Harnessing the environmental and economic potential of seaweed to create a resilient future of aquaculture

Faseeha I.[1]; Hafeez-ur-Rehman M.[1*]; Ullah I.[2]; Khan T.[1]; Mustaqeem S.[3]

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Abstract

From the past 25 years the demand of macro-algae increase globally and its culture grown rapidly due to their environmental, nutritional and industrial strengths. It is also known for their rich content of lipids, fibers, protein, minerals and bioactive compound that make it priceless for the consumption of human animals, and aquatic organisms also use in pharmaceutical, nutraceutical and in cosmetics. Due to their rich content of polyunsaturated fatty acids and vital amino acids, macro-algae are developing as a sustainable substitute for fish oil in aquaculture feed. Historically employed in agriculture for their plant-growth-promoting properties, seaweeds continue to provide to enhancing crop yield. Furthermore, seaweed farming supports environmental stewardship by enhancing coastal ecosystem health and contributing a viable source of biofuel through anaerobic digestion. The diversity of seaweed species adaptable to various climates from tropical to temperate underscores the importance of increased investment in scientific exploration**,** technological advancement**,** and strategic policy-making to accelerate the development of the seaweed industry and its contribution to advancing the blue economy.

Keywords:

Seaweed, Sargassum, Macro-algae, Cultivation

1-University of Veterinary and Animal sciences, Department of Fisheries and Aquaculture, Lahore, Pakistan
2-Islamia College University Peshawar - Department of Zoology, Peshawar, Pakistan
3-Gomal University - Department FVAS, Dera Ismail khan, Pakistan
*Corresponding author's Email: mhafeezurehman@uvas.edu.pk

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Introduction

Macroalgae, or seaweed, are photosynthetic marine organisms from the kingdoms *Chromista* or *Plantae*, serving as key primary producers in coastal ecosystems. The contribution of seaweed aquaculture to the economics of coastal communities is the employment of the millions of people; with 96% of all aquaculture engagement located primarily in Asian countries (FAO, 2020). It has been estimated that macroalgae have 9000 species worlwide (Khan *et al.,* 2009). They are plant-like in form but they lack true roots, stems, and vascular tissue (Dawes, 2016). Beyond its commercial importance, seaweed cultivation plays a key role in promoting environmental sustainability by improving diverse ecosystem functions. It supports ecological processes such as nutrient cycling, primary production, species diversity, and habitat integrity, while also aiding in the regulation of sediment flow, atmospheric interactions, and biological systems, including the reduction of eutrophication (Hasselström *et al.,* 2018)

Seaweed play an important role in maintaining the food chain in aquatic environment, and the absence of macro-algae show the disturbance in the water body (Khan *et al.,* 2009). Seaweed is considered as the living resources of marine and also known as the wealth of ocean (Paul *et al.,* 2007). The seaweed can store good amount of carbon and lessen its free level. As it is observed that global warming is intimidating remark seen on earth (Botkin *et al.,* 2007; De Schryver *et al.,* 2009). They amend the ecosystem of marine and reserve the diversity. Various organisms of marine are seen adhered near the algal biodiversity, and play a productive role in the food cycle (Jones *et al.,* 2000). Single kelp can engage 8000 macro invertebrates organisms (Burrows *et al.,* 2014) and the individual engaged here will elevate with increase in the number of algae and provide larger habitat area (Christie *et al.,* 2003). Sea cucumbers, starfish, shrimp, snails, and crabs are examples (Burrows *et al.,* 2014).

Nutritional profile

Commonly, macro-algae comprise macronutrients including lipids (vital fatty acids, n-3 and n-6), proteins (essential amino acids), and carbohydrates (dietary fiber), micronutrients, such as vitamins and minerals. This composition has good health benefits on the health of living organism's e.g, anti-obesity, anti-oxidant, antibacterial and anti-inflammatory (Buschmann *et al.,* 2017). High amount of various vitamins (A, K and B12), present in seaweeds, minerals, protective pigments and trace elements that are important in the diet of humans, might collaborate with European union permitted nourishing entitlements (such as iron, iodine, magnesium or calcium) linked with cognitive function, bone health, muscle function, normal growth and maintaince of normal metabolism (Mabeau S and Fleurence, 1999; Macartain *et al*., 2007; Barbier *et al*., 2019) (Fig. 1).

