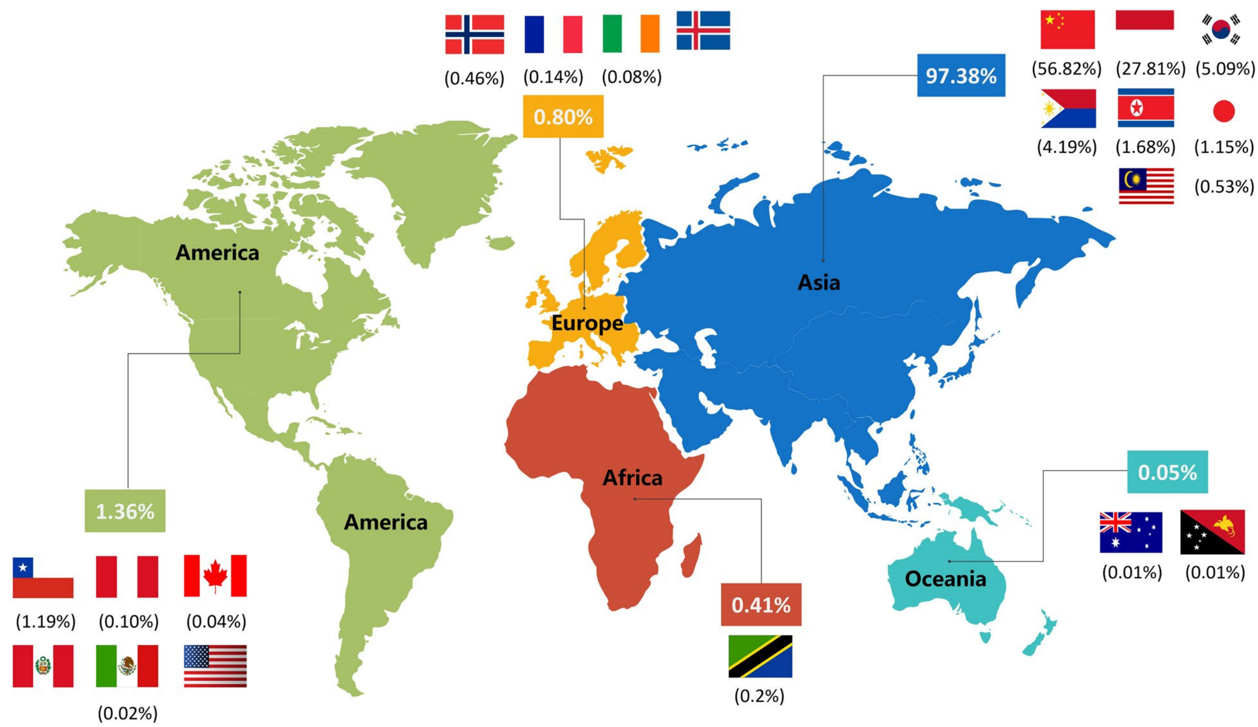


Fig. 2 Seaweed production in the year 2019 (FAO 2021)

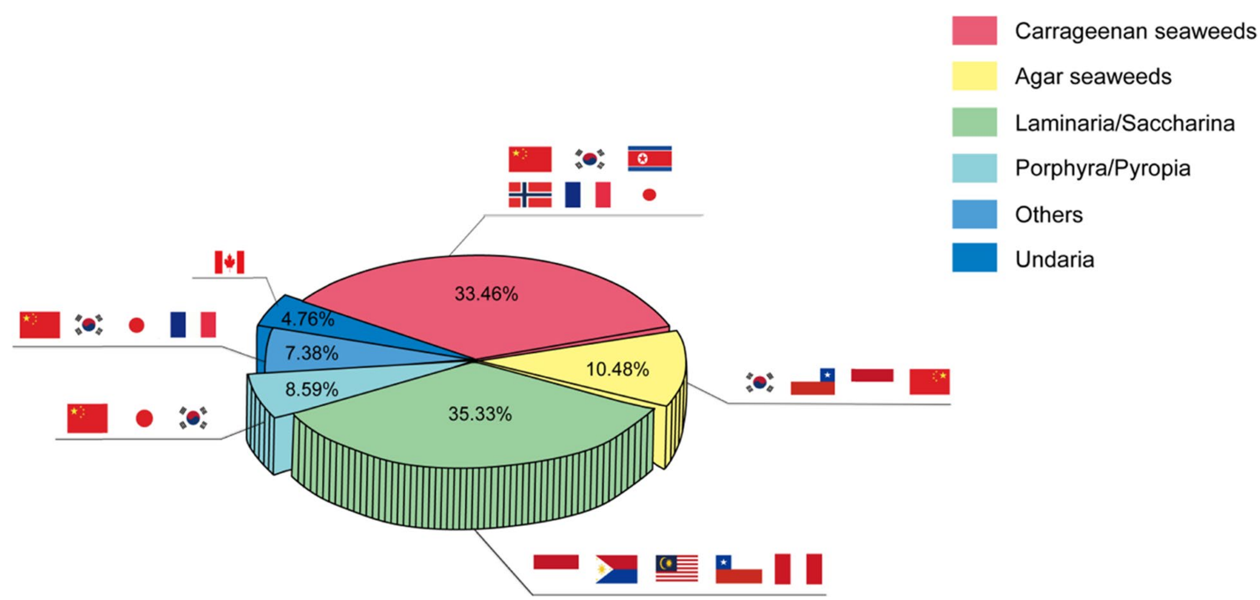


Fig. 3 Percent seaweed aquaculture production per species and countries in the year 2019 (FAO 2021)

were introduced (Fig. 4). The present situation of seaweed processing and extraction technologies were also reviewed. Moreover, the new applications of seaweed products in food, agriculture, medicine, and cosmetics were introduced. Finally, the challenges of seaweed farming and processing were discussed.

Global seaweed farming and processing

Current research progress of active substances

Diseases such as cancer, diabetes, inflammation, and chronic cardiovascular diseases are major global health problems (Pradhan et al. 2020a). Currently, the chemotherapy and synthetic drugs are widely used in the

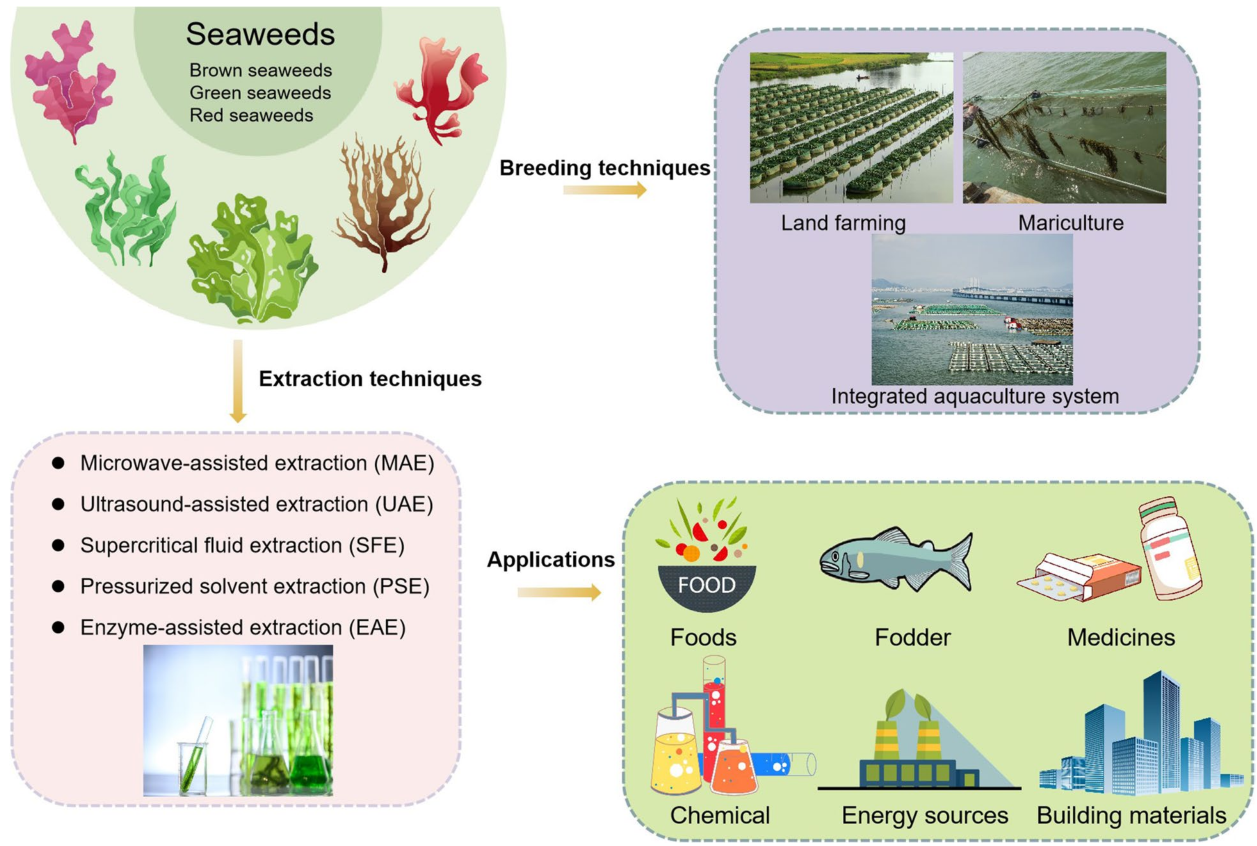


Fig. 4 Overview of the global state of farming, extraction, and applications of seaweeds

