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Review article

Seaweed farming for food and nutritional security, climate change mitigation and adaptation, and women empowerment: A review

Fahmida Sultana [a], Md Abdul Wahab [b], Md Nahiduzzaman [b], Md Mohiuddin [a], Mohammad Zafar Iqbal [a], Abrar Shakil [a], Abdullah-Al Mamun [c], Md Sadequr Rahman Khan [a], LiLian Wong [d], Md Asaduzzaman [a,*]

[a] Department of Marine Bioresource Science, Faculty of Fisheries, Chattogram Veterinary and Animal Sciences University, Khulshi, Chattogram, 4225, Bangladesh
[b] ECOFISH-II Activity, WorldFish, Bangladesh and South Asia Office, Banani, Dhaka, 1213, Bangladesh
[c] Department of Fisheries and Marine Science, Noakhali Science and Technology University, Noakhali, 3814, Bangladesh
[d] Institute of Marine Biotechnology, Universiti Malaysia Terengganu, Kuala-Terengganu, Terengganu, 21030, Malaysia

A R T I C L E I N F O

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A B S T R A C T

Seaweed is a promising marine macroalgae of the millennium, providing various ecological, social, and economic benefits. At present, seaweed production reached 35.8 million t from farming, accounting for 97% of global seaweed output, with a world market of US$ 11.8 billion. Seaweeds are an excellent source of nutritious human food because of their low lipid content, high minerals, fibers, polyunsaturated fatty acids, polysaccharides, vitamins, and bioactive compounds. Many seaweed sub-products offer unique properties to develop various functional foods for the food processing industries. In the perspective of climate change mitigation, seaweed farms absorb carbon, serve as a CO_2 sink and reduce agricultural emissions by providing raw materials for biofuel production and livestock feed. Seaweed farming system also helps in climate change adaptation by absorbing wave energy, safeguarding shorelines, raising the pH of the surrounding water, and oxygenating the waters to minimize the impacts of ocean acidification and hypoxia on a localized scale. Moreover, it contributes substantially to the sustainable development of the economic condition of coastal women by providing livelihood opportunities and ensuring financial solvency. This review paper highlights the significance of seaweed farming in global food and nutritional security, mitigation and adaptation to global climate change, and women empowerment within a single frame. This review paper also outlined the major issues and challenges of seaweed farming for obtaining maximum benefits in these aspects. The main challenges of making seaweed as a staple diet to millions of people include producing suitable species of seaweeds, making seaweed products accessible, affordable, nutritionally balanced, and attractive to the consumers. Various food products must be developed from seaweeds that may be considered equivalent to the foods consumed by humans today. Lack of effective marine spatial planning to avoid user conflicts is vital for expanding the seaweed farming systems to provide aquatic foods and contribute globally for mitigation and adaptation of climate change impacts. Hence, women's empowerment through seaweed farming is primarily constrained by the lack of technical knowledge and financial resources to establish the coastal farming system. All the information discussed in this paper will help to understand the critical needs for large-scale seaweed farming for climate resilience mariculture, potentials for global food security, and future research on various aspects of seaweed farming and their diverse utilization.

1. Introduction

Seaweed and seagrass are two marine eukaryotic photosynthetic organisms. Seagrass is a marine flowering and true vascular plant that has a true stem, roots and leaves. In contrast, seaweed is the common name for a range of macroscopic and multicellular marine algae under the kingdom Protista that have no roots, stalks, leaves, flowers, fruits, or seeds and grow and live by attaching themselves to rocky formations or other hard substrata beneath the water's surface or drifting in the sea (McHugh, 2003). The whole plant is referred to as a thallus, which

* Corresponding author.
E-mail address: a_zamanbau@yahoo.com (M. Asaduzzaman).

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comprises the holdfast, stipe, and blade (Jayaprakash et al., 2017). Seaweed species are widespread across the world's coastal climate regions, from tropical, temperate, and polar areas (Sarkar et al., 2016). It is considered the millennium's plant, having social, economic, and environmental benefits. Seaweeds are high-profile commercial marine biota because of their wide range of applications, including biochemical raw materials (agar, alginate, agarose, and carrageenan), colors, food, enzymes, medicines, animal feed, fertilizer, cosmetics, textiles, and biotechnology. They also generate a wide range of secondary metabolites with diverse biological functions (Jeeva et al., 2012). Apart from these commercial applications, seaweeds have the potential to dominate the total benthic ecosystem, providing not just primary food but also homes for a diverse array of marine creatures (Siddiqui et al., 2019).

Seaweed supplies from the wild have become insufficient to satisfy industrial demands; thus, mariculture should provide additional demands. Because wild seaweed has a broad range of compositions, seaweed aquaculture may offer new methods to standardize or regulate the nutritional content of seaweeds (Leandro et al., 2020). By the mid-twenty-first century, human civilizations will be faced with the tremendous task of feeding and sustaining a population of well over 9 billion people while also dealing with the disproportionate effects of climate change and resource degradation (FAO, 2018, p. 124). The production of seaweed will be vitally important, supplying diverse foods for people, animal feeds, and chemical extracts for medicinal and laboratory use. Seaweed cultivation, unlike land-based agriculture, does not require freshwater or arable land. In most circumstances, fertilization is also unnecessary, and the farming system can provide economic activity while also providing ecological benefits. Also, it has a substantially smaller or no consequence on the marine and coastal environment than other forms of aquaculture, such as shrimp and finfish culture (Eggertsen & Halling, 2021). The carbon capture capability of seaweed is a significant advantage of seaweed cultivation (Froehlich et al., 2019), potentially contributing significantly to global climate change (GCC) mitigation strategies (Chung et al., 2011; Duarte et al., 2017; Turan & Neori, 2010). Apart from carbon capture, other potential benefits in GCC mitigation include the manufacture of low carbon food, biofuel production, depletion of methane emission via the addition of seaweed in cattle feed, and avoidance of adverse effects through the substitution of seaweed for inorganic fertilizers.

Coastal areas are home to about 40% of the globe's total population (UNEP World Conservation Monitoring Centre and Census of Marine Life on Seamounts (Programme). Data Analysis Working Group, 2006). Many tropical nations have coastal regions with nutrient-dense water and fishing communities eager to produce different seaweed species for food and revenue. Based on the socio-economic perspective, Stévant et al. (2017) and Barbot et al. (2016) had suggested seaweed farming as an alternative or supplement to agricultural production. Women's empowerment through the seaweed industry can be a crucial option to build a climate-resilient coastal community, particularly in the disadvantaged, vulnerable, and geographically isolated areas. Seaweed farming systems have enormous promise for providing food and livelihoods while maintaining ecological criteria, generating jobs for coastal women, and producing high-value species for worldwide export markets (Hussain et al., 2017). The seaweed business has already grown to a multi-billion dollar sector by now. In many developing nations, the cultivation of seaweed has been advocated as a management approach for minimizing the fishing pressure (Sievanen et al., 2005), decreasing poverty, and empowering women in resource-poor coastal communities through offering an alternative source of income (Mantri et al., 2017; Msuya, 2006; Valderrama, 2012). Some countries like Tanzania, Indonesia, the Philippines, and the Pacific Islands have demonstrated the beneficial economic effects of seaweed cultivation (Arnold, 2008; Namudu & Pickering, 2006; Sievanen et al., 2005). As a consequence of this initiative, many organizations have stepped in to promote seaweed farming as a viable alternative economic choice for the coastal poor, especially for coastal women from the fishing communities (Mohamed, 2015). The establishment of a community-based seaweed farming sector seeks to boost seaweeds output and productivity and improve the community's income and living conditions, particularly for those living in coastal regions. Furthermore, it is anticipated to boost seaweed exports, increase foreign currency earnings, and improve raw materials to satisfy the requirements of different processing sectors and the coastal region's economy via increased employments and income (Muthalib et al., 2019).

The significance of worldwide seaweed farming mainly lies in food and nutritional security, industrial uses, women empowerment, and climate change mitigation and adaptation. Therefore, this review paper aims to document the contribution and prospects of seaweed farming in food and nutritional security, women's empowerment, and climate change mitigation and adaptation in both national and global frameworks. The main questions address here are: (1) what are the prospects of seaweed farming in contributing to global food security in terms of nutritional aspects? (2) can seaweed farming help with the mitigation and adaptation of climate change that the globe has been experiencing recently? (3) how does seaweed farming contribute to the women's empowerment and livelihood resilience of the vulnerable coastal communities, particularly in developing countries? (4) what are the issues and challenges of seaweed farming in contributing above mentioned aspects, and what further actions are needed? In order to address these questions, firstly we discuss prospects of seaweed farming in contributing to global food security from a nutritional point of view. More intrinsically, we outline it by listing the commonly utilized edible seaweed species across the globe together with their application as direct foods, processed food and functional foods, and synthesize their nutritional profiles as millennium foods. Secondly, we documented the potential role of seaweed farming as a strategy for climate change mitigation and adaptation. Under this topic, we discussed the role of seaweed farming to the direct uptake of CO_2 with mentioning the additional role in adaptation to specific impacts of climate change in the marine environment. Thirdly, we synthesize all the relevant information across the globe to outline the contribution of seaweed farming to the women's empowerment and livelihood resilience in developing countries. Finally, we outlined the major issues and challenges of seaweed farming and propose a number of actions required for obtaining maximum benefits in these aspects. All the information included in this paper would be beneficial for understanding the crucial needs of developing large-scale seaweed farming and further research needs on various aspects of seaweed farming and utilization.