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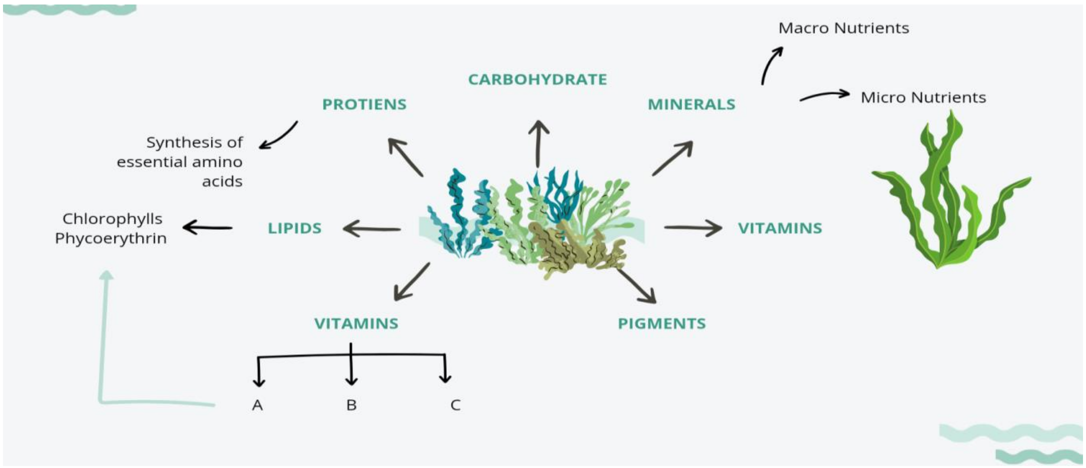

Figure 1: Nutrional components in macro-algae.

Some macro-algae are a great source of protein, carbohydrates, and vitamins A, B, B2, and C. Eatable seaweed has polysaccharides (starch, hydrocolloids, floridoside, laminarin, cellulose and hemicellulose such as agar, carrageenan and alginate) vitamins (A, B1, B2, B9 (folic acid), B12, C, D, E, and K), protein, minerals (Na, I, Mg, Fe, K, Ca, Se, Zn, and F), polyphenols (flavonols, phlorotannins, and catechins) low amount of fat which are poly and monounsaturated with little caloric value and antioxidants (polyphenols, vitamin C and E, carotenoids, sulphated polysaccharides, sterols, phlorotannins, proteins and catechins) (MacArtain *et al*., 2007; Fernández *et al*., 2018; Pandey *et al*., 2020). In addition to these, there are several trace elements and minerals, with iodine being the most notable. Its low calorie content and suitability for all types of vegetarians is an added benefit. Minerals like calcium, potassium, sodium, sulphur, magnesium, phosphorus, chlorine micronutrients that are present in different seaweed are iron, copper, molybdenum, manganese, nickel, iodine, cobalt, zinc, selenium, fluoride and boron. Normally brown seaweed has (upto 15%) protein whereas red and green seaweed have high protein (upto 30%) (Kolanjinathan *et al*., 2014).

Many of its species include a variety of minerals; brown seaweed is typically the best provider of iodine. Although the amount of protein and calcium varies from species to species, the amount of fat is minimal. In general, the protein content of red and green seaweeds is higher (up to 30%), whereas that of brown seaweeds is lower (up to 15%) (Kolanjinathan *et al*., 2014). Glutamic and aspartic acid collectively constitute enough portion of amino acid in various seaweed (Astorga *et al*., 2016; Bikker *et al*., 2020) mainly in *A. nodosum* (38.22% of total amino acids) (Kadam *et al*., 2017), *U. rotundata* (32%), *U. rigida* (26%) and *Fucus spp.,* 22–44%), (Fleurence, 1999) *C. crispus* (38.62%), *Gracilaria spp.,* 25.82%), *Ulva spp.,* formerly *Enteromorpha spp.*) (28.11%) (Kazir *et al*., 2019).

The minimum amount of carbohydrates is recorded in *Dictyota dichotoma* a brown seaweed (10.63%) and highest amount of carbohydrates are

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seen in green macro algae *E. intestinalis* 28.58 % (Parthiban *et al*., 2013). Chakraborty and Santra 2008, reported the content of carbohydrates in *E. intestinalis* (30.58%) and *U. lactuca* (35.27%).