medical field. However, some drugs are often associated with side effects such as toxicity, drug tolerance, and metabolic disorders (Pradhan et al. 2020b). Therefore, the natural bioactive ingredients have become interesting substitutes to prevent diseases. Seaweed is one of the most abundant and promising sources of biologically active metabolites. These bioactive components of seaweed include polysaccharides, unsaturated fatty acids, phenols, peptides, terpenoids, and other compounds with unique structures and properties, which have the antioxidant, antiviral, anticoagulant, antibacterial and antitumor effects. Many active substances are found in the brown, red, and green seaweeds, which have the great potential in agricultural, edible, and medical fields.

Brown seaweeds

Brown seaweeds are multicellular algae with a high degree of evolution that are found in cold water of continental coastal waters and are uncommon in fresh water. The main species of brown seaweeds include *Laminaria digitata, Sargassum, Ascophyllum, Undaria* and *Laminaria* (Li et al. 2021a, 2021b). Take *Sargassum* for example, because it contains polysaccharides, proteins, polyphenols, lipids, sterols, carotenoids, and other active compounds, showing a variety of pharmacological properties, so it is called the twenty-first century medicinal food (Yende & Chaugule 2014). Some bioactive compounds of brown seaweed and their important bioactivities are summarized in Table 1.

Polysaccharides are the main components of brown algae. The concentration of total polysaccharides in common seaweed species ranges from 4–70% of dry weight, and the main bioactive polysaccharides include alginate, fucoidan, mannitol and laminarin (Mohd et al. 2021; Holdt & Kraan 2011; Shen et al. 2017). Alginates, the only polysaccharide with carboxyl groups in monomers, provide several health advantages, including anti-inflammatory, antioxidant, anti-obesity, antiallergic and immunomodulatory (Feng et al. 2020; Horibe et al. 2016; Wang et al. 2018, 2021; Yu et al. 2020). Fucoidan is a sulfated polysaccharide found in large quantities in the cell wall. It has the potential to be employed as an antioxidant, anticancer, anti-angiogenic, antiphotoaging and antitumor drug, according to several in vitro investigations (Cong et al. 2016; Jing et al. 2021; Palanisamy et al. 2018; Park

Table 1 The bioactivity and characteristics of brown seaweeds

Compounds	Algae source	Activities	Mechanisms	References
Polysaccharide	*Sargassum fusiforme*	Immune regulation	CD14/IKK/NF-κB and P38/NF-κB signaling pathways were induced to enhance immunity	Chen et al. 2018
	Laminaria japonica	Anti-hyperlipidemia	Regulate mRNA transcription and protein expression levels associated with liver lipid metabolism	Zhang et al. 2020
Sulfated polysaccharide	*Undaria pinnatifida*	Hypoglycemic		Zhong et al. 2021
	Sargassumhenslowianum C. Agardh, *Fucus vesiculosus*	Antitumor	The proliferation of melanoma cells was inhibited, and apoptosis was induced by caspase-3 activation in vitro	Ale et al. 2011
	Sargassum fulvellum	Anti-inflammatory	Lps-induced inducible nitric oxide synthase expression was inhibited by NF-κB pathway in RAW 264.7 cells	Gwon et al. 2013
	Sargassum cristaefolium	Anti-inflammatory	The expression of inducible nitric oxide synthase was significantly inhibited by inhibition of phosphorylation of P-38, ERK and JNK signaling proteins and LPS-stimulated nuclear factor-κB activation in RAW264.7 cells	Wu et al. 2016a, 2016b
Alginate	*Laminaria japonica*	Antiallergic	In OVA-triggered mice, inhibiting mast cell degranulation in the jejunum, maintaining T cell balance, and recovering allergic mediator overproduction	Yu et al. 2020
	Brown seaweed	Anti-inflammatory, antioxidant	To prevent McT-induced pulmonary vascular remodeling by inhibiting TGFβ1/p-Smad2 signaling pathway	Feng et al. 2020
	Brown seaweed	Anti-obesity, immunoregulation	Alleviating obesity and chronic metabolic diseases by enhancing the biological function of the small intestine, especially the colon; It plays an immunomodulatory role by restoring the structure and function of colon genome	Wang et al. 2018
	Brown seaweed	Anti-inflammatory	Secreted mRNAMuc2 and membrane associated Muc1, Muc3, and Muc4 are expressed in the small intestine. In indomethacin induced SII, alginate prevented the increase of MUC1-4 mRNA expression	Horibe et al. 2016

Table 1 (continued)

Compounds	Algae source	Activities	Mechanisms	References
Fucoidan	*Fucus vesiculosus*	Anti-inflammatory	By inhibiting NF-κB, MAPK and Akt activation in LPS-induced BV2 microglia	Park et al. 2011
	Sargassum polycystum	Antioxidant, anticancer	The antioxidant and anticancer properties (breast and colon cancer cell lines) were evaluated by cytomorphologic and nuclear morphological analyses	Palanisamy et al. 2018
	Fucus vesiculosus	Anti-angiogenesis, Antitumor	Inhibition of HIF-1*α* inhibits the expression of VEGF to induce apoptosis and anti-angiogenesis, thus playing an anticancer role in ATC cells	Shen et al. 2017
	Undaria pinnatifida	Antiphotoaging	By regulating sirT-1 /PGC-1*α* signaling pathway to alleviate mitochondrial dysfunction, ROS production is inhibited and UV-induced skin photoaging is improved	Jing et al. 2021
	Sargassum fusiforme	Anti-angiogenic	Structural characterization and inhibition of tube formation and migration in human microvascular endothelial cells	Cong et al. 2016
Mannitol	Brown seaweed	Osmotic		Holdt et al. 2011
	Padina boergesenii	Free radical scavenger		Karthikeyan et al. 2010
Laminarin	Brown seaweed	Immunostimulatory	To evaluate the immune stimulatory effects on inflammatory mediators such as calcium, H_2O_2, NO, cytokines, transcription factors and immune response genes in macrophages of RAW 264.7 mice	Lee et al. 2012
	Brown seaweed	Anticancer	Inhibition of ovarian cancer cell growth through mitochondrial dysfunction and ER stress	Bae et al. 2020
	Salicornia herbacea	Antioxidant	Stimulation of glucose uptake via the AMPK-p38 MAPK pathway in L6 muscle cells	Ji et al. 2020
	Laminaria digitata	Antibacterial	To evaluate its inhibitory effect on the growth and toxigenic production of *Aspergillus flavus*	Hu et al. 2012
Oligosaccharide	*Sargassum confusum*	Anti-diabetic	It can improve hepatic insulin resistance by regulating IRS1/PI3K and JNK signaling pathways and regulate intestinal flora	Yang et al. 2019
Peptide	*Undaria pinnatifida*	Antihypertension	Animal experimental feeding was performed to evaluate whether hypertension was significantly inhibited in spontaneously hypertensive rats	Sato et al. 2002
Lectin	*Hizikia fusiformis*	Antioxidant	The antioxidant capacity was evaluated by measuring the scavenging activity of hydroxyl, DPPH and ABTS + radicals	Wu et al. 2016a, 2016b

Table 1 (continued)