2. Diversity of seaweeds

Seaweeds are largely classified depending on their morphological and anatomical features (Abdel-Kareem & ElSaied, 2022). At all taxonomic levels, there are still a lot of classification issues despite the enormous number of published identifying and taxonomic keys (Silberfeld et al., 2014). In spite of the fact that the taxonomy of algae has undergone a significant transformation over the past 30 years, no worldwide classification system has been adopted by all specialists working in the field (Pereira & Neto, 2014). Phycologists can also differentiate and contrast different algae species to produce a reliable taxonomic system by varying the chemical composition of the cell wall, photosynthetic storage components, pigment ratios, and metabolic by-products (Dawczynski et al., 2007). A proposed classification system by Pereira and Neto (2014) placed the three categories of seaweeds, namely Chlorophyta (green algae), Ochrophyta (brown algae, formerly known as Phaeophyta), and Rhodophyta families (red algae). Among these three categories, a number of adjustments have been made to the categorization systems of brown algae as a result of the fast development of new molecular technologies. Despite the application of the new molecular technologies in Phaeophycean algae classification, phycologists still have blurred vision with regard to their classification. A lot of contradictory and unexpected data on the higher taxonomic ranks of

Phaeophyceae species have emerged over time, and hence it has become more difficult to provide an accurate taxonomic ranking for a certain genus. Overall, several reputable studies have lately been published on the taxonomy of algae, combining their morphological and genetic data to produce an accurate, widely-accepted categorization scheme (Abdel-Kareem & ElSaied, 2022). There are around 900 green, 4000 red, and 1500 brown seaweed species available in nature. Approximately 221 seaweed species (Chlorophytes 32, Phaeophyceae 64, and Rhodophytes 125) are currently harvested worldwide, among which 145 species are utilized as different food items, and 101 species are used to produce hydrocolloid (Nayar & Bott, 2014). However, this review paper highlighted the most widely used edible 20–25 seaweed species across the globe.

3. Present status of seaweed farming

Seaweed farming is one of the world's fastest-growing industries, with their farming regions spanned 48 million km^2 and spread across 132 nations, with 37–44 countries actively producing seaweed (Froehlich et al., 2019). While seaweed from natural sources stayed at 1.1 million tonnes for half a century, cultivated production grew to 35.8 million tonnes in 2019, accounting for 97% of global seaweed production (FAO, 2021). Between 1950 and 2019, the global seaweed farming tonnage grew 1000 times, from 34.7 thousand tonnes to 35.8 million tonnes (FAO, 2021), a worldwide market of US$ 11.8 billion in 2019, and a forecast of US$ 22.13 billion by 2024, based on an annual growth rate of 8.9% (Cotas et al., 2020; Mac Monagail et al., 2017). The increased output might provide the coastal population with 25% more food, 1.5 million tonnes of oil, 5 million tonnes of plant protein, and 125 million MWh of bioenergy (Hossain et al., 2020). According to FAO data, 27 different seaweed species were farmed globally in 2019. Brown seaweed farming increased from 3.1 million to 16.4 million tonnes, red seaweed cultivation rose from 1 million to 18.3 million tonnes, but green seaweed cultivation decreased from 31, 000 to 17,000 tonnes (FAO, 2021). In 2019, only five genera accounted for more than 95% of global seaweed farming production: *Laminaria/Saccharina* (35.4%), *Kappaphycus* and *Eucheuma* (33.5%), *Gracilaria* (10.5%), *Porphyra* (8.6%), and *Undaria* (7.4%) (Fig. 1A).

Aquaculture production of seaweed species in 2019 in different countries is shown in Fig. 1B. Asian markets are now driving worldwide development in the seaweed industry (Camia et al., 2018) and accounted for over 97% of global seaweed output in 2019 (FAO, 2021). In Asia, only four countries (China, Indonesia, Korea, and Japan) accounted for more than 90% of total production in 2019 (FAO, 2021). By far, China and Indonesia are the biggest seaweed producers in Asia as well as in the world, with combined output exceeding 30 million tonnes in 2019 with earnings of USD 578 million through the exportation of seaweed and seaweed-based hydrocolloids worldwide (FAO, 2021). China produced around 20.29 million tonnes of seaweed in 2019 from wild harvest and farming, among which 99% came from farming. In 2019, Indonesia produced 9.92 million tonnes of seaweed from aquaculture, which was 28.6% of the total global cultured seaweed production. China produced mostly edible kelp (*Undaria pinnatifida* and *Saccharina japonica*) and red seaweed from the genera *Pyropia* and *Gracilaria* (FAO, 2016) while Indonesia is famous for its carrageenophytes *Eucheuma* and *Kappaphycus* production, leading to the export earnings of USD 329 million in 2019 (FAO, 2021). According to the FAO report, the Republic of Korea and Philipines are in the 3rd and 4th rank of seaweed production with 1.81 and 1.49 million tonnes of yield, respectively, of cultured seaweed in 2019. Approximately 90% of the farmed output from the Philippines are *Kappaphycus* spp. and *Eucheuma* spp., namely *K. alvarezii* and *E. denticulatum*, with the remainder being green seaweed (FAO, 2018, p. 124). The Philippines produced almost 80% of the world's entire *Kappaphycus alvarezii* (formerly *Eucheuma cottonii*) output (FAO, 2018, p. 124). The Philippines produced almost 80% of the world's entire *E. cottonii* output (FAO, 2018, p. 124). FAO's recent report suggested that in terms of volume, the Democratic People's Republic of Korea is at the 5th position with 0.60 million tonnes of production, and Japan is at the 6th position with 0.35 million tonnes of production in 2019 in the global seaweed farming industry. Japanese farms along the coastal region contributed more than 90% of the demand for *Porphyra* spp., *Saccharina japonica*, and *Undaria* spp., commonly known as nori, kombu, and wakame (FAO, 2018, p. 124). Some other Asian countries like Malaysia, India, Vietnam are also producing different kinds of seaweeds.

4. Prospects of seaweeds in contributing to global food security

Global food security is a dynamic operational notion that has been evolving over decades with regards of its definition and policy application (Clay, 2003). Food security is acquired when all individuals have physical, financial, and social access to nutritious, adequate, and safe food which can fulfill their unique dietary requirements and choices of food for a healthy and active lifestyle (Leandro et al., 2020). By 2050, the globe will need to produce 50%–70% more food to sustain current

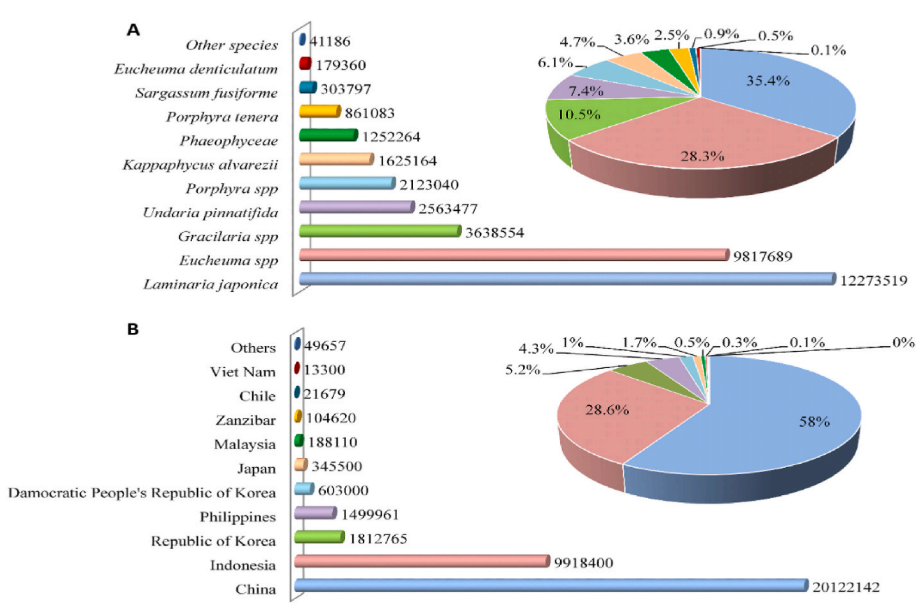

Fig. 1. Percentage of cultured seaweed production based on species (A) and countries (B) (FAO, 2021).

consumption patterns (Yarish et al., 2016). Because the world's population is continuously increasing, it's vital to maintain sustainable food production, particularly in terms of maintaining appropriate quality and quantity to fulfill global demands (Leandro et al., 2020). The current agricultural land must provide for 90% of the global demands of the food supply through increased productivity per unit area, while the remaining 10% can come through the inclusion of additional land (Clay, 2011; FAO, 2013; Garnett et al., 2013; Godfray & Garnett, 2014). On the other hand, water is a significant stumbling block to improving agricultural production. Over 70% of the world's available freshwater has already been utilized for irrigation (Madramootoo & Fyles, 2010; OECD-FAO, 2012). Only a tiny amount of additional water can be redirected to agriculture (Radulovich, Umanzor, et al., 2015). Intensive agriculture has resulted in over-exploitation of cultivable landmass, decreased freshwater availability, aggravating climate changes, and having significant environmental effects. All of these factors may redirect a shift in research toward the development of new and sustainable feedstuffs and the advancement of underutilized crops (Leandro et al., 2020).

Seaweed, sometimes known as a sea vegetable, is one of the most underutilized crops. It can play a significant role in global food security since they are nutrient-dense food when produced and eaten according to safety standards (Leandro et al., 2020). An essential benefit of developing seaweed cultivation is that it is self-sufficient in terms of the three primary resources (land, freshwater, and fertilizer). Massive water savings for food production are possible if seaweed farming is expanded compared to agriculture (Radulovich, 2011). Additionally, the world's extensive coasts and marine regions absorb enormous nutrients from the land, especially from rivers and wastewater discharges (Karl et al., 1997), including epiphytes attached to seaweeds (Phlips et al., 1986). Seaweeds have a great potential to become an essential supplement to the global vegetable diet, thus enhancing the supply chain of foods. Maximum seaweed species are edible and provide a significant and long-term supply of macro-and micronutrients in the human diet (Forster & Radulovich, 2015). Hence, seaweed farming has the potential to grow not just as a supplement to agriculture but also as a substitute for it. It is anticipated that cultivating just 2% of the ocean's surface area with seaweed species would double present agricultural food output in bulk tonnage (Radulovich, Umanzor, et al., 2015). It is conceivable that the worldwide extension of the seaweed cultivation sector can supplement our current food supply. Moreover, it will also act as a hedge against agriculture's potential inability to adequately address the challenges associated with food security that we are now facing, with the added benefit of environmental services (Forster & Radulovich, 2015).