Types of seaweed

Macroalgae categorize on the basis of presence of photosynthetic pigment and cell wall structure *Rhodophyta* (red), *Chlorophyta* (green), and *Phaeophyta* (brown). Their color is due the pigments fucoxanthin, chlorophyll and phycoerythrin (Khan *et al.,* 2009). Amoung 200 known species of seaweed, nearly 10 species of macroalgae are cultivated extensively which contain brown seaweeds (*Undaria pinnatifida, Saccharina japonica, Sargassum fusiforme*), green seaweeds (*Cauleurpa* spp*., Monostroma nitidum, Enteromorpha clathrata*) and red seaweeds (*Kappaphycus alvarezii, Eucheuma* spp*., Porphyra* spp*., Gracilaria* spp.) (FAO, 2018).

Green seaweed

Chlorella, enteromorpha and *ulva* are predominant seaweed. Approximately 305 species of macroalgae with blade-like or filamentous morphologies are known to exist in the genus *Ulva*. Many species of *Ulva* are edible (Pereira, 2016), and they typically have intriguing traits that make them very appealing for aquaculture, including broad distribution, rapid growth, high environmental tolerance, low susceptibility to epiphytism, and high capacities for nutrient uptake (Carl *et al*., 2014; Hiraoka *et al*., 2020).

The green macroalgae *Enteromorpha intestinalis* and *Ulva lactuca* found to have enough contribution in its carbohydrate content i.e 30.58% and 35.27% (Chakraborty and Santra, 2008; Parthiban *et al*., 2013). The content of fiber in edible seaweed varies from 33-62% of dry mass which high in amount as compare to other higher plants. In seaweed lipid content concentration varies from 1.33% in *E. intestinalis* and 4.6% in *E. clathrata*. It is reported in some studies the amount of lipid, that is 1.33% in *Kappaphycus alvarezii* and *Utricularia rigida* 12%, respectively (Satpati and Pal, 2011; Rajasulochana *et al*., 2012) (Fig. 2).

Green seaweed has acidic nature polysaccharide e.g sulfated galactans, xylans and sulfated polysaccharides that present in the green seaweed's cell wall (Wu *et al*., 2020; Wang *et al*., 2020b, Wassie *et al*., 2021; Li *et al*., 2021a; Cao *et al*., 2022; Chen *et al*., 2022). β-carotene have antioxidant quality that can be formed by microalgal *Dunaliella salina* that help to control the damaging effect of free radicals, that can cause serious problems of life including coronary heart disease, arthritis, premature aging and cancer (Dembitsky and Maoka, 2007; Miyashita, 2009). Astaxanthin are produced from *haematococcus pluvialis*, it's a red component of carotenoid make astaxanthin interesting by showing antioxidant properties, anti-inflammatory, anti-diabetic and anti-cancer (Ambati *et al*., 2014; El-Baz *et al*., 2018) (Table 1).

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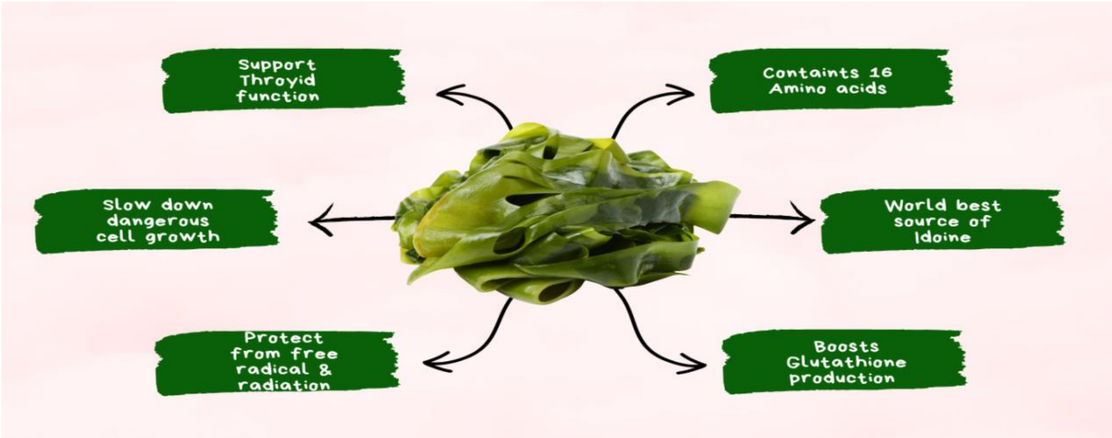

Figure 2: Functions of Green macro-algae.

Table 1: Role of green seaweed.