Compounds	Algae source	Activities	Mechanisms	References
Polyunsaturated fatty acids	*Undaria pinnatifida*	Anti-inflammatory	Their inhibitory effect on inflammatory symptoms such as edema, erythema and blood flow were evaluated in animal experiments	Khan et al. 2007
Fucosterol	*Undaria pinnatifida*	Anti-inflammatory	The coordinated regulation of IKK significantly inhibited LPS-induced inflammatory mediators in RAW 264.7 macrophages through NF-κB inactivation	Yoo et al. 2012
	Pelvetia siliquosa	Anti-oxidant	Serum transaminase, superoxide dismutase, catalase and glutathione peroxidase activities were evaluated	Lee et al. 2003
	Ecklonia stolonifera	Antidiabetic	Inhibition of PTP1B activates insulin signaling pathway in insulin resistant HepG2 cells	Jung et al. 2016
	Ecklonia stolonifera	Anti-obesity	Inhibition of PPARγ and C/EBP*α* expression resulted in reduced lipid accumulation in 3T3-L1 preadipocytes	Jung et al. 2014a, 2014b
Sterol	*Sargassum horneri*	Antidepressant	The levels of major monoamine neurotransmitters and their metabolites in the mouse brain were also evaluated by structural characterization	Zhao et al. 2016
	Jolyna laminarioides	Hypolipidemic	Solvent fractions (n-hexane, chloroform, methanol) and fractions containing alginate sterols were evaluated, and marker enzyme levels in the heart and liver were compared	Ruqqia et al. 2020
Fucosterol and phlorotannins	*Eisenia bicyclis*	Anti-inflammatory	The expression of inflammatory genes regulated by NF-κB was inhibited by ROS inhibition	Jung et al. 2013

Table 1 (continued)

Compounds	Algae source	Activities	Mechanisms	References
Carotenoid (fucoxanthine)	*Phaeodactylum tricornutum*	Antiproliferative, antioxidant	Increased fucoxanthin caspase 3/7 activity and dose-dependent antioxidant effect resulted in decreased chemiluminescence of blood neutrophils and a greatly increased ratio of reduced to oxidized glutathione	Neumann et al. 2019
	Phaeodactylum tricornutum	Anti-obesity	Selected genes related to lipid and energy metabolism were analyzed for weight gain, fat depots weight, adipocyte size distribution and expression in adipose tissue, as well as parameters related to glucose control	Gille et al. 2019
	Laminaria	Antitumor	The cell cycle was inhibited, and apoptosis was induced by regulating the expression of p53, p21, Fas, PUMA, Bcl-2 and caspase-3/8	Mei et al. 2017
	Brown seaweed	Neuroprotection	Regulation of NrF2-ARE and NrF2-autophagy pathways provides neuroprotection in TBI models	Zhang et al. 2017
Phlorotannin	*Ecklonia stolonifera*	Anti-adipogenic, activity	Inhibit lipid accumulation and adipocyte differentiation in 3T3-L1 cells by inhibiting C/EBP and PPAR expression	Jung et al. 2014a, 2014b
	Ecklonia stolonifera	Anti-Tyrosinase, antioxidant	Reduce melanin content and tyrosinase activity, as well as down-regulated production of melanin-producing enzymes (tyrosinase, TRP-1, and TRP-2)	Manandhar et al. 2019
	Eisenia bicyclis	Anti-obesity	Inhibition of pancreatic lipase activity	Eom et al. 2013
	Ishige foliacea	Memory improvement	The ERK-CREB-BDNF pathway is regulated to improve scopolamine-induced memory impairment	Um et al. 2018

et al. 2011; Shannon et al. 2021; Shen et al. 2017). Mannitol is a monosaccharide found in the cytoplasm of brown seaweeds. It has a high permeability and shows promise as a free radical scavenger, lowers stroke-related edema and tissue damage, and is frequently employed in the production of chewing gum, diabetic foods, and various tablets (Bereczki et al. 2007; Cavone et al. 2012; Dai et al. 2017; Ruiz et al. 2017; Holdt et al. 2011; Karthikeyan et al. 2010). Laminarin is a storage β-glucan containing up to 35% laminarin (on a dry weight basis) and is increasingly recognized for its bio-functional activities (Kadam et al. 2015). Laminarin has been reported to have biological functional activities, including anticancer, antioxidant, anti-bacterial and immune stimulation (Bae et al. 2020; Hu et al. 2012; Ji et al. 2020; Lee et al. 2012; Liu et al. 2017).

Brown seaweeds usually have a small protein content ranges from 5 to 15% of its dry weight. It has been reported that peptides isolated from *Undaria pinnatifida* have hypotensive effects on blood pressure in spontaneously hypertensive rats (Sato et al. 2002; Suetsuna et al. 2004). Furthermore, lectins, a functional active protein isolated from the brown seaweed *Hizikia fusiformis*, have been demonstrated to have high antioxidant capacity and robust free radical scavenging activity (Wu et al. 2016a, 2016b).

Various bioactive substances, including omega-3 PUFAs, omega-6 arachidonic acid (ARA), and fucoxanthin, can be found in brown seaweed lipids (Miyashita & Hosokawa 2013). The active forms of omega-3 PUFA include eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which lower the risk of cardiovascular disease (Lavie et al. 2009; Ruxton et al. 2007; Yanai et al. 2018). Additionally, ARA is crucial for the functioning of the immune system, thrombosis, and the brain (Miyashita & Hosokawa 2013).

Fucoxanthin is the most abundant pigment of all carotenoids in brown seaweed and has been shown to have anti-inflammatory, anti-obesity, antioxidant, and anti-diabetic properties (Jung et al. 2016, 2014a, 2014b; Lee et al. 2003; Yoo et al. 2012). Furthermore, sterols have been found in brown seaweed and have been associated with antidepressant and lipid-lowering properties (Ruqqia et al. 2020; Zhao et al. 2016). In particular, fucosterol, which is the characteristic sterol of all brown seaweed phylum, has antioxidant, anti-diabetic anti-inflammatory and other biological activities (Abdul et al. 2016; Jung et al. 2016, 2014a, 2014b; Lee et al. 2003; Sun et al. 2015; Yoo et al. 2012).

Most brown seaweeds contain fucoxanthin pigments and brown tannins, which give their distinctive greenish-brown hue. Among these, phenolotannins are the most abundant phenolic chemicals in brown seaweed, accounting for 25% of dry weight (Qin 2018). Phlorotannins are found only in brown seaweed and have the 2–tenfold antioxidant activity of ascorbic acid and tocopherol (Bogolitsyn et al. 2019). In addition to the anti-oxidative properties of phlorotannins from brown seaweed, phlorotannins also can prevent obesity by inhibiting the adipocyte differentiation of stem cells (Suzuki et al. 2016). In particular, tannins can improve memory by modulating the ERK-CREB-BDNF pathway (Um et al. 2018).

At present, many active ingredients in brown seaweed have been proved to have functional activities such as antioxidant, anti-inflammatory, anti-tumor, and anti-diabetic. For example, mannitol has been used medicinally as a good diuretic and hyperosmolar antihypertensive agent, but verification of these functional activities with mannitol extracted from brown seaweed is rare. In addition, studies on functional components in brown seaweed mainly focus on macromolecules, such as polysaccharides, sulfated polysaccharides. There are few reports on the mechanism of action of alginate and fucoidan contained in polysaccharides in brown seaweed.

Red seaweeds

The majority of red seaweeds grows in the deep sea, which is the largest group of marine macroalgae. The bioactive compounds of red seaweed and their important bioactivities are summarized in Table 2.

Red seaweed contains comprises polysaccharides (carrageenan or agar), proteins, amino acids, sterols, carotenoids, bromophenols, and other natural bioactive compounds. Polysaccharide is the most developed molecule in the cell wall of seaweed, accounting for 40–50 percent of its dry matter. It is worth noting that carrageenan and agar are the most relevant and developed compounds in red seaweed (Carpena et al. 2022). Carrageenan, the primary algal group of red seaweed, has been extensively studied for its wide range of biological activities, including its antitumor, antiproliferation, antiviral and anticoagulant activities (Guo et al. 2019; Cotas et al. 2020a, 2020b, 2020c; Jazzara et al. 2016; Gomaa & Elshoubaky et al. 2016; Carlucci et al. 1997). Agar is a mixture of polysaccharides with similar functional properties to carrageenan, exhibiting antiviral, anti-diabetic, anti-colon cancer and anti-inflammatory properties (Ślusarczyk & Czerwik-Marcinkowska 2021; Geetha & Tuvikene 2021; Hardoko et al. 2015; Yun et al. 2021; Lee et al. 2018).

The amount of protein in red seaweed varies depending on the species and other conditions such as season, temperature, and light (Cotas et al. 2020b). Protein content ranges from 35 to 47%, which is comparable to or higher than that of legumes and soybeans (Murata & Nakazoe 2001). Most total proteins found in red seaweeds are phycobiliproteins, which also give these species their characteristic red color and are widely used as natural colorants in food and cosmetics (Francavilla et al. 2013). This compound has medicinal potential due to its antioxidant and anti-inflammatory activities (Kim et al. 2018; Lee et al. 2012, 2017). Recently, bioactive peptides with therapeutic and anti-inflammatory effects have attracted particular attention (Lee et al. 2015). In addition, it has shown great therapeutic potential in the lectin of red seaweed, which has anti-inflammatory, hypoglycemic and antioxidant effects (Alves et al. 2020; Mesquita et al. 2021). Furthermore, red seaweed contains numerous glycine, arginine, alanine, and glutamic acids, including mycosporine-like amino acids, which have been demonstrated to provide UV protection and antioxidant characteristics (De et al. 2009; Karsten et al. 1998; Sun et al. 2020).