4.1. Seaweed as food for direct human consumption

Many seaweed species are regarded as nutritious, healthy, and delicious meals, despite being produced on a small scale in world food production (Radulovich, Umanzor, et al., 2015). Some of these are edible seaweeds, and their direct food applications are enlisted in Table 1. They are mainly cultivated and consumed in the Asian continent, where a variety of species have been utilized as traditional sources of food for generations, but they are becoming more well recognized and enjoyed in the western countries as a result of the popularity of Asian cuisine (Forster & Radulovich, 2015). Along with the growing attraction of seaweed as a "sea vegetable" in the western world, claims for their nutritive and/or therapeutic properties are numerous and becoming more notable in dietary literature (Jaspars & Folmer, 2013; Rajapakse & Kim, 2011). People from the Asia-Pacific islands directly consume these seaweeds as salad, snacks, desserts, and side dishes. They also use these seaweeds as a flavoring agent for soups, noodles, stews, garnishes, and beverages (Novaczek & Athy, 2001; Teas et al., 2007). Seaweed-based edible products come in a variety of forms: fresh, dried, powdered, and flaked (Buschmann et al., 2017; Madhusudan et al., 2011). Apart from traditional seaweed-based products such as Korean Wakame and Japanese Nori or Purple Laver, commercial seaweed-based foods such as burgers, juices, sandwiches, ice cream, cake, chocolate, salad, chips, and biscuits, are also produced (Sarkar, 2015).

Table 1
List of the most commonly utilized edible seaweeds and their direct food applications for human consumption.

Seaweed species	Food application	References
Rhodophyta (Red seaweeds)		
Porphyra spp.	Vegetable, soup ingredients, sushi wrap, snacks, beef meal, fish curry	FAO (2021)
Gracilaria spp.	Salad, pickles	FAO (2021)
Kappaphycus sp., *Eucheuma* sp.	Salad, pickles	FAO (2021)
Palmaria palmata	Sea vegetable	Leandro et al. (2019)
Condrus crispus	Sea vegetable	Leandro et al. (2019)
Phaeophyceae (Brown seaweeds)		
Laminaria sp./*Saccharin* sp.	Snacks, soup ingredients, beef meal, fish curry	FAO (2021)
Undaria pinnatifida	Salad, vegetable, wrap, noodles, snacks, soup, beef meal, fish curry	FAO (2021)
Himanthalia elongata	Sea vegetable	Leandro et al. (2019)
Sargassum spp.	Sea vegetable	Forster & Radulovich, 2015; Leandro et al., 2019
Chlorophyta (Green seaweeds)		
Caulerpa spp, *Caulerpa racemosa*	Fresh salad and fried	Forster and Radulovich (2015)
Ulva lactuca, Ulva rigida, Ulva australis (formerly *Ulva pertusa*	Sea vegetable and salad	Leandro et al. (2019)
Cladophora spp.	Sea vegetable	Leandro et al. (2019)
Codium spp.	Fresh salad and fried	Forster and Radulovich (2015)
Chaetomorpha spp.	Prepared and served like spinach;	Forster and Radulovich (2015)

4.2. Seaweed as processed food

Seaweed is consumed raw or processed to produce food additives that may or may not alter the taste character. Due to the rheological characteristics, like gelling and thickening agents, seaweed species and their polysaccharides are regarded as valuable additives in the food industry. It increases texture, improves fat replacement, product yields, and helps in seafood binding (Ahmed et al., 2017). Agar, carrageenan, and alginate are three kinds of hydrocolloids derived from seaweed (Table 2). Hydrocolloids are becoming more important in the baking industry, intending to make the dough easier to handle, enhance the quality of bread, extend stored bread's shelf life, and increase the nutritional content of finished products (Keyimu, 2013; Menezes et al., 2015; Arufe et al., 2018). The details of sources of the hydrocolloids and their uses and functions in different food products are listed in Table 2.

4.3. Seaweed as functional food

Seaweeds are great candidates for functional food applications due to their nutritional density in meat-based (Table 3) and plant-based products (Table 4). Additionally, their physical capacity to emulsify and hold water contributes to their technological functionality as food components (Shannon & Abu-Ghannam, 2019). Seaweed-based lipid powders and flour are prevalent in contemporary cooking, bakery and vegan-based products (Pina-Perez et al., 2017; Oh et al., 2020). Bread is

Table 2
Seaweed derived hydrocolloids and their functions in the food industry.

Hydrocolloid	Source	Food products	Function	References
Agar	*Gelidium* sp., *Gracilaria* sp., *Pterocladia/Pterocladiella* sp., *Gelidiella* sp.	Jellies, bakery and dairy items, confectionery, canned fish and meat items, sauces, soup beverages, pie fillings, and icings	• utilized in a wide variety of food operations due to gelling and stabilizing characteristics • used in candies to enhance the gel strength • used in canned products because of its high melting temperature and resilience to autoclaving • helps dairy food products to have a better texture • used in the beverage sector as a flocculant and clarifying agent	Menon, 2011; Rioux & Turgeon, 2015
Alginate	*Ascophyllum nodosum*, *Durvillaea* sp., *Laminaria* sp., *Macrocystis pyrifera*, *Ecklonia maxima*, *Lessonia* sp.	Ready-to-eat soups, dehydrated soups, sauces, mayonnaise, ice creams, Alfredo sauces, canned meat meals, margarine, caramels, desserts, granola bars, cake icings, yogurt, juices, and beverage	• utilized in food products as a gelling, thickening, stabilizing, and emulsifying agent • used in canned meat products to help with heat transfer during sterilization • used as an emulsifier or stabilizer to keep insoluble components suspended in oil-in-water emulsions, different juices, etc. • when alginate is incorporated in ice creams, the ice crystals' size decreases, and the texture of the ice cream becomes smoother, syneresis is avoided, and melting is postponed • used to restructure food items • have excellent film-forming characteristics that help many food items in minimizing water loss, controlling diffusion, and structure of food items • used in pastry to prevent fruit contents from hydrating the cake or prevent cake frosting from adhering to the packing • helps to prolong shelf life, preserve product appearance, and reduce the rate of respiration and ethylene generation of freshly cut fruits	Whistler & BeMiller, 1997; Olivas et al., 2007; Rojas-Graü et al., 2007; Maftoonazad et al., 2008; Helgerud et al., 2009; Díaz-Mula et al., 2012; Rioux & Turgeon, 2015
Carrageenan	*Kappaphycus alvarezii, Eucheuma denticulatum, Anatheca, Ahnfeltia, Gynmogongrus, Furcellaria, Gigartina, Iridaea, Hypnea, Phyllophora, Meristotheca,*	Canned meat, cooked sliced meat, fruit juices, puddings, ice cream, cream desserts, creams, mousses, chocolate milk, milkshakes, and pie fillings	• used in various food items as a thickening, gelling and stabilizing ingredients • K-carrageenan forms a hard and brittle gel in cake icings and water-based gelled sweets • helps in retention of water and texture in canned and cooked sliced meat • a combination of K- and L-carrageenan is employed in dairy products to make a creamy gel • K-carrageenan enables a rise in the chocolate milk's viscosity to keep the cocoa molecules suspended • used to avoid whey separation while making ice cream, creams, and milkshakes • works synergistically with other polymers to enhance each polymer's usefulness in both water-based and dairy-based products.	Whistler & BeMiller, 1997; Imeson, 2000; Rioux & Turgeon, 2015

another excellent cereal-based food item that can serve as a carrier for a variety of bioactive ingredients, including seaweed. The inclusion of *Ulva lactuca* (Chlorophyta) and 2.5% powdered *Laminaria* (Phaeophyceae) improves the bread's quality (Cofrades et al., 2013). Edible seaweeds include a variety of bioactive chemicals that have health advantages, and their application as functional additives in food processing, including meat product compositions, offers new possibilities (Kılınç et al., 2013).

4.4. Nutritional value of seaweed as millennium food

Like plants, seaweed contains protein, lipid, carbohydrates, vitamins, and minerals, and they often have many or all of the particular nutrient components that are considered necessary in the human diet (de Oliveira et al., 2009; Forster & Radulovich, 2015; Manivannan et al., 2008; Marinho- Soriano et al., 2006; Marsham et al., 2007). However, the nutritional components of seaweed differ by species, harvesting period, geological habitat, and ambient circumstances, including light intensity, water temperature, and concentration of nutrients in the

Table 3
Seaweed species as functional food in meat-based products.