Green Macroalgae	Compound	Bioactivity	References
Ulva fasciata	Sulpholipids	Antibacterial	El Baz *et al.,* 2018
-	-	Antiviral	-
-	-	Antitumoral	-
Codium vermilara	Sulphated polysaccharides	Anticoagulant	Ciancia *et al.,* 2007
Codium dwarkense	-	-	Siddhanta *et al.,* 1999
Ulva australis	-	Antioxidant	Qi *et al.,* 2005
Ulva rigida	-	Antitumoral immunodulatory	Leiro *et al.,* 2007
Ulva prolifera	-	-	Kim *et al.,* 2011
Monostroma latissimum	-	Antiviral	Kazłowski *et al.,* 2012
Codium fragile	-	Antiviral	Ohta *et al.,* 2009
Codium fragile	Siphonaxanthin	Antitumorl	Ganesan *et al.,* 2010
-	-	Antiangiogenic	Ganesan *et al.,* 2011
Ulva armoricana	Glycolipids	Antitumoral	Kendel *et al.,* 2015
Codium tomentossum	Lipids	Antioxidants	Rey *et al.,* 2020
Caulerpa racemosa	Squalene	Anti-inflammatory	Fernando *et al.,* 2018
Bryopsis spp	Depsipeptides	Antiviral	Suárez *et al.,* 2003
-	-	Antimalarial	-

Red seaweed

The Rhodophyta (red algae) are red in color due to the pigments (Knowler *et al*., 2020). Important pigment named Phycocyanin seen in red seaweed (Cian *et al*., 2014). The profitable use of this compound is used as natural dyes in soft drinks, chewing gums, cosmetics and in dairy products e.g eyeliner and lipstick (Spolaore *et al*., 2006). In all that, these compounds are good for advantageous bioactivities, so they are represented as nutraceutical products (Sekar and Chandramohan, 2008). Component extracted from seaweed called Carrageenan. It is taken from one nominated group named carrageenophytes which is known as carrageenan producers; belong to the family Gigartinales (Gurgel *et al*., 2007; Pereira and Mesquita, 2003) (Fig. 3).

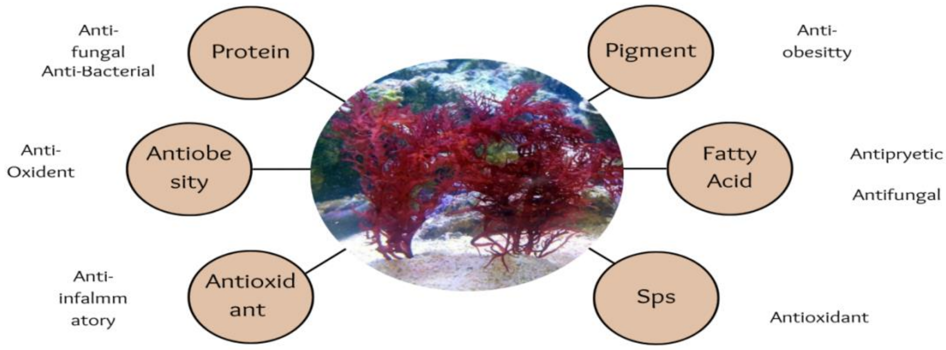

Figure 3: Role of red macro-algae.

Eucheuma and *Kappaphycus* are important red seaweed, also collectively known as eucheumatoids produced highly due to universal demand (Buschmann *et al*., 2017). From seaweed carrageenan is produced but it is not adapted by humans, with no nutritional value and low fiber, it is just used for thicken food products (Imeson, 2009). Carrageenan is similar to the carboxymethyl cellulose (CMC) it is used as binder in toothpaste (Bixler and Porse, 2011). Among all three phyla high digestibility seen in the red seaweed (Tibbetts *et al*., 2016), compare the values with various plants, some grains (69–84%), fruits (72-92%), vegetables (68-80%) and legumes (72–92%) (Tibbetts *et al*., 2016; Bleakley and Hayes, 2017). 17% of digestibility recorded in *U. pinnatifida* (brown) 66.6% when using pepsin (acidic pH, 37 ◦C) and pancreatin (pH 7.6, 37 ◦C), respectively (Fujiwara *et al*., 1984).

Red macroalgae are typically characterized by flavonoids and phenolic acids among compounds of phenols. Additionally compound of phenol (bromphenol and phlorotannins) sole to sources of marine in less quantity and have good antioxidant activity (Olsen *et al*., 2013; Cotas *et al*., 2020a; Dong *et al*., 2021). It contains anti-inflammatory anti-oxidant and anti-aids property (Choi *et al*., 2018; Paudel *et al*., 2019). Major terpenoids are named as carotenoids that seen in red macroalgae that contribute to distinct pigmentation, that characterized by zeaxanthin, α-carotenes, β-carotenes and lutein (Holdt and Kraan, 2011; Zubia *et al*., 2014; Kavalappa *et al*., 2019; Cotas *et al*., 2020b; Ávila-Román *et al*., 2021).