Palmitic acid, EPA, arachidonic acid, oleic acid, linoleic acid (LA), and alpha-linolenic acid (ALA) are the main fatty acids in the red and brown seaweeds. Red seaweed in Japan and South Korea mainly contains docenoic acid, and *Undaria pinnatifida* and kelp mainly contain arachidonic acid (Dawczynski et al. 2007; Tamama 2021). Despite the low lipid content of their constituents, they include vital fatty acids for human health (Amador-Castro et al. 2021). Most sterols present in red seaweed are cholesterol and its derivatives, such as 24-propylidene

Table 2 The bioactivity and characteristics of red seaweeds

Compounds	Algae source	Activities	Mechanisms	References
Polysaccharide	*Gracilaria lemaneiformis*	Anti-aging	Through the insulin pathway, Daf-16 increased the adult lifespan of wild-type and polyQ nematodes	Wang et al. 2019
	Gracilaria lemaneiformis	Anti-inflammatory	Inflammatory responses were reduced by decreasing levels of TNF-α, IL-6, and IL-1β in the colon and MPO activity	Han et al. 2020
	Gracilaria lemaneiformis	Anti-obesity	Regulation of lipid metabolism and inhibition of fat accumulation in body organs through SCFAs dependent pathway	Sun et al. 2018
	Chondrus canaliculatus	Antioxidant, kidney and blood protectant	The antioxidant and therapeutic potential of MB-induced hematological and nephrotoxicity were simultaneously evaluated by its structural characteristics	Jaballi et al. 2019
Sulfated polysaccharide	*Gracilaria lemaneiformis*	Anti-Food Allergic	KU812 activation was inhibited by inhibition of P38 mitogen-activated protein kinase	Liu et al. 2016
	Porphyra haitanensis, *Gracilaria lemaneiformis*	Anti-diarrhea	Inhibition of immunoglobulin A secretion by inhibiting the release of proinflammatory cytokines	Liu et al. 2019
Sulfated oligosaccharide	*Gracilaria lemaneiformis*	Anti-allergic	Protected mice from food allergy by upregulating immunosuppression	Liu et al. 2020
	Gracilaria lemaneiformis	Immunoregulation	MTOR signaling and T cells were regulated to inhibit their activation and IFNγ production	Liu et al. 2022
Carrageenan	*Gigartina pistillata*	Antitumour	Structural identification was performed by FTIR-ATR, and the area of tumor spheres and viability of SW620 and SW480 cells were evaluated	Cotas et al. 2020a, 2020b, 2020c
	Laurencia papillosa	Anti-proliferative	The proliferation of MDA-MB-231 cells was inhibited by up-regulating pro-apoptotic genes caspase-8, caspase-9 and caspase-3	Jazzara et al. 2016
	Acanthophora specifira	Antiviral		Gomaa & Elshoubaky et al. 2016
	Gigartina skottsbergii	Anticoagulant, anti-herpes simplex virus	Carrageenan binds to viral envelope glycoproteins and prevents the virus from binding to cell-surface receptors	Carlucci et al. 1997
Agar	Red seaweed	Antiviral		Geetha & Tuvikene 2021
	Gracilaria gigas	Antidiabetic		Hardoko et al. 2015
	Red seaweed	Anti-colon cancer	Inhibits proliferation and induces apoptosis of human colon cancer cells	Yun et al. 2021
	Gelidium amansii	Anti-inflammatory	Anti-inflammatory is achieved by increasing the production of anti-inflammatory cytokines and levels of lipolysis proteins	Lee et al. 2018

Table 2 (continued)

Compounds	Algae source	Activities	Mechanisms	References
Glycoprotein	*Porphyra yezoensis*	Anti-inflammatory	It plays an anti-inflammatory role by regulating TLR4 signaling, thereby inhibiting the activation of NF-κB and MAP kinases	Shin et al. 2011
Phycobiliproteins	*Palmaria palmata*	Anti-inflammatory	Anti-inflammatory activity was assessed by stimulation of macrophages and paw edema in mice induced by carrageenan	Lee et al. 2017
	Palmariapalmata	Anti-inflammatory	Tumor necrosis factor-*α*, interleukin-6, and nitric oxide levels were reduced in murine macrophages (RAW 264.7 cells), as was proinflammatory mediator secretion	Lee et al. 2012
	Porphyra haitanensis	Antitumor	By increasing the immune and antioxidant capacity of S180 tumor-bearing mice, it promoted apoptosis by increasing protease gene expression and TNF-*α* secretion	Pan et al. 2013
	Pyropia yezoensis	Antioxidant	Nrf2-sod pathway is involved in phycoerythrin mediated antioxidant effects	Kim et al. 2018
Bioactive peptide	*Pyropia yezoensis*	Anti-inflammatory	Macrophages were stimulated to exert potent inhibitory activity, reducing the release of proinflammatory cytokines (inducible NO synthase, cyclooxygenase-2, interleukin-1*β*, and tumor necrosis factor-*α*) in a dose-dependent manner	Lee et al. 2015
Lectin	Amansia multifida	Anti-inflammatory	Edema formation is reduced by modulating the action of vascular mediators, neutrophil migration, proinflammatory cytokines, and oxidative stress control	Mesquita et al. 2021
	Bryothamnion seaforthii	Antihyperglycemic, antioxidant	Decrease insulin resistance and improve pancreatic *β* cell function and enzyme activity	Alves et al. 2020
Mycosporine-like amino acids	*Chondrus crispus*	Ultraviolet light protection		Karsten et al. 1998
	Gelidium corneum *Ahnfeltiopsis devoniensis*	Antioxidant	Water-soluble free radicals, antioxidant activity in lipid media and superoxide free radical scavenging ability were evaluated	De et al. 2009

Table 2 (continued)

Compounds	Algae source	Activities	Mechanisms	References
Fatty acid	*Palmariapalmata*	Anti-inflammatory	Inhibit lipopolysaccharide-induced nitric oxide production in RAW264.7 macrophage cells	Banskota et al. 2014
	Grateloupia turuturu	Antioxidant, anti-inflammatory	The radical removal of p-2, 2-diphenyl-1-sulfamide (DPPH) and 2,2′-azino-bis-3-ethyl benzothiazoline-6-sulfonic was evaluated. The potential to carry out acid (ABTS) free radicals and anti-inflammatory activities were evaluated based on the ability to inhibit cyclooxygenase 2 (COX-2) enzyme	Da et al. 2021
Sterol	*Laurencia papillosa*	Antibacterial	The antibacterial activity was tested on Gram-negative human pathogens and the active components were characterized	Kavita et al. 2014
Polyphenol	*Eucheuma cottonii*	Tumour-suppressive	The tumor was inhibited by inducing apoptosis, down-regulating endogenous estrogen biosynthesis and improving the antioxidant status of rats	Namvar et al. 2012
	Laurencia undulata	Anti-asthmatic	Inhibition of OVA-induced airway hyperresponsiveness and inflammation in asthmatic mice	Jung et al. 2009
Bromphenol	*Symphyocladia latiuscula*	Anti-alzheimer's disease	It was characterized by inhibition of cholinesterases (AChE and BChE), β-site amyloid precursor protein lyase 1 (BACE1), and glycogen synthase kinase	Paudel et al. 2019
	Vertebrata lanosa	Antioxidant		Olsen et al. 2013
	Symphyocladia latiuscula	Antioxidant	It protects HaCaT skin cells from oxidative damage through NrF2-mediated pathway	Dong et al. 2021
	Polysiphonia morrowii	Anti-inflammatory	Inhibit LPS-induced inflammation by inhibiting ROS-mediated ERK signaling pathway in RAW 264.7 macrophages	Choi et al. 2018
Carotenoid	*Gracilariopsis tenuifrons*	Antioxidant		Zubia et al. 2014
	Red seaweed	Anti-inflammatory, anticancer		Ávila-Román et al. 2021
	Gracillaria sp.	Anticancer	It effectively attenuates the growth of human hepatocellular carcinoma (HepG2) cells by regulating various molecular pathways	Kavalappa et al. 2019
Alkaloids	*Gracilaria* sp.	Anti-Inflammatory		Souza et al. 2020
	Gracilaria edulis	Antibacterial		Kasanah et al. 2019

cholest-5-en-3β-ol, a compound that could be used as a potential lead molecule in the development of anti-broad-spectrum drugs (Kavita et al. 2014).