Food products	Seaweed species	Composition	Characteristics/Functions	References
InsBeef burgers, Pork frankfurters, Restructured poultry steaks	*Undaria pinnatifida, Himanthalia elongata* and *Porphyra umbilicalis*	5.6% dried and milled *Undaria pinnatifida/Himanthalia elongate/Porphyra umbilicalis*	• reduced the index of thrombogenicity • lowered Na level but increased K, Mg, Ca, Mn, and soluble polyphenolic substances • increased total polyphenolic content • increase antioxidant capacity	López-López et al. (2009)
Beef patties Beef patties	*Himanthalia elongata*	40% blanched and blended *Himanthalia elongata*	• improved consumer acceptance • fiber content increased • the fat level decreased • moisture loss and final lipid oxidation decreased • tenderness of the product improved significantly	Shannon and Abu-Ghannam (2019)
	Undaria pinnatifida	Low fat and low salt beef patties + 3.3% seaweed + olive oil	• reduced thawing and cooking losses • enhanced mineral content • excellent technical, sensory, and nutritional characteristics.	Lopez-Lopez et al. (2010), Freitas et al., 2015
Turkey meat sausages	*Gongolariabarbata* (formerly *Cystoseria barbata*)	0.04% fucoxanthin extracted from *Cystoseria barbata*	• increased antioxidant capability, color stability, lipid oxidation prevention, and angiotensin-I converting enzyme level • reduced quantity of $NaNO_3$ needed as an antibacterial agent by 47%	Sellimi et al. (2017)
Frankfurter sausages	*Himanthalia elongata*	Low-fat frankfurters +5.5% seaweed Low-fat, low-salt Frankfurters+ 0–19.3% konjac glucomannan gel + 0–3.3% seaweed	• resulted in Ca-rich, low-Na with improved Na/K ratio and a greater fiber content. • reduced the fat content by 15% without changing the sensory quality	López-López et al. (2009), Freitas et al. (2015) Jimenez-Colmenero et al. (2010), Freitas et al. (2015)
Pork patties	*Saccharina japonica* (formerly *Laminaria japonica*	Pork patties+ 0–5% seaweed	• greater moisture, carbohydrate, and ash content • lower fat and protein content, cooking loss, and hardness • enhanced qualitative attributes, comparable to control patties with a 20% fat content.	Choi et al. (2012), Freitas et al. (2015)

Table 4
Seaweed as functional food in plant-based products.

Food products	Seaweed species	Composition	Characteristics/Functions	References
Wheat flour noodles	*Kappaphycus alvarezii* (formerly *Eucheuma cottoni*)	90g wheat flour+5g dried & milled *Eucheuma cottoni* + dried Spirulina platensis powder	• highest protein content, lowest fat level, and highest customer acceptance • decreased carbohydrate content, but increased crude fiber content • increased protein content by 87%, and mineral content nearly tripled	Kumoro et al. (2016)
White bread	*Fucus vesiculosus*	300g white wheat flour+6g fresh yeast+5.4g salt+192g tap water+0.006g ascorbic acid+2–8% (6–24g) *Fucus vesiculosus* powder	• high antioxidant profile • did not alter the bread crumb's textural characteristics • addition of up to 2% seaweed did not influence the thickness	Arufe et al. (2018)
Wholemeal and white wheat flour breadsticks	*Himanthalia elongata*	10–30% flour+5–15% air-dried and milled *Himanthalia elongate*+2.13% yeast+34.65% water + 1.21% butter + 1.21% salt	• maximum acceptability of color and texture and nutritional improvement • the total phenolic content increased by 427% • antioxidant capacity and the total amount of dietary fiber increased	Cox and Abu-Ghannam (2013)
Fresh noodles	*Monostroma nitidum*	Noodles with 4–8% seaweed powder	• improved crude fiber content increased yields from boiling, and reduced springiness and extensibility	Chang and Wu (2008), Freitas et al. (2015)
Pasta	*Undaria pinnatifida*	Pasta with semolina and 10% blended seaweed	• Increased fucosterol and fucoxanthin levels • improved the nutritional composition, amino acid, and fatty acid profiles • satisfactory in terms of sensory quality	Prabhasankar et al. (2009), Freitas et al. (2015)

seawater (Marinho-Soriano et al., 2006; Marsham et al., 2007).

The details of the nutrient contents of edible seaweeds are presented in Table 5. For many decades, seaweed species have been utilized as a source of protein (Peng et al., 2015). On a dry weight basis, seaweeds have a protein content ranging between 5% and 47% (Shannon & Abu-Ghannam, 2019). Among all species, red seaweed has the highest protein content (14–47 g/100 g DW), whereas green seaweed has the moderate (7–27 g/100 g DW), and brown seaweed has the lowest protein content (7–16 g/100 g DW) (Abdallah, 2008; Collins et al., 2016; Dawczynski et al., 2007; Fleurence, 1999; McDermid & Sturcke, 2003; Patarra et al., 2011; Wong & Cheung, 2000). The red seaweed *Porphyra tenera,* also known as Nori, is a high-protein seaweed that contains 47%

Table 5
Reported nutritional contents of the most commonly utilized edible seaweed species across the world (% DW).

Seaweed species	Protein	Lipid	Carbohydrate	Fiber	Reference
Rhodophyta					
Eucheuma spp.	5–6	0.2	63–67	5.9	Matanjun et al., 2008; Yarish et al., 2016
Gracilaria spp.	12	0.3	74	24.7	Pereira, 2011; Yarish et al., 2016;
Porphyra spp.	31–44	2	44	12–35	Pereira, 2011; Yarish et al., 2016
Palmaria palmata	8–35	0.7–3	46–56	29–46	Morrissey et al., 2001; Rupérez, 2002; Yuan, 2008; Holdt and Kraan (2011)
Condrus crispus	11–21	1–3	55–68	10–34	Morrissey et al., 2001; Rupérez, 2002; Yuan, 2008; Holdt and Kraan (2011)
Phaeophyceae					
Saccharina japonica	7–8	1–2	52	10–41	Pereira, 2011; Yarish et al., 2016
Undaria pinnatifida	12–23	1–5	45–51	16–51	Pereira, 2011; Yarish et al., 2016
Fucus vesiculosus	3–14	1.9	46.8	45–59	Pereira, 2011; Schmid et al., 2018
Sargassum fusiforme	11.6	1.4	30.6	17–69	Pereira, 2011; Schmid et al., 2018
Himanthalia elongata	5–15	0.5–1.1	44–61	33–37	Saá, 2002; Burtin, 2003; Yuan, 2008; Plaza et al., 2008; López-López et al., 2009; Gómez-Ordóñez et al., 2010
Laminaria digitata	8–15	1.0	48	36–37	Fleurence et al., 1995; Castro-Gonzalez et al., 1996; Rupérez, 2002; Burtin, 2003; Yuan, 2008
Chlorophyta					
Ulva lactuca	10–15	0.6–1.6	36–43	29–55	Pereira, 2011; Schmid et al., 2018
Ulva rigida	18–19	0.9–2.0	43–56	38–41	Santoso, Yoshie-Stark and Suzuki, 2006; Kumar et al., 2010; Taboada et al., 2010;
Ulva australis (formerly *Ulva pertusa*)	20–26	–	47.0	–	Fujiwara-Arasaki, Mino and Kuroda, 1984; Fleurence et al., 1995
Codium fragile	8–11	0.5–1.5	39–67	5.1	Ortiz et al., 2009; Guerra-Rivas et al., 2010
Cladophora sp.	13.68	0.96	48.38	13.9	Anh (2020)
Chaetomorpha linum	19.29	1.89	39.87	15.82	Anh (2020)

protein in dry weight (Shannon & Abu-Ghannam, 2019). Among the brown seaweed species, *Undaria pinnatifida* (wakame) is an exception that has a protein content of 11–24 g/100 g of dry weight (Abdallah, 2008; Collins et al., 2016; Dawczynski et al., 2007; Fleurence, 1999). Seaweed proteins consist of essential amino acids, accounts for 42%–48% of the entire amino acids (Wong & Cheung, 2000). As a result, seaweeds are excellent source of protein, not only because of their overall protein level but also because of their amino acid composition (Wong & Cheung, 2000). Seaweeds have non-essential amino acids, with glutamic and aspartic acid accounting for a significant portion of 20%–32% of total amino acids (Dawczynski et al., 2007; Pereira, 2011; Wong & Cheung, 2000). Due to the large quantities of these two amino acids, seaweeds have a distinctive taste and "umami" flavor (Salehi et al., 2019; Wong & Cheung, 2000). On a scale of 0.0–1.0, with 1.0 being egg protein, most seaweeds score higher than all the plant-derived proteins, except for soy protein, which scores 1.0. *Undaria pinnatifida*, for example, has a score of 1.0 for amino acids, the same as egg and soy, *Pyropia/Porphyra* has a score of 0.91, and *Saccharina latissimi* (formerly *Laminaria saccharina*) (Phaeophyceae) has a score of 0.82 (Murata & Nakazoe, 2001).

Seaweeds are recognized as foods that are low in calories because of their low lipid content, 0.5%–4.5% of dry weight (Dawczynski et al., 2007; Schmid et al., 2018; Wong & Cheung, 2000). Many essential fatty acids are found in seaweed lipids, which may increase their effectiveness as a food supplement or as a part of a well-balanced diet (Dembitsky et al., 2003). Approximately 50% of the lipids of seaweed are polyunsaturated fatty acids (PUFA), for example, eicosapentaenoic acid (EPA) and arachidonic acid (AA). Rhodophyta and Phaeophyta have high concentrations of EPA and AA, whereas Chlorophyta such as *Ulva pertusa* contains high concentrations of oleic, hexadecatetraenoic, and palmitic acids (Ortiz et al., 2006). The most common monounsaturated fatty acid in seaweed is linoleic acid (Belattmania et al., 2018). Both omega-3 and omega-6 fatty acids are necessary for the human diet; however, eating them in an unbalanced ratio may lead to chronic inflammatory illnesses (Patterson et al., 2012). The ideal omega-3: omega-6 ratio should be between 1:3 and 1:5 (Miles & Calder, 1998; Simopoulos, 2002, 2016). In red seaweed species, this ratio varies from 0.1 to 8.2, in green species from 0.2 to 2, and in brown species from 0.2 to 2.4 (Cardoso et al., 2015; Denis et al., 2010; Holdt & Kraan, 2011; Neto et al., 2018; Schmid et al., 2018; Seca et al., 2018). Seaweeds have a low omega-6: omega-3 fatty acid ratio, making them excellent sources of dietary lipids (Biancarosa et al., 2018).

Carbohydrates with low molecular weight are abundant in seaweeds. Sucrose is the sugar found in green seaweed species, while and red seaweed species include isofloridoside, digeneaside and floridoside. (Ascêncio et al., 2006; Martinez-Garcia & van der Maarel, 2016; Pade et al., 2015). Additionally, mannitol, an approved food, and a medicinal component may account for 3%–30% of the dry weight in brown seaweed (Biancarosa et al., 2018; Hamid et al., 2015; Karsten et al., 1992; Reed et al., 1985). Despite these low-molecular-weight molecules, long-chained polysaccharides (made up of more than 10 monosaccharides) are the most typical carbohydrates in seaweeds (Stiger-Pouvreau et al., 2016). Seaweed's total polysaccharide content varies from 4% to 76% (dry weight) (de Jesús Paniagua-Michel et al., 2014). Polysaccharides in seaweeds are classified into structural and storage polysaccharides (Leandro et al., 2020). Structural polysaccharides in seaweeds are similar to those found in terrestrial plants and consist primarily of cellulose, hemicellulose, mannans, and xylans. On the contrary, storage polysaccharides including agar, carrageenan, and alginate are unique to seaweed species and are the most economically valuable components of seaweeds (Ferrara, 2020; McHugh, 2003). Brown seaweeds mostly contain alginates, fucoidans, and laminarin (Rodrigues et al., 2015); red seaweeds contain agarans and carrageenans; green seaweeds contain ulvans (Jiao et al., 2011). The polysaccharide 'porphyran' is found in the red *Porphyra* seaweed in quantities up to 48% by dry weight, and can be used in different food products (Takahashi et al., 2000). *Porphyra* spp. contains up to 42% dry weight of a starch-based polymer known as floridoside (MacArtain et al., 2007). *Palmaria palmata* contains 45% of xylan linked to the pentose (MacArtain et al., 2007).

When algae are eaten as food, a significant portion of dietary fibers is also consumed. Total dietary fiber content varies between 33 and 50 g/100 g of the dry weight of algae (Ruperez & Saura-Calixto, 2001). *Sargassum fusiforme* (formerly *Hizikia fusiformis*) had the highest fiber content (almost 60% dry weight), while *Laminaria/Saccharina* spp. had the lowest fiber content (36% dry weight) (Dawczynski et al., 2007). Algal fiber has structural chemistry distinct from the terrestrial plants (Shannon & Abu-Ghannam, 2019) that provide them with functional and bioactive characteristics not seen in other types of terrestrial sources of fiber (Jiménez-Escrig and Cambrodón, 1999). Dietary fiber should be consumed in a daily quantity of 24 g (McCance et al., 1993). Seaweeds may supply up to 12.5% of an individual's daily basis fiber requirements in an 8 g serving (MacArtain et al., 2007). *Porphyra umbilicalis*, which is often processed as 'Nori' sheet, contains more fiber than a banana (3.8 g/100 g vs 3.1 g/100 g, respectively) (MacArtain et al., 2007).

Seaweeds are enriched sources of both water-soluble and fat-soluble vitamins (Table 6). Many vitamins, including thiamine (VB_1), riboflavin (VB_2), cobalamin (VB_{12}), l-ascorbic acid (VC), folic acid, and the derivatives of it (for example, 5-methyltetrahydrofolate, 5-formyltetrahydrofolate, tetrahydrofolate), tocopherols (VE), and carotenoids, have been reported in seaweeds (Mišurcová, 2011). Vitamin C is found in extremely high concentrations with a range of 500 mg/kg-3 000 mg/kg (DW) in various green and red seaweeds, such as 3 000 mg/kg (DW) in the green seaweed species *Ulva flexuosa* (formerly *Enteromorpha flexuosa*) (McDermid & Stuercke, 2003) and 2000 mg/kg (DW) in the red seaweed species *Eucheuma denticulatum* (McDermid & Stuercke, 2003). Most brown and red seaweed species contain vitamin-B, particularly thiamine and riboflavin (MacArtain et al., 2007). Compared to green and red seaweed, brown seaweed has greater vitamin E concentration (Peng et al., 2015). Vitamin E content in the brown seaweed species such as *Durvillaea antarctica* is greater (245.9 mg/kg DW) than green seaweed species *Ulva lactuca* (25.8 mg/kg DW) (Ortiz et al., 2006). Potent antioxidants, carotenoids, may also be found in brown, red, and green seaweeds (Peng et al., 2015). *Gracilaria changii*, a Rhodophyta, is also an excellent b-carotene source, with a high concentration of 5.2 mg/kg DW (Norziah & Ching, 2000). Around 100 g of seaweed offers more than the daily need for some vitamins such as VA, VB_2, and VB_{12}, as well as two-thirds of the daily need for vit-C (Leandro et al., 2020). *Porphyra* spp. and *Ulva* spp. contain more vitamin C per gram than a kiwi or an orange (Gebhardt & Thomas, 2002; Hamid et al., 2015; Paiva et al., 2014). Additionally, *Gelidiella acerosa* (Rhodophyta) and *Fucus spiralis* (Phaeophyceae) provide about 133 and 104 mg of vitamin D per 100 g of dried seaweed, respectively (MacArtain et al., 2007; Syad et al., 2013). Since seaweeds are among the few vegan sources of VB_{12}, they are a great source of this critical nutrient and help vegetarians and vegans meet their daily dietary needs (MacArtain et al., 2007).

Seaweed species are incredible sources of different minerals and trace elements (8%–40% of DW) as well as the most incredible natural source of dietary iodine that is bioavailable (Table 7). WHO and FAO recommend 150 μg/d (i.e., 2.0 μg/kg/day) of iodine for adults (>13 years) (Collins et al., 2016; Mišurcová et al., 2011; Yates et al., 1998). Furthermore, according to Narayan et al. (2008), seaweeds may contain 1 000 times the amount of iodine found in marine seafood like cod. Ingestion of seaweeds may be a method to cure a variety of dysfunctions or reduce pathological symptoms caused by mineral deficiency (Matsuzaki & Iwamura, 1981). This is shown by an 8 g serving of Sea lettuce or *Ulva lactuca* containing 260 mg of calcium, or around 37% of an adult male's RNI for calcium (Food Safety Authority of Ireland, 1999). Seaweeds have more significant amounts of minerals like iron and copper than many familiar land-based mineral sources like spinach and meats (MacArtain et al., 2007). Copper has a daily reference nutritional intake of 1.2 mg, and an 8 g piece of Wakame or *Undaria pinnatifida* provides 14% of this mineral's RNI (MacArtain et al., 2007). Brown seaweed species bioaccumulate various elements and are an excellent source of copper, iodine, iron, and magnesium, among others. Daily consumption of 8 g of 'Kombu,' used in Asian cuisine, provides 65% of the recommended daily allowance (RDA) for magnesium (Institut de Phytonutrition, 2004). The Ca (calcium) concentration of seaweed species is not just up to 10 times greater than cow's milk, but it is also considerably simpler for the human body to absorb. Pregnant and breastfeeding females and children suffering from malnutrition should eat seaweed regularly to make sure that they receive sufficient amounts of these minerals (Leyman, 2002).

To survive in the complex oceanic environment, seaweed possesses various bioactive secondary metabolites as a chemical defense. Many secondary metabolites also reported from seaweeds, including sesquiterpenes (Guella et al., 1997; Tori et al., 1994), monoterpenes (Kladi et al., 2004), diterpenes (Geo & WO, 2020), C15-acetogenins (Kladi et al., 2008), meroterpenoids (Areche et al., 2009), steroids (Kamenarska et al., 2002), and phlorotannins (Xu et al., 2004). All these components can provide health benefits in the forms of antioxidation, anticancer and antibacterial activity, chemoprevention against several vascular diseases, and antidiabetic complications (Peng et al., 2015). According to global dietary research, nations that eat seaweed daily have substantially lower rates of obesity and diet-relevant illnesses (Iso,

Table 6
Vitamin contents of some edible seaweeds species (mg per 8 g Dry weight) *μg/100g wet weight).

Seaweed species	Vitamins								References
	A	C	E	B_1	B_2	B_3	B_6	B_{12}	
Rhodophyta									
Porphyra umbilicalis	3.65[a]	12.885	0.114	0.077	0.274	0.761	0.119	0.769*	Quirós et al., 2004; MacArtain et al., 2007
Palmaria palmata	1.59[a]	5.520	1.296	0.24	0.080	0.800	0.002	1.840*	Morrissey et al., 2001; Saá, 2002; Quirós et al., 2004; MacArtain et al., 2007
Condrus crispus	–	10–13[b]	–	–	–	–	0.6–4[b]	–	Morrissey et al., 2001; Rupérez, 2002
Gracilaria sp.	–	16–149[c]	–	–	–	–	–	–	Tsuchiya (1950)
Phaeophyceae									
Ascophyllum nodosum	–	0.654	0.029	0.216	0.058	000	0.001	0.131*	MacArtain et al. (2007)
Laminaria digita	–	2.842	0.275	0.011	0.011	4.896	0.513	0.496*	MacArtain et al. (2007)
Undaria pinnatifida	0.04–0.22[a]	14.779	1.392	0.403	0.936	7.198	0.259	0.345*	Kolb et al., 2004; MacArtain et al., 2007
Fucus vesciculosus	0.307[a]	14.124[a]	–	0.02[a]	0.035[a]	–	–	–	García et al., 1993; Saá, 2002
Himanthalia elongata	0.079[a]	28.56[a]	–	0.020[a]	0.020[a]	–	–	–	García et al., 1993; Saá, 2002; Quirós et al., 2004
Saccharina japonica	0.481[a]	–	–	0.2[a]	0.85[a]	1.58[a]	0.09[a]	–	Kolb et al. (2004)
Chlorophyta									
Ulva spp.	–	10.00	–	0.060	0.030	8.000	–	6.300*	MacArtain et al. (2007)
Ulva lactuca	0.017[a]	<0.242[a]	–	<0.024[a]	0.533[a]	98[b]	–	–	García et al., 1993; Morrissey et al., 2001
Ulva rigida	–	9.42[a]	19.70[a]	0.47[a]	0.199[a]	<0.5[a]	<0.1[a]	–	Taboada et al. (2010)
Codium fragile	0.527[a]	<0.233[a]	–	0.223[a]	0.559[a]	–	–	–	García et al. (1993)

*μg/100 g wet weight.
[a] mg/100 g edible portion.
[b] expressed as ppm.
[c] expressed as mg%).