Red seaweeds are mostly represented by phenolic acids and flavonoids among phenolic compounds. Additionally, In addition, phenolic compounds (phlorotannins and bromphenol) unique to Marine sources, although in small quantities, have strong antioxidant activity (Cotas et al. 2020a; Dong et al. 2021; Olsen et al. 2013). It possesses anti-AIDS and anti-inflammatory properties in addition to its antioxidant action (Choi et al. 2018; Paudel et al. 2019). Carotenoids are thought to be one of the major terpenoids found in red seaweed and also contribute to their special pigmentation, mainly represented by α-carotenes and β-carotenes, lutein and zeaxanthin. This carotenoid has antioxidant, anti-inflammatory and anticancer properties, which may reduce the risk of eye disease in humans (Ávila-Román et al. 2021; Cotas et al. 2020b; Holdt & Kraan 2011; Kavalappa et al. 2019; Zubia et al. 2014). Red seaweeds of the *Gracilaria genus* have been identified as excellent sources of these Marine alkaloids, and their anti-inflammatory and antimicrobial mechanisms of action have been extensively characterized (Kasanah et al. 2019; Souza et al. 2020).

At present, polysaccharide is still the most studied functional component, but the research on red seaweed polysaccharide mainly focuses on monosaccharide composition, molecular weight, etc., but there are still few reports on its advanced structure. In addition, although there are many research on the active ingredients of red seaweed, there is a lack of in-depth pharmacological research and clinical trial research. In conclusion, to realize the further development and application of red seaweed active ingredients, these problems and challenges must be solved first. It is believed that soon, the application of red seaweed functional activity in the medical field will no longer be a limitation.

Green seaweeds

There are over 6700 species of green seaweed in the world, the majority of which live in fresh water. Despite their microscopic size, they are bursting with life and contain nearly all of the nutrients required for human survival. It is regarded as the most ideal diet of the twenty-first century by the United Nations FAO due to its high protein, low fat, low sugar, and low cholesterol content. The bioactive compounds of green seaweed and their important bioactivities are summarized in Table 3.

Enteromorpha, *Ulva*, and *Chlorella* are the most prevalent green seaweed. *Ulva* and *Enteromorpha* are rich sources of polysaccharides from green seaweed, especially *Ulva* (total polysaccharide content up to 65% of dry weight). Green seaweed polysaccharide is a kind of acidic polysaccharide (such as sulfated polysaccharides, sulfated galactans and xylans) located on the cell wall of green seaweed. It has special molecular structure and can play a variety of biological functions by regulating cell signal transduction function, such as anti-hyperuricemia, anti-oxidation, anti-coagulation, anti-virus, and blood glucose regulation (Cao et al. 2022; Chen et al. 2022; Li et al. 2017, 2021a, 2021b; Lin et al. 2020; Wang et al. 2020a, 2020b, 2013a, 2013b; Wassie et al. 2021; Wu et al. 2020). *Chlorella* is a type of single-celled green seaweed. It grows quickly and is the only plant that may double in size in 20 h. *Proteinucleococcus* has high protein content and can be used as high nutritional value food. It contains bioactive glycoproteins, polysaccharides and up to 13% nucleic acid and has antioxidant, immunomodulatory, anti-aging, and anti-tumor properties (Chen et al. 2018a, 2018b; Tanaka et al. 1998; Wan et al. 2021; Yang et al. 2006). Lectins are one of the protein types binding to carbohydrates or substances in a reversible manner. It has been reported that green seaweed lectins can show potent anti-influenza virus activity with the help of high affinity binding to viral hemagglutinin (Mu et al. 2017).

Because green seaweed contains just 5% fat and very little cholesterol (mostly in the form of sitosterol), there is no risk of elevated cholesterol from animal protein. The fats in green seaweed are mainly unsaturated fatty acids, of which EPA and DHA are important unsaturated fatty acids in marine lipids, which are mainly produced by Eustigmatophyte species. They have potential therapeutic effects in cardiovascular disease, Alzheimer's disease, hypertension, coronary artery disease, arthritis, and cancer (Leone et al. 2019; Peltomaa & Taipale 2017; Van et al. 2011).

The antioxidant qualities of β-carotene produced by the microalgal *Dunaliella salina* help to regulate the detrimental effects of free radicals, which have been related to a variety of life-threatening disorders, including cancer, coronary heart disease, premature aging, and arthritis. It may also aid the body in combating the effects of ultraviolet light-induced accelerated aging (Dembitsky & Maoka 2007; Miyashita 2009). *Haematococcus pluvialis* is known to produce astaxanthin, a blood-red carotenoid whose antioxidant properties give astaxanthin an interesting therapeutic potential as an anti-cancer, anti-diabetic, and anti-inflammatory agent (Ambati et al. 2014; El-Baz et al. 2018). Compared with brown seaweed, green seaweed contains relatively few polyphenols. Preliminary studies have shown that *Enteromorpha prolifera* can demonstrate anti-inflammatory and hypoglycemic effects by regulating signaling pathways (Huang et al. 2022; Yan et al. 2019).

Although there has been some advancement in recent years in the study of structure and activity, particularly in the study of the polysaccharide activity of green seaweeds, other green seaweeds active components have not yet been fully developed and utilized, and the specific biological active components have not been fully explored. Research on the mechanism of action is also necessary.

Table 3 The bioactivity and characteristics of green seaweeds

Compounds	Algae source	Activities	Mechanisms	References
Polysaccharide	*Ulva lactuca*	Antihyperuricemic	Regulating urate transporters	Li et al. 2021a, 2021b
	Ulva lactuca	Hypoglycaemic, anti-ageing	By regulating the expression levels of p16Ink4a, MMP2, FoxO1, GLP-1/GLP-1R, STAT3 and GLUT4, it can improve the aging and diabetes status	Chen et al. 2022
	Enteromorpha prolifera	Antioxidant	Down-regulation of miR-48, miR-51 and miR-186 up-regulated the expression of SKN-1 and DAF-16, thereby improving the accumulation of intracellular reactive oxygen species and DNA damage	Lin et al. 2020
	Chlorella pyrenoidosa	Antioxidant	Down-regulation of Mir-48-3p, Mir-48-5p and Mir-51-5p translocation up-regulated the expression of DAF-16 and SKN-1 genes	Wan et al. 2021
	Chlorella pyrenoidosa	Immunomodulatory	T cells were activated by delayed hypersensitivity reaction and antibody titer was increased	Yang et al. 2006
	Chlorella pyrenoidosa	Anti-ageing	Physicochemical properties as well as antioxidant in vitro and anti-aging activity in vivo were evaluated	Chen et al. 2018a, 2018b
Oligosaccharide	*Enteromorpha prolifera*	Hypoglycemic	Induced high expression of GLP1 receptors in the brain, thereby controlling glucose metabolites through the brain-gut axis	Ouyang et al. 2022
	Ulva lactuca	Hypoglycemic, antioxidant	Regulate microRNAs in *Caenorhabditis elegans*	Wu et al. 2020
Sulfated Polysaccharide	*Monostroma angicava*	Anticoagulant	thrombin inhibitor mediated by heparin cofactor II	Li et al. 2017
	Monostroma nitidum	Antiviral	EV71 infection was inhibited by targeting the PI3K/Akt pathway or viral particles	Wang et al. 2020a, 2020b
	Caulerpa racemosa	Anti-inflammatory	antinociceptive and anti-inflammatory activities in a way dependent on HO-1 pathway activation	Ribeiro et al. 2014
	Enteromorpha clathrata	Anti-obesity	Reducing obesity by increasing the intestinal abundance of the butyrate producing bacterium *Eubacterium xylophile*	Wei et al. 2021
Sulfated oligosaccharide	*Ulva lactuca*	Anti-tumor, immunomodulatory	Enhance the expression of p53, promoted the activation of IKKα, and inhibit the activation of P65 in NF-κB pathway	Zhao et al. 2020
Glycoprotein	*Chlorella vulgaris*	Anti-tumor	Enhances anti-metastatic immunity by activating T cells in lymphoid organs	Tanaka et al. 1998
Lectin	*Halimeda*	Anti-Influenza	It exhibits effective anti-influenza virus activity through high affinity binding with viral hemagglutinin	Mu et al. 2017
Unsaturated fatty acid	*Ulva lactuca*	Antioxidant	Nrf2 is stabilized by inhibiting Keap1-mediated ubiquitination of Nrf2 and subsequent accumulation and nuclear translocation of Nrf2	Wang et al. 2013a, 2013b

Table 3 (continued)