Table 7
Mineral contents of some edible seaweeds species (mg/100 g DW).

Seaweed species	Ca	Cu	I	Fe	Mg	Mn	P	Zn	K	Na	References
Rhodophyta											
Gracilaria spp.	402	*	*	3.65	565	*	*	4.35	3417	5465	Krishnaiah et al. (2008)
Porphyra spp.	390	<0.63	1.7	10–11	565	3	*	2–3	3500	3627	Yuan, 2008; Rupérez, 2002
Palmaria palmata	250–1200	<0.5	10–100	7.30–50	120–610	0.41–1.14	210–235	2.86	2800–9000	320–2500	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Condrus crisous	420–1300	<0.5-0.76	24.5	4–20	600–900	1.32–2.2	135–240	7.14	1350–3184	1200–4270	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Phaeophyceae											
Saccharina japonica	225–910	0.25–0.40	130–690	1.19–43	550–757	0.13–0.65	150–300	0.89–1.63	4350–5951	2532–3260	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Undaria pinnatifida	331–1380	0.19–2.0	22–30	1.54–30	277–680	0.27–0.56	235–450	0.94–4.03	864–6810	1600–7000	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Fucus vesiculosus	725–3000	<0.5	14.50–26	29–11	670–994	3.7–5.50	100–315	3.7	2500–4322	1800–5469	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Sargassum fusiforme	1860	*	43.6	88.6	687	*	*	1.35	*	*	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Laminaria digitata	1005	<0.5	*	3.29	659	<0.5	*	1.77	11,579	3818	Rupérez (2002)
Himanthalia elongata	720	*	14.7	59	435	*	240	*	8250	4100	Saá (2002)
Chlorophyta											
Ulva lactuca	840–1600	0.71	0.43	66–180	2700	2.6	140–220	*	2800	700	Pereira, 2011; Biancarosa et al., 2018; Paz et al., 2019
Ulva rigida	524	0.5	*	283	2094	1.6	210	0.6	1561	1595	Taboada et al. (2010)
Caulerpa racemosa	1852	0.6–0.8	*	30–81	384–1610	4.91	29.71	1–7	318	2574	Santoso et al., 2006; Kumar et al., 2010

2011; Nanri et al., 2017). Due to their nutritional and medical value, interest in consuming seaweed as a "sea vegetable" also increases worldwide (Forster & Radulovich, 2015). Consumption of seaweed as food has several other health benefits, including controlling cholesterol level and blood sugar, decreasing lipid absorption in the gastrointestinal system, weight reduction, anti-obesity impact, and improvement of cardiac and intestinal health (Forster & Radulovich, 2015). Therefore, seaweed is considered the 21st century's medicinal food because of its nutritional value (Khan & Satam, 2003).

5. Seaweed farming and climate change mitigation

In the era of industrialization, climate change is happening worldwide with lots of disastrous consequences. Although it is happening worldwide, the primary sufferers are the developing nations, as they cannot afford the high cost of climate change mitigation. Climate change mitigation refers to strategies and policies that aim to decrease the concentration of greenhouse gases in the atmosphere, either by reducing their emissions or increasing their capture. Global climate change impacts are becoming more visible and affecting both terrestrial and marine environments (Hoegh-Guldberg et al., 2018; Poloczanska et al., 2013), all of which have significant economic consequences (DeFries et al., 2019). The ability of some coastal and marine ecosystems to absorb and sequestrate of carbon can be crucial to mitigation attempts (Duarte et al., 2013). Considering these criteria, seaweed farming can be a viable approach for developing coastal countries to mitigate climate change as it requires meager investment and has many additional benefits. The role of seaweed farming in climate change mitigation and adaptation is summarized in Fig. 2.

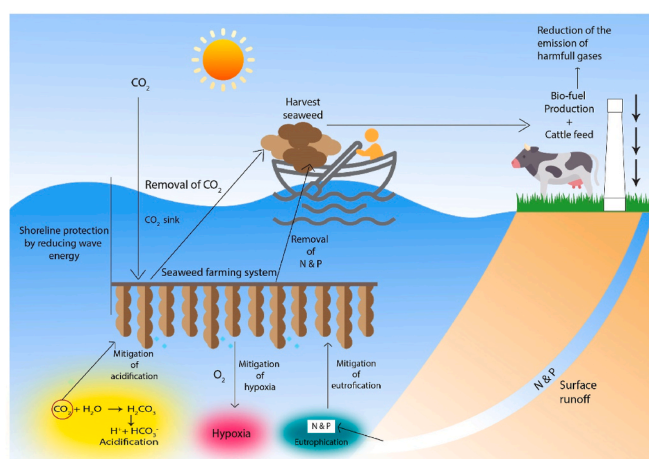

Fig. 2. Role of seaweed farming in climate change mitigation and adaption.

5.1. *Seaweed farming uptakes CO_2 responsible for global climate change impacts*

The term Blue Carbon (BC) is directly linked to the role of seaweed in CO_2 uptake, which is responsible for the global climate change impacts. BC is the term used to describe organic carbon absorbed and stored by coastal and oceanic ecosystems, most notably the vegetated habitats (Macreadie et al., 2019). The potential for BC to reduce climate change while delivering co-benefits like coastal preservation and fisheries improvement had achieved global attention (Duarte et al., 2013;

McLeod et al., 2011; Nellemann et al., 2009). Algae contribute to approximately half of the worldwide carbon fixation (Chung et al., 2011). They can account for most of the world's biological carbon storage, making them a natural method of reducing greenhouse gas emissions (Buschmann et al., 2017). While there is some debate regarding whether or how wild seaweed fulfilled the BC framework's requirements, there is growing evidence supporting seaweeds' involvement in carbon sequestration, especially concerning farmed production (Krause-Jensen et al., 2018; Raven, 2017; Trevathan-Tackett et al., 2015). So, seaweed beds can be a good option for sequestering and storing BC.

Seaweeds have significant contributions to marine carbon sinks worldwide (Krause-Jensen & Duarte, 2016). Chung et al. (2013) demonstrated that seaweed acted as CO_2 sinks by sequestering/converting carbon within their biomass throughout their whole life cycle, and seaweed farming is one of the numerous strategies being used to combat global warming by increasing natural sinks. Recent scientific data suggested that wild seaweeds might be able to sequester large quantities of carbon in the seas by exporting organic matter (dissolved and particulate) to the deep ocean (>1 000 m), where it is effectively buried (Krause-Jensen & Duarte, 2016; Wernberg & Filbee-Dexter, 2018). Seaweeds accounted for 1.5 million tonnes of carbon sequestration each year via commercial harvest seaweeds (Hossain et al., 2020), approximately 3.2% of the carbon released to seawater yearly by the emission of greenhouse gases. Seaweed farming is a significant route for removing CO_2 from the atmosphere, annually taking up 1.5 Pg C through its total production worldwide (Krause-Jensen & Duarte, 2016). Therefore, seaweed is responsible for a significant CO_2 capture in oceanic vegetated environments (Duarte & Cebrian, 1996).

Seaweed can reduce pCO_2 in seawater by converting dissolved inorganic carbon directly or indirectly from seawater through photosynthesis. As a result, these life forms act as an important medium for producing biomass and sequestration of CO_2 (Duarte et al., 2005) by removing a large quantity of carbon from the sea when harvested (Tang et al., 2011). It could sequester dissolved CO_2 at a daily rate of 80.5 mg/g WW. Still, their emission rate via respiration is just 10 mg/g WW per day since most green and brown seaweeds utilize the respiratory emission of CO_2 inside the cells for the photosynthesis process (Kaladharan et al., 2009). The seaweed culture system emitted carbon, buried in sediments or transferred to the deep ocean, serving as a sink for CO_2 (Duarte et al., 2017). While the culture system does not currently have the scale to play a worldwide role in mitigating climate change, it has a high capability CO_2 sequestration intensity of approximately 1 500 t CO_2 km^{-2} $year^{-1}$ (Duarte et al., 2017). The CO_2 capture potential of seaweed farming is estimated as 2.48 million t of CO_2 (0.68 Tg C) per year, representing the top limit of the industry's CO_2 capture potential (Duarte et al., 2017). Kaladharan et al. (2009) estimated that the biomass of seaweed along the coastal area of India could utilize 3017 tonnes CO_2/d compared to its 122 t CO_2/d emission, resulting in a net carbon credit of 2895 tonnes/d. According to the calculation by Zacharia et al. (2015), in Indian coastal water, the standing crop of 182 613 t (WW) green seaweed absorbed 7 487 t of CO_2 per day, while 41 740 t (wet wt) brown seaweed absorbed 981 t of CO_2 per day, and 36 523 t (wet wt) red seaweed absorbed 584 t CO_2 per day. A study done by Hossain et al. (2020) suggested that in Bangladesh, the annual production of 390 t (=97.5 t DW, 30% carbon in dry seaweed) of seaweed from aquaculture can sequestrate around 29 250 t of carbon.

Considering the significance of seaweed in mitigating climate change, the BC strategies are now being reassessed. The BC initiative based on seaweed was established in Korea (Sondak & Chung, 2015). In 2012, a total of 30 381.90 t (3.48 t/ha) of carbon was accumulated, and the seaweed aquaculture beds of Korea sequestrated 111 501.57 tonnes (12.80 t/ha) under the blue carbon initiative (Sondak & Chung, 2015). Cultivating climate-tolerant seaweed, e.g., *Eucheuma denticulatum,* as an implementation of the BC idea, could help mitigate climate change by absorbing and sequestering carbon (Lovelock & Duarte, 2019). The highly productive species could significantly contribute to the yearly biological depletion of CO_2 and the global carbon cycle (Turan & Neori, 2010). Carbon capture has been proposed as a possible advantage of seaweed culture (Froehlich et al., 2019), possibly contributing significantly to global climate change mitigation efforts (Chung et al., 2011; Duarte et al., 2017; Turan & Neori, 2010). Due to their high biomass and relatively lengthy turnover period, seaweed could be more efficient carbon sinks than marine phytoplankton (Delille et al., 2009; Gao & McKinley, 1994).