Compounds	Algae source	Activities	Mechanisms	References
Phytosterols	*Dunaliella tertiolecta*	Reduce cell proliferation	N-3 polyunsaturated fatty acids induced anti-inflammatory cytokine profiles, while increasing IL-10, IL-6 and decreasing IL-1β	Ciliberti et al. 2017
	Chlorella sp. S14	Antiproliferative, Antioxidant	By cytotoxic effects on MCF-7 and A549 cells, regulation of CAT activity, GSH and MDA levels, and inhibition of nitric oxide production	Vilakazi et al. 2021
Carotenoid	Codium cylindricum	Antioxidative	To protect the body stress caused by obesity by restoring the antioxidant signal regulated by Nrf2	Zheng et al. 2020a, 2020b
	Dunaliella salina	Antioxidative		Chidambara et al. 2005
	Haematococcus pluviali	Antioxidative		Régnier et al. 2015
Polyphenol	*Enteromorpha clathrata*	Anti-inflammatory	Inhibition of MAPKs/NF-κB signaling pathway alleviated LPS-induced inflammation in RAW 264.7 cells	Huang et al. 2022
	Enteromorpha prolifera	Antidiabetic	Hypoglycemic effects were demonstrated by activation of IRS1/PI3K/AKT and inhibition of the hepatic JNK1/2 insulin pathway	Yan et al. 2019

Although the application of seaweed active substances has developed rapidly in recent years, the following problems still need to be solved: most studies on anti-tumor peptides from seaweed currently ignore peptide preservation, which is very unfavorable for peptides with unstable chemical properties. It is useful to improve the stability of anti-tumor active peptides from seaweed by developing existing active peptide preservation and delivery technologies, such as encapsulation of chitosan nanoparticles and administration of multi-encapsulated liposomes. Furthermore, the active substance of seaweed extract must be produced in a more efficient manner. The method of trehalose synthase catalytic synthesis is simple and low-cost. However, it has some advantages of high energy consumption material, but the enzyme also has some disadvantages, such as resistance to high temperature and pH. To tackle this challenge, trehalose synthase's structure and function need to be learned more. In addition, seaweed extracts are limited to purify the active substance. If the purification enhanced, it will be helpful to further study its function and excitation, which is also the future research direction of seaweed extract. It is worth emphasizing that most of the bioactive studies currently being conducted are non-human including in vitro and in vivo animal models. However, due to the different enzyme catalytic centers and the complexity of organisms, the applicability and safety of algal bioactive substances as drugs for further research remain to be solved. Therefore, the stability, spatial structure, and physiological function of these bioactive substances still need to be further studied.

Seaweed farming technologies

Early algae were mainly from natural growth, and people mainly collected wild algae (Tseng et al. 2001). With the growing market for food industrial and medical use of seaweed products, the wild seaweed resources are limited, which has promoted the seaweed farming. Seaweed culture can be cultivated on land, sea, desert and even in integrated aquaculture system. Even the seaweed farming technology is not different in essence, there are obvious differences in culture methods due to the different environment.

Land farming

The cultivation of algae on land is mainly in closed systems such as water tanks, ponds, lagoons, and pipelines (Sara et al. 2020). The culture method is suitable for a wide range of seaweed genera. It has simple and easily accessible equipment that allows real-time monitoring and effective regulation of seaweed culture conditions (nutrients, light, pH value, CO_2 and salinity) to produce more target products. However, land-based aquaculture occupies scarce cultivated land and water resources, which requires high maintenance cost and cannot achieve mass production. In recent decades, there has also been a way to use saline alkali groundwater for algal culture (Sara et al. 2020), using the existing salt water resources at low cost and high economic efficiency. A circular culture system was developed to reduce the cost by reducing the required medium (Sebök et al. 2017).

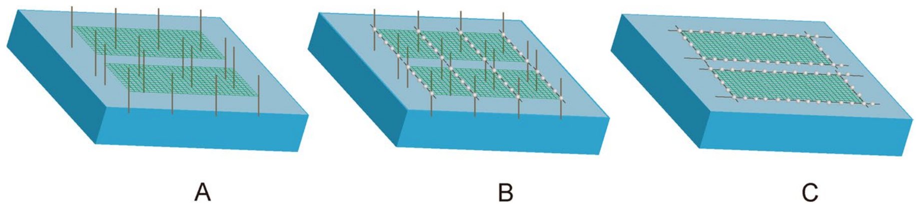


Fig. 5 Three farming techniques of seaweed. A: pillar type; B: Semi floating raft: C: full floating raft composed of long rope and floating ball

Mariculture

Inshore shallow water aquaculture is carried out in the sea area close to the land and is the main method of algae culture, at sea depth of 5–50 m, using fixed piles off the bottom. It has sufficient land nutrients and benefits from moderate seawater velocity and wind wave degree. To meet the growing demand for seaweed products, the field of seaweed culture has extended outward, and there is a way of offshore deep-water culture that relies on floating rafts or long ropes to make culture rafts (Fig. 5). Mariculture does not occupy scarce land resources. Compared with shallow sea culture, offshore deep-water culture is greatly affected by uncertainties such as wind and waves, and alien species, and is difficult to manage and costly to maintain. It has high requirements for breeding equipment, seaweed varieties and technology, which has not been popularized. Semi floating rafts and supporting rafts are mostly used in intertidal aquaculture, with high requirements for the selection of sea areas. Due to the increasing breeding density, pest and disease problems occur frequently, inshore aquaculture appeared, which does not occupy scarce land resources and is free from the impact of marine turbulence. Desert farming technology through water and nutrient recycling effectively exploits the rich desert resources and alleviates the shortage of land resources (Buschmann et al. 2017).

Integrated aquaculture system

In the integrated aquaculture recycling system, the algae can absorb nitrogen and phosphorus from the waste produced by aquatic products and serve as feed when algae and aquatic products are mixed. The cultivation of seaweed in this cycle system can reduce marine eutrophication and repair the damaged marine ecological environment system better (Sun et al. 2016). Sashimi seaweed quantitative ecological breeding model was developed. The advantages of high yield and benefit by using kelp culture raft for large-scale economic algae and sea cucumber multi variety rotation culture was proved. Algae-bacteria symbiotic system is used for algae culture to treat organic wastewater and human and livestock waste. The integrated high-rate algal ponds (HRAP) system is applied for wastewater treatment and algae production. However, the system has too many links and is inefficient. It is only suitable for large-scale aquaculture in ponds and lakes, but not for industrial aquaculture. Moreover, the seaweed seedling raising technology in China is weak and the supply of seedlings is insufficient to meet the demand for year-round supply of seedlings for this system.

Seaweed processing and applications

Current status of development

The Financial Times has reported that the global population will rise to 10 billion by 2050. And algae could supply the protein needed for people while conserving natural resources (Koyande et al. 2021). Because algae grow 10 times faster than terrestrial plants, less than one-tenth of the land is needed to produce the same amount of biomass. The growth of algae does not compete with other crops for land and does not require fresh water. It fertilizes more efficiently than land crops, and avoids the intensive water use, fertilizer wasting, and downstream eutrophication associated with modern agriculture (Tzachor 2019). Therefore, seaweed has aroused great interest as for these advantages around the world, especially in Asia, Europe, and South America, as well as in North America and Australia. Particular attention has been paid to seaweed resource processing and utilization (García-Poza et al. 2020). Forbes reported that the market for algal products was expected to be approximately $4 billion in 2018, growing to $5.2 billion by 2023 (Kite-Powell 2018). In the past twenty years, algae contain high levels of minerals, dietary fiber, and low fat levels, which has regarded as an attractive raw material in food, medicine, chemical industries, and even as the natural source of CO_2 and biomass energy.

Current extraction techniques

In recent decades, research on extracting bioactive ingredients from natural resources have attracted special attention. Studies have shown that many ingredients have a variety of biological characteristics and potential industrial application prospects. Therefore, it is necessary to find new technologies for improving the production of algae extracts, instead of choosing extraction conditions which are time consuming, low selectivity, low efficiency and harmful for human health. In this paper, the extraction methods of algae oil and the extraction techniques of volatile substances from algae in recent years are summarized, and the new extraction techniques such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), supercritical fluid extraction (SFE), pressurized solvent extraction (PSE), and enzyme-assisted extraction (EAE) are introduced. Additionally, the traditional extraction technology is compared with the new extraction technology in order to better develop and utilize algae resources (Table 4).

MAE is a relatively new extraction technique that combines microwave and traditional solvent extraction. The use of microwave radiation, which generates heat directly in the matrix through the friction and collision between molecules, has been used to extract seaweed hydrocolloids and other derivatives from red and brown seaweeds to obtain high quality seaweed hydrocolloids with less extraction time and solvent consumption. Compared to the traditional methods of extracting compounds from natural products, MAE has shorter extraction time, less solvent, higher extraction rate, and lower cost (Delazar et al. 2012).

UAE can be carried out at low temperatures by taking advantage of the vibration cavitation effect of ultrasonic waves, which reduces heat loss from high temperatures and prevents bioactive substances. It is suitable for the extraction of heat-resistant compounds and is simpler and faster than microwave-assisted extraction and has great potential for large-scale production (Chandrapala et al. 2013). However, the process is also affected by many factors such as extraction time, microwave power, and solid–liquid ratio. Currently, this technique has been used in the extraction of many plant materials by significantly reducing extraction time and increasing the maximum extraction rate (Ma et al. 2010; Surin et al. 2020).

SFE is a process of extracting valuable substances by using solvents at pressures and temperatures above critical points, which is environmentally friendly, inexpensive, widely available, non-flammable, and timesaving. Carbon dioxide and water are the most common uses of supercritical fluids. Hydrocolloid from marine algae contains many bioactive substances that are susceptible to degrade at high temperatures. SFE-CO_2 provides a non-oxidizing atmosphere during the extraction, thus preventing the degradation of the extract. Kumar extracted total phenols with antioxidant activity from brown seaweed (*Sargassum wightii* and *Turbinaria*), and this activity was greatly improved compared to the traditional organic solvent extraction method (Kumar et al. 2020). Although extracting algal flavor compounds usually takes several hours, it is expensive and difficult for machines to clean (Dmytryk et al. 2015).

PSE is a relatively new automated technique that extracts target compounds at 200℃ and 3000 psi, using solvents or mixtures of solvents with low boiling points. The solubility, solvent diffusivity and mass transfer rate increased significantly by PSE method, while solvent viscosity and surface tension decreased significantly. Compared with SFE, PSE extraction can use a wider range of solvents. However, PSE is not suitable for heat-resistant compounds that are sensitive to high temperature and high pressure and is not selective for SFE. It has been shown that the extraction of carotenoids from *Dunaliella halogensis*, as well as kavanolides from pepper, can yield higher yields with less solvents in a shorter time while maintaining chemical integrity (Hossain et al. 2011).

EAE uses specific enzymes to break down unwanted components of the cell wall, thereby releasing the desired components. Compared with the traditional water extraction method, this method has the advantage of high catalytic efficiency, and retains the original effect of the compound to a large extent. Billakanti et al. (2012) extracted haloxanthine from wakame by alga lyase hydrolysis with the optimum temperature at 37℃ and pH at 6.2 to yield well performing bioactive compounds.

It is necessary to select appropriate extraction technologies for different active substances. In particular, the combination technology has great potential to minimize the degradation of bioactive compounds caused by different extraction steps. Many bioactive substances from seaweed play an important role and have promising applications in functional foods, health care products, cosmetics, and medicine. However, more researches are needed to improve modern extraction technologies to enlarge industrial scale.

New applications

Food industry

Today, seaweed is as widely used as a vegetable. In many Asian countries, seaweed is an important part of human diet in its fresh, dried, flaky, and flour form. Commercial production of seaweed has been the focus of seaweed research in the past, but recently the researches has been a shift towards high-value products with health benefits. Studies have shown that adding *Chlorella* to foods (such as pasta and biscuits) can improve the nutritional quality of the diet. *Chlorella* and *Spirulina* are mostly applied in tablet, capsule, and liquid form for nutritional supplements because of their high nutritional value and ease of growth. Moreover, an edible cyanobacterium *Spirulina platensis* has gained worldwide attention as a food additive due to its high nutritional value as a human food (Andrade et al. 2018; Batista et al. 2017; Martelli

Table 4 Extraction methods of seaweed processing and their advantages and disadvantages

Classification	Advantage	Shortage	Species	Reference
Extraction in Soxhlet apparatus	Simple operation, relatively safe; reliable, effective and efficient; Suitable for lipid extraction	Small scope of application; Alcohol—water mixtures or non-polar solvents are involved	*Chlorella* sp.	Ramluckan et al. 2014; Aravind et al. 2021
Hydrothermal liquefaction	Different strains with high water content were transformed into high bio-oil yield; low coke and low energy consumption	Solvent influence, applicable scope is small	Microalgae	Vua et al. 2021; Chiaramonti et al. 2017
Simultaneous distillation extraction	Extraction of trace components, non pre-drying of biomass, cost saving	Large sample size, complex operation, easy to produce by-products	*Nannochloropsis oculata* (N. oculata); *Dunaliella salina* (D. salina)	Tanzi et al. 2013
Vacuum hydrodistillation for extraction	Non high temperature, conducive to low boiling point and high boiling point compounds extraction	Some volatile compounds may be lost or changed during concentration		LePape et al. 2002
Liquid–liquid extraction	Continuous extraction; Minimizes the viability of microalgae	Extraction solvent is large; most of the solvent is toxic; more difficult to deal with	Microalgae; Dunaliella *salina*	Marchal et al. 2013
Dynamic headspace extraction	Flexible; Widely used; No need to heat the initial product	Complex: Concentration is difficult to achieve; Extract only low-boiling compounds	*Palmariapalmata;Spirulina platensis*	Pape et al. 2004; Aguero et al. 2003
Solid phase microextraction	Simple and fast operation; Low sample demand; Solvent-free sampling technique; Widely used; It can be used to analyze volatile compounds	Insensitive to low volatile substances	Green, brown, and red algae	Alonso et al. 2003
Pulsed electric field	Irreversible electroporation inactivates microorganisms; Helps release substances from plant cells; Fast green	Size limit	Microalgae	Joannes et al. 2015
Microwave-assisted extraction	Short extraction time; less solvent; high extraction rate and low cost	Sensitive to heat and pressure; Energy is needed to provide radiant power; Additional separation processes are required to remove solids or unwanted materials from the solvent	Brown seaweeds	Delazar et al. 2012; Michalak & hojnacka; 2014
Ultrasound-assisted extraction	Easier to operate; Faster; Mass production; Good solubilizing effect; Energy saving and environmental protection	Used for heat resistant compounds; Extraction time; Microwave power; Influence of solid liquid ratio	Brown alga *Sargassum*	Chandrapala et al. 2013; Ma et al. 2010; Surin et al. 2020
Supercritical fluid extraction	Environmental protection, cheap, widely available, non-flammable, time-saving	High cost; The machine is difficult to clean; The extraction range of compounds is small; Polar compounds are not applicable	Brown algae *Fucus vesiculosus*; Nannochloropsis sp.; marine algae *Fucus vesicu-losus*; *Laminaria*	Kumar et al. 2020; Dmytryk et al. 2015; Güçlü-Üstündağ et al. 2005
Pressurized solvent extraction	Common use; Fewer solvents yield more in a shorter time; Maintain the integrity of chemical composition	Sensitive to high temperature and pressure; Produces non-selective compound extraction; High initial cost	*Haematococcus pluvialis*; *Dunaliella salina*	Hossain et al. 2011; Turner & Waldebäck 2013; Reighard & Olesik 1996; Denery et al. 2004

Table 4 (continued)

Classification	Advantage	Shortage	Species	Reference
Enzyme-assisted extraction	Biocompatibility, non-toxic; environmental protection; high catalytic efficiency; Retain the properties of the compound	Long time, high temperature, low extraction efficiency	Nordic seaweeds; *Scenedesmus* sp.; brown macroalgae	Billakanti, 2012; Nguyen et al. 2020

et al. 2020). It has proven to be a rich source of protein, polyunsaturated fatty acids, and pigment. Clearly, the food industry is beginning to focus on developing high-value non-commercial products for human health. In the future, many seaweeds are likely to become important components of functional products.

Agriculture

Farmland natural ecology is currently deteriorating due to excessive usage of artificial fertilizers and pesticides. Seaweed is abundant in unique mineral elements, nutrients, and biologically active chemicals. In recent years, agricultural output has played an increasingly vital role. Seaweed can be utilized as a protectant for diseases and as a stimulant in horticulture, promoting and enhancing all aspects of plant growth and development (Battacharyya et al. 2015). Green seaweed *Ulva* crude extracts and sulfated polysaccharides have antibacterial activity against common bean (*Phaseolus vulgaris L.*) anthracnose, as well as considerably promoting soybean growth (Paulert et al. 2009). Furthermore, seaweed can boost the ability of plants to absorb nutrients, hence improving plant quality. A new study showed that leaf spraying and seed soaking can significantly improve the yield and nutritional quality of carrots treated with seaweed (*Sargassum vulgare*) extract (Mahmoud et al. 2019). Seaweed is a valuable animal feeding as well as a source of agricultural chemicals. A variety of algal diets have been utilized to grow a range of fish, shrimp, crabs, and shellfish throughout the last two decades. The most commonly alga are *Chlorella*, *Spirulina*, and other microalgae (Kim et al. 2006). Many minerals remain in the waste biomass after cyanobacteria recovering oil and carbohydrate, which can be used as fertilizers to improve various physical and chemical properties of soil while boosting yield and conserving fertilizer nitrogen. The Asia–Pacific region accounted for more than 15% of global seaweed fertilizer market revenue in 2017. By 2025, the global market for seaweed fertilizer is estimated to reach 17.1 million US dollars. Organic agriculture is gaining traction, and the usage of seaweed fertilizer is on the rise. As a result, seaweed processing is predicted to become a key resource guarantee in green and modern agriculture.