5.2. Additional roles of seaweed farming in climate change mitigation and adaptation

Because seaweeds are extremely good at absorbing and storing carbon throughout their lives, they could offset the emissions caused by burning fossil fuels (Langton et al., 2019). Seaweed biofuels, also known as "Blue biofuel," did not compete with agriculture for resources because they did not need freshwater, land, fertilizer, or pesticide. Therefore, these biofuels are environmentally more sustainable than biofuels produced from terrestrial crops (Duarte et al., 2009, 2013). Converting seaweed to bioethanol will also significantly increase carbon sequestration (Zacharia et al., 2015). The harvested seaweed could be utilized in whole or in part to produce biofuel with a significant CO_2 mitigation capability of around 1 500 t of CO_2 km^{-2} $year^{-1}$ concerning avoiding fossil fuel emissions (Duarte et al., 2017). According to Borines et al. (2013) and Hargreaves et al. (2013), several seaweed species have a high concentration of polysaccharides that may be turned into ethanol through suitable technology. The seaweed residual from different processing industries could be used to produce biofuel (bioethanol) (Zacharia et al., 2015). Successful conversion of seaweed to bioethanol on a wide scale would offer enormous climate resilience advantages (Zacharia et al., 2015). By analyzing the life cycle, Alvarado-Morales et al. (2013) documented that the total amount of CO_2 elimination from the atmosphere through biofuel production from seaweed farming is around 961 kg CO_2 per tonne dry weight seaweed. Using highly nutritive leftovers from biofuel production as fertilizer could help retain carbon in soil (Seghetta et al., 2016). The idea of seaweed cultivation as a non-traditional biofuel feedstock aligned with the goals of Climate Resilient Agriculture (Zacharia et al., 2015).

Seaweed farming could also decrease agricultural emissions by improving the quality of soil replacing synthetic fertilizer, and reducing the emission of methane from cattle when added to cattle feed (Duarte et al., 2017). According to *in vitro* experiment, the fermented seaweed could stimulate the ruminant digestion, which significantly minimized the production of methane gas (Kinley et al., 2016; Klinger, 2021; Maia et al., 2016), and adding just 2% of particular seaweed species to the feed of cattle could potentially decrease the ruminant methane emission of up to 99% (Machado et al., 2016). According to Roque et al. (2019) in the lab integrating only 5% organic component of *Asparagopsis* (Rhodophyta) into the feedstock could decrease the emission by up to 95%. In the case of agriculture, the use of highly nutritive seaweed biochar (Zacharia et al., 2015) or compost seaweed (Cole et al., 2016) could improve crop productivity through the enhancement of soil quality and, as a result, emissions associated with artificial fertilizer manufacturing could be avoided (Smith, 2002).

The potential of seaweeds to sequester carbon is regarded as a way to prevent ocean acidification. A low pH value degrades the availability of the shell-formulating mineral essential for crustaceans, mollusks, corals, and a diverse array of microorganisms in the marine environment (Gattuso & Hansson, 2011). Large masses of seaweeds can absorb a sufficient amount of carbon to raise the pH of surrounding water and mitigate the effects of ocean acidification (Campbell et al., 2019). Langton et al. (2019) suggested that seaweed farming led to a net positive rise in pH and oxygen in the surrounding farm operations, especially during the exponential development phase of their life cycle. The seaweed farms offer oxygen-rich environments, acting as a refuge from hypoxia and falling oxygen levels, allowing marine species to adapt to this aspect of a warming ocean (Duarte et al., 2017).

Furthermore, the presence of substantial seaweed farms, as well as their strategic placement, may provide coastal protection by damping wave energy, decreasing the physical damage caused by rising storm severity as a consequence of climate change (Langton et al., 2019). Farmed seaweed canopies, like wild seaweed canopies, reduce wave energy and therefore act as living protection for coastal structures against seashore erosion (Løvås & Tørum, 2001). The canopies of farmed seaweed are generally suspended from the sea's surface rather than benthic, making a significant difference in their ability to attenuate wave energy (Duarte et al., 2017).

6. Seaweed farming and women empowerment in the developing countries

Women empowerment is a global development variable (Malhotra et al., 2002). It is strongly linked to economic development as it significantly reduces the inequalities among men and women, and empowering women can benefit development (Duflo, 2012). Domestic women are encouraged to work in the public sector to achieve one of the MDGs' (Millennium Development Goals) 2020 targets of fostering gender equality and women empowerment in developing countries. It is the fact that females work for a livelihood or work in the public sector; they do not negate their primary responsibilities as housewives (Handayani & Artini, 2009). In most low-income and developing countries, the establishment of seaweed farming has been regarded as a powerful strategy to empower coastal women (Abowei & Ezekiel, 2013; Tobisson, 2013). In the Gorontalo Utara regency of Indonesia, a high number of female-led seaweed farming demonstrated the effectiveness of the local government's "fisher's community empowerment" initiative, supported by many society components, including village counselors and youths community leaders. The participation of these components provided an opportunity for interaction that allowed the sharing of experience and knowledge of seaweed farming (Kamuli, 2019). Seaweed cultivation significantly impacted female farmers' socio-economic position since it enables women to participate in an income-generating activity while still maintaining conventional household responsibilities (Valderrama, 2012).

Some countries have set examples of empowering women in the coastal communities through the seaweed farming industry; the most noticeable one is Tanzania. In Tanzania, the income from seaweed cultivation had aided women's economic empowerment and improved family food security (Besta, 2013). Seaweed farming is performed mainly in the Zanzibar Archipelago of Tanzania. It contributes significantly to the economy, whereby over 80% of seaweed growers are women in Tanzania (Msuya, 2012). Kalumanga (2018) recommended that the farming and processing system of seaweed be integrated for women's empowerment and sustainable development in Tanzania. According to gender statistics collected from the Ministry of Agriculture, Natural Resources, Livestock and Fisheries (MANRLF) in Zanzibar, the seaweed sector employed 26,000 farmers, 78% of whom were women; mainland Tanzania had 5000 farmers, of which 90% were women (Msuya & Hurtado, 2017). Based on the MANRLF data of 2012, the number of female seaweed farmers in Unguja was 8 094, and in Pemba, it was 10 378, compared to 605 and 4 612 male farmers, respectively (Msuya & Hurtado, 2017). By July 1990, along the west and south coasts of Zanzibar, over 1 000 female farmers had joined the seaweed farming industry, having discovered that the returns were more significant than other occupations typically done by coastal community women (URT, 2005). According to Kalumanga (2018), in the eastern coastal area of Zanzibar Archipelago, women produced 412 t of seaweed in 2016/2017, 80% of total seaweed output, while males produced just 103 t, equal to 20% of total output. In Zanzibar, women manufactured over 20 items from seaweed, including cake, cookies, juice, jam, salad, shampoo, and soap, and these items helped them enhance livelihood (Kalumanga, 2018). The income generated by their participation and entrepreneurship in sustainable seaweed farming enabled them to upgrade their standards of living by providing funds for their children's education, medical care, public housing and clothing improvements (Msuya & Hurtado, 2017). In this Archipelago, women who relied on males for home goods now contribute substantially to basic family necessities such as paying school fees and purchasing clothing for themselves and other family members (Msuya, 2010). In Kenya, commercial seaweed cultivation began in the year 2010 on the south coast, with the majority of workers being women (Msuya & Hurtado, 2017).

In Asian countries like India, Indonesia, Malaysia, the Philippines, and Sri Lanka, coastal women have engaged themselves in the seaweed industry for income generation and boosting family earnings. In Indonesia, out of all types of aquacultures, seaweed farming had the most significant percentage of female involvement (MMAF, 2014; Taryono, 2004). Eranza et al. (2015) conducted a quantitative study and recorded women's participation in seaweed aquaculture in the Jeneponto region of South Sulawesi. According to Geo and WO (2020), in Southeast Sulawesi, Indonesia, most seaweed production systems women know how to make seaweed-based goods like cendol, dodol candy, and cake. This skill was acquired via training provided by the local government and giving them an opportunity for extra income. In Indonesia, the involvement of females in seaweed cultivation resulted in work satisfaction and social recognition, something that was also observed in Malaysia and the Philippines (Msuya & Hurtado, 2017). Women were the earliest and most enthusiastic adopters of seaweed cultivation in India, which provided them with a source of income in a safe environment (Krishnan & Narayanakumar, 2013, pp. 163–184). Immanuel and Sathiadhas (2004) reported the participation of women in India's seaweed sector, stating that 5000 women were reliant on seaweed relevant activities and income generation for their livelihoods. At that time, the Indian seaweed industry employed approximately 10 000 workers, 50% of whom were females. In fact, the early success of female farmers in seaweed cultivation encouraged males to join in this sector (Msuya & Hurtado, 2017).

Different government and non-government organizations of India established some seaweed culture projects in the coastal region in which women's participation was ensured. For example, the "Tamil Nadu Women's Empowerment Project" in Tamil Nadu, India, was an internationally funded seaweed farming project where 50% women participation was ensured (Krishnan & Narayana Kumar, 2010). Training programs were developed as part of this seaweed farming plan to target females (Msuya & Hurtado, 2017) selectively. In Sri Lanka, the seaweed culture provided female farmers with suitable employment opportunities, which could be managed easily with their household chores (Ginigaddara et al., 2018). The positive impact of income creation through seaweed farming promoted household economic resilience and allowed for a sustainable way of life, raising the farming communities' overall standards of living (Crawford, 2002). Since the late 1970s, when seaweed farming was established in Malaysia, it had been mainly centered in eastern Sabah (Suhaimi, 2011). In the east of Sabah, the main reason for the success of the seaweed industry was males and females joint-participation (Msuya & Hurtado, 2017). The establishment of the 'Mini-Estate System' for the production of seaweeds in Sabah in 2009 provided more possibilities for women to attain sustainable productivity (Hussin et al., 2015). The raised social status via seaweed farming kept the Malaysian women involved in this industry (Msuya & Hurtado, 2017). In the Philippines, both male and female seaweed farmers have equally participated in decision-making on household and farming activities of seaweed (Msuya & Hurtado, 2017). Rather than rivalry and conflict, males and females are often seen in scenarios of cooperation and co-production due to the participation of women (Hurtado, 2005). Women's important and beneficial involvement in seaweed farming has been further highlighted after the devastation caused by Typhoon Haiyan in different regions of the Philippines when women actively engaged themselves in the restoration of the affected seaweed farms after the disaster (Msuya & Hurtado, 2017).

7. Major issues and challenges

The major challenge of considering seaweed as a staple food is making seaweed food products accessible, appealing, and cheap to billions of people. Moreover, it is also challenging to avoid confusion among these vast consumers that seaweed-based foods are nutritionally comparable to the other foods they regularly consume (Forster & Radulovich, 2015). It takes time for any new food product to be accepted by society and worldwide, and here seaweed is an entirely new food ingredient for many regions of the world. So, it will be a big challenge to achieve consumer acceptance like any other primary agricultural food product. According to Forster and Radulovich (2015), the apparent health advantages of seaweed might not be similarly applicable to all users since the health advantages of some species seemed to be dependent on their digestibility. According to Fleurence (2004), the presence of antinutritional substances such as trypsin inhibitors and polysaccharides seems to restrict the digestion of seaweed protein present in *Palmaria palmata*. Seaweed polysaccharides for utilizing thickening and gelling agents in processed food products provide several health advantages but provide little or no digestible dietary energy (Forster & Radulovich, 2015). After conducting comparative research on nutrient utilization of Wakame (*Undaria pinnatifida*) and Nori (*Neopyropia tenera*, formerly *Porphyra tenera*) in diet, Urbano and Goñi (2002) suggested that these two seaweed species could be an excellent source of fiber but they might alter digestion of dietary minerals and proteins. As plants, the maximum nutritional benefits of seaweeds differ significantly according to species, nutritional requirements, and status of people who consume them. In that case, species-specific nutritional research must be conducted alongside cultivation and product development research. In this regard, it's worth noting that in Japan, where seaweed species have been consumed for centuries, some individuals digest it more quickly than others (Forster & Radulovich, 2015). This is because of the presence of some specific bacteria in their intestines, and the bacteria have obtained genes for enzyme production that degrade the polysaccharide present in Porphyra (nori) (Forster & Radulovich, 2015). It is believed that these genes were initially obtained from marine microorganisms that were likely consumed with "nori" (Ledford, 2010). For this reason, people who have newly added seaweed to their diet may face some digestibility problems. Another nutritional concern is related to the high mineral contents of seaweeds, and excessive consumption might negatively impact human health. For example, the iodine in certain seaweed species may induce elevated thyroid-stimulating hormone levels, and cases of carotenoderma (skin yellowing) were found when significant quantities of seaweed were consumed regularly (Nishimura et al., 1998). If seaweeds are cultivated in contaminated waters, they may be contaminated with the accumulation of pollutants, particularly heavy metals. Toxins are accumulated in particular seaweed species (Giusti, 2001; Sudharsan et al., 2012), and they can be toxic and threatening to human health. In developing value-added seaweed based functional food products for human consumption, the lack of human trials and clinical data to defend animal and cell-based evidence were the barriers (Brown et al., 2014; Hafting et al., 2015). Regulatory restrictions on seaweeds that had not historically been utilized by humans in localities was a major impediment to the integration of seaweed species in functional foods (Hafting et al., 2015).

In the perspective of climate change, the major challenge of seaweed cultivation is the emission of halocarbons from seaweed beds (Phang et al., 2015). Chloroform and bromoform are naturally produced by seaweed species (Nightingale et al., 1995; Pyle et al., 2011). Volatile halocarbons contribute significantly to the atmospheric concentration of halogen radicals implicated in ozone's catalytic destruction (Phang et al., 2015). In large-scale culture systems of seaweed, different artificial materials create a firm substrate. The highest portion of these materials is made of a combination of synthetic polymers, which are very much resistant to deterioration. If culture systems are not correctly maintained, marine pollution from wasted and lost materials can occur (Campbell et al., 2019). It also increases the plastic level in the food webs of the marine ecosystem (Andrady, 2011; Derraik, 2002). Competition for the sunlight between seaweeds and other organisms may be another critical issue of seaweed farms as the seaweed cultivation on seawater surface may shadow underlying ecosystems with autotrophic species (Campbell et al., 2019). Present seaweed farming technology, mainly dependent on simple structures, can only be used in comparatively sheltered regions, limiting the farming sector to a fraction of its potential zone (Duarte et al., 2017). The warming of ocean waters may decrease fucoid canopies because of physiological stress, extra pressures from herbivores of warm oceanic waters (Harley et al., 2012), storms and cyclones, and reduced supply of nutrients (Callaway et al., 2012) may potentially reduce the opportunity of seaweed farming. The potential consequences of expanding seaweed aquaculture by introducing exotic seaweed species must also be considered (McLaughlan et al., 2014). 2017). Seagrass fields are the hotspots for carbon sequestration and, therefore, important for BC ecosystems (Duarte et al., 2005, 2013; Fourqurean et al., 2012). They are susceptible to human disturbances by adjacent seaweed farms' operations, resulting in mechanical damages and shading (Waycott et al., 2009). To avoid unfavorable interactions with other users of the coastal area, like navigation, and to limit environmental effects from seaweed farming, spatial planning is compulsory before establishing the farm. The major difficulties in China include competing for an appropriate area with other uses and maintaining a healthy profit (Duarte et al., 2017). Indeed, to expand the contribution of seaweed farming to climate change mitigation and adaptation, continued growth in seaweed outputs is needed. However, increased seaweed outputs may lower market pricing, deterring farmers from participating in this activity (Duarte et al., 2017).

Intensive seaweed farming for the production of bioenergy or biofuel concurrently carbon capture and storage is one of the suggested strategies. Although this strategy is fundamentally appealing and deserves to be the subject of research, implementation challenges exist—for example, the massive amount of sea area is needed and the viability of the strategy to fulfill the twin goals of producing energy and capturing carbon had been questioned (Melara et al., 2020). In spite of decades of research, seaweed-based biofuels have not yet reached the market, nor their manufacturing has yet been proven commercially feasible (Raven, 2017). In the case of ocean acidification, Britton et al. (2019) proved that only the carbon uptake technique could not be served as an indicator of seaweed responses to ocean acidification. Furthermore, the effectiveness of seaweed afforestation for the removal of CO_2 will certainly be influenced by planetary feedbacks, raising concerns about its role in climate change mitigation measures (Bach et al., 2021).

The main challenge in the case of women's involvement in seaweed farming is the lack of technical knowledge. Hedberg et al. (2018) studied women who cultivated seaweed in Zanzibar and found that they could not swim and could not access boats. As a result, seaweed farming by women is confined in very shallow water regions. Women's activities are limited to working only at low tide, which might be 3–5 days per week, while men farmers could work daily (Fröcklin et al., 2014). Women cannot play a significant role in setting up the seaweed farms because lots of hard work and strength are needed to set the bamboo, tieing rope, and build up the entire structure. The majority of women cannot operate the boat for transportation and cannot use various equipment. Because of these reasons, women have to pay for transportation and have to be dependent on men during farm setup and harvesting. Previous studies have shown that female farmers face various health problems due to their job (Vestling and Forsberg, 2018). According to Fröcklin et al. (2012), tiredness and other discomfort were prevalent among seaweed farmers, and the physical labor was higher in contrast to the economic return.

8. Conclusion

Seaweeds are considered a vital component of current global food security with their additional roles in climate change mitigation and women empowerment. Some recent research represents seaweed farming as an alternative to terrestrial agriculture because of its simple culture method, impressive nutritional composition, and contribution to global climate change mitigation and adaptation strategies. The seaweed industry is anticipated to help most farmers, especially women, by boosting their economic buying power, enhancing social empowerment, and contributing to poverty reduction efforts. While seaweed farming technology has advanced significantly over the past several decades, there are still significant obstacles to overcoming its sustainable production technologies, diversified uses, and societal acceptance. In the case of cultivation, the first step should involve careful selection of the appropriate species and suitable culture sites in the coastal waters to ensure sustainable production at an affordable cost with maximum benefits. Maintaining a market price that motivates the farmers to participate in the farming system is also necessary. It is imperative to establish essential regulations to improve the quality of seaweed species and their derived products for human consumption. It is also crucial to determine the daily intake of seaweed or seaweed products for a healthy diet. To develop a sustainable seaweed farming industry, it is essential to improve collaboration and coordination among the seaweed producing and utilizing nations and countries. Best management practices for the economically viable, environmentally benign, and socially acceptable seaweeds farming technologies should be developed and disseminated among tropical and subtropical countries by national and international bodies. This should be done without delay to ensure the contribution of these nutritious aquatic foods for a healthy planet and human populations.

Credit authorship contribution statement

Conceptualization, M.A.; Data curation, F.S., M.A.; Writing – original draft preparation, F.S., M.A., M.A.W., M.Z.I.; Writing-review and editing, M.N., A.A.M., M.M., A.S., M.S.R.K., L.L.W.; Funding acquisition, M. A., M.A.W., M.N. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare that there no conflicts of interest to report.

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