Biological medicine

In medicine, seaweed has attracted a lot of attention as a potential source of various drug properties. In the last two decades, seaweed polysaccharides have been shown to have a variety of promising biological activities, such as anti-tumor (Zhao et al. 2020), immunomodulatory (Huang et al. 2015), antioxidant (Maheswari et al. 2021), anti-hyperglycemic (Pantidos et al. 2014), anti-cancer (Lee et al. 2013), antiviral, anti-fungal (Pallela & Kim, 2011), anti-diabetic (Lin et al. 2018; Zhao et al. 2018), anti-hypertensive (Seca & Pinto 2018), anti-inflammatory, uv-protective, and neuroprotection effects (Schepers et al. 2020). Meanwhile, algal hydrogels and hydrocolloids are valuable components in the medical field, which are widely used in wound healing, drug delivery, in vitro cell culture and tissue engineering (Senthilkuma et al. 2017). These gels maintain structural similarity to the extracellular matrix in tissues and can be manipulated to perform several key roles. Although some specific drug-specific gels have been clinically used for wound healing, they play a rather passive role. In wound healing and drug delivery applications, there is a great need for precise control of single drug delivery versus multiple drug delivery, or continuous and sequential release in response to changes in the external environment, which is useful for future development of products (Lee & Mooney 2012).

Chemical industry

For nearly 20 years, the bioactive substances from macro- and micro-algae are popular in the cosmetic industry. Compared with terrestrial plants, algae contain many unique and novel bioactive ingredients such as polyphenol compounds, halogen, terpenoids, sterol compounds, unsaturated fatty acids, and polysaccharides in addition to vitamin, protein, minerals and trace elements (López-Hortas et al. 2021). Various algal composition as a thickener, water binder, antioxidant, and UV blockers, are present in a variety of facial and skin care products (such as masks, eye creams, and sunscreens) to improve moisture balance, reduce wrinkles, and improve skin tone (Priyan Shanura Fernando et al. 2018; Wijesinghe & Wedamulla 2019). Thus, seaweed could be a sustainable and profitable source of bioactive substances with the growing demand for cosmetics and cosmetic ingredients.

Other applications

Algae is a decent candidate because of its renewable and sustainable features, as well as its economic viability meeting the world's demand of fuels for transportation. Algae can be used to produce biodiesel, bioethanol, biohydrogen, and biomethane. And it is particularly popular in energy applications due to its high safety, lack of competition from food crops, high reproductive capacity, and short cycle (Adeniyi et al. 2018). In addition, algae has been used in the construction industry. Vijayaraghavan and Joshi (2015) developed a new alga-based green roof growth matrix, which found that the green roof's runoff quality improved after adding brown seaweed (*Turbinaria conoides*) to the growth matrix. It can improve building insulation, rainfall attenuation, sound insulation, and lessen the heat island effect and extend the life of the roof. Besides, algae can also help to tackle the problem of eutrophication in water bodies. Green algae were utilized to treat municipal wastewater in ponds (Woertz et al. 2009). They may remove up to 99% of ammonium and phosphate under cultivation conditions, and then offer valuable wastewater treatment services and supply raw materials for liquid biofuel synthesis. Seaweed would encapsulate its value in a variety of industries due to its unique composition.

Challenges and solutions

Over the past 20 years, the situations of algal breeding and processing industry have risen steadily, which playing the active role in economic, social, and ecological aspects. Especially, the marine ecological problems have been alleviated due to the positive ecological benefits of breeding algae. However, this field still faces some challenges including the lack of improved varieties, poor growth environment, immature breeding and processing technology, shortage of cultivated land resources, and restrictions of relevant policies. Due to the continuous expansion of seaweed market and the increased demand for seaweed products, it is urgent to overcome their own and external constraints.

External challenges

The external challenges are mainly in the following aspects: global warming and sea-level rise lead to the declined seaweed biomass and quality. In order to deal with the harsh environment, the cost of breeding management including equipment maintenance, renewal and growth environment management has been increased. However, it is a burden for many low-income areas for the increase of technical investment in the development of high-quality seaweed species and processing products. Seawater eutrophication and the emergence of harmful algal blooms are happened due to rapidly expanding human activities (Yu et al. 2016). Harmful algal blooms usually contain the toxic substances. Accidental poisoning may occur by eating contaminated food (Lewitus et al. 2012). The environmental problems caused by the development of algae breeding and processing will eventually become factors affecting themselves. For example, halogenated hydrocarbons produced by many algae will affect the flux of ozone and ultraviolet rays. The density on growing environment is easy to bring about the invasion of alien species. The breeding equipment is the attachment base of the green algae. And the water body in the breeding area is relatively stable because a large number of rafts hinder the flow of sea water. With the increase of temperature, these large amounts of green algae reproduce and eventually enter the ocean to form a "green tide" (Yu et al. 2016). Microplastics in the ocean will be captured by cultured algae and spread to a higher nutritional level through the food chains, resulting in a significant burden on marine ecology.

Internal challenges

Seaweed production and processing technology does not match its increasing demand. At present, the cultivation of seaweed is mainly developed in some underdeveloped areas. Only a small number of countries such as China, have realized industrialized seedling raising, large-scale offshore cultivation, and mechanized harvesting, forming an industrial chain from product processing to sales. However, most countries mainly focus on basic cultivation, the automation of large-scale harvesting and processing are not high. It results in the unguaranteed quality, low efficiency, high employment cost, and processing waste. Most seaweed processed products are mainly used as edible and industrial raw materials. In recent years, large amounts of bioactive compounds from seaweed have been studied. However, the value-added products is generally low because of the lack of advanced techniques for extraction and purification (Pérez et al. 2016).

Response measures

The large-scale human activities at sea should be restricted, while the implement staggered peak aquaculture of algae and timely issue relevant water quality protection policies should be encouraged. Algae with high temperature resistance and disease resistance need to be cultivated. The advantages of algae should be used to solve problems and realize a virtuous cycle. For example, macroalgae can absorb carbon, nitrogen, and phosphorus in seawater through photosynthesis. The absorption of CO_2 can play the ability of marine carbon fixation. Algae can reduce nitrogen and phosphorus in the enrichment of waters by inorganic nutrients. *Ulva ohnoi* has been proved to be an ideal target species for bioremediation activities at land-based aquaculture facilities in eastern Australia (Lawton et al. 2013). Seaweed has also been used to treat anaerobic digestion piggery effluent (Nwoba et al. 2016). In the integrated multi-trophic aquaculture (Chopin et al. 2012), the waste nutrients released or excreted into the water in the aquaculture system can be used by algae as the source of nutrients, which can achieve the goal of recirculating aquaculture system and regulating water quality.

Conclusions

The development of seaweed farming is growing year by year. The seaweed farming technologies are constantly updated, and seaweed processed products are emerging. Therefore, seaweed plays a huge role in the economic, social, and ecological fields. It is rich in a variety of biological active substances as drug sources, cosmetics, and agricultural regulators, which have been largely developed. It is necessary to strengthen investment in seaweed farming and processing technologies and develop high value-added products with the integrated multi-trophic aquaculture, which have great market potential and need in-depth exploration.

Abbreviations
FAO: Food and Agriculture Organization; ARA: Arachidonic acid; EPA: Eicosapentaenoic acid; DHA: Docosahexaenoic acid; LA: Linoleic acid; ALA: Alpha-linolenic acid; HRAP: High rate algal ponds; MAE: Microwave-assisted extraction; UAE: Ultrasound-assisted extraction; SFE: Supercritical fluid extraction; PSE: Pressurized solvent extraction; EAE: Enzyme-assisted extraction.

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Authors' contributions
Lizhu Zhang, Wei Liao, and Yajun Huang: Formal analysis, Investigation, Resources, Writing- Original Draft, Writing- Review & Editing, Visualization. Yuxi Wen & Yaoyao Chu: Writing- Review & Editing. Chao Zhao: Conceptualization, Resources, Writing- Review & Editing, Visualization, Supervision, Funding acquisition. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors hereby declare no conflict of interest.

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