Gracilaria

Two of the most widely grown seaweeds in the world are the red algae *Gracilaria* and *Gracilariopsis*, which produce about 3.8 million tons a year and are valued at approximately US $1 billion (FAO, 2017). China and Indonesia have been the primary producers of *Gracilaria/Gracilariopsis*, accounting for 70% and 28% of global production, respectively, whereas Chile is the most producing nation in the Americas (FAO, 2014). Presently, 185 species of *Gracilaria* and 24 species of

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Gracilariopsis are taxonomically recognized (Guiry, 2014). Approximately 66% of all agar is produced by *Gracilaria/Gracilariopsis* (Pereira and Yarish 2008). Currently, 24 species of Gracilariopsis and 185 species of *Gracilaria* are recognized taxonomically (Guiry and Guiry, 2016). There are four primary methods for cultivating Gracilaria/Gracilariopsis including pond tank cultures, near-shore bottom cultivation, and open water rope cultivation (Oliveira *et al*., 2000; Sahoo and Yarish 2005; Pereira and Yarish, 2008). *Gracilaria* is mostly utilized for agar production and as feed for abalone, while *Kappaphycus/Eucheuma* is predominantly used for carrageenan extraction. Similar to alginate that is taken from brown seaweeds, seaweed-based hydrocolloids like agar and carrageenan are utilized extensively in both the food and non-food industries. The coastal populations where *Gracilaria* and Kappaphycus/*Eucheuma* are grown also eat them as human foods (such as pickles and salads). Porphyra are typically consumed by humans as ingredients in soups and sushi wraps (FAO, 2018) (Table 2).

Table 2: Brown seaweed.

Country		Laminaria/Saccharina cultivation	
		Tonnes	**Share of world (%)**
World		**12273748**	**100.00**
1	China	10978362	89.45
2	Japan	32600	0.27
3	Spain	0.14	0.00
4	Republic of Korea	662557	5.40
5	Norway	73	0.00
6	Faroe Island	156	0.00
7	Democratic people’s republic of Korea	600000	4.89

FAO 2021 Fishery and Aquaculture Statistics.

Brown seaweed

Asia produced almost all of the kelp: South Korea 6.6%, North Korea 4.4%, and China 88.3% (FAO, 2017). Traditionally used primarily for human food, kelp has recently seen a rise in use as abalone feed because of its inexpensive production costs (Hwang *et al*., 2013). 358 taxonomic species of brown seaweed, among all genuses Sargassum is richest one (Guiry and Guiry, 2016). Beds of Sargassum are essential habitat that provides nursery, spawning and grounds of feeding for different aquatic organisms (Komatsu *et al*., 2014) play role an important ground for the support of aquatic life and whole ecosystem, good enough habitat for mangrove forests, coral reefs and seagrass beds. In addition Sargassum also has potential to use as an animal feed (Kim *et al*., 2015) and fertilizer (Williams *et al*., 2010).

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In the cell wall of brown seaweed alginates are seen with varies structures of chemical, characteristics depends on the various genera of brown seaweed. *Durvillaea, Laminaria, Ecklonia, Macrocystis, Lessonia, Ascophyllum* and *Sargassum spp*. are the species of brown seaweed that have alginate. Use of alginates in cosmetic, food, textile, pharmaceutical and construction industries due to its capability to be used as thickeners, emulsifiers, gel forming agent, binding agent because of its condense aqueous nature (Wiltshire *et al*., 2015).

From brown algae get fucoidans (*Costaria costalla, Undaria pinnnatifida, Eclonia cava, Sargassum horney*) that hinder the spread of colon cancer cells and melanoma in human, and used as an operative agent for anti-tumor (Suganthy *et al*., 2010; Ermakova *et al*., 2011). The strong antioxidant activity of various macroalgae are used for decreasing the oxidative stress on cell and treat different serious diseases. These macroalgae also contain hepatoprotective, wound curative properties and anthelmintic (Sharma *et al*., 2016) (Table 3).

Table 3: Bioactivity of brown macro-algae.

Brown Macroalgae	Compound	Bioactivity	References
Ascophyllum nodosum	Sodium alginate	Prebiotic	Okolie *et al.,* 2020
Fucus vesiculosus	Fucoidan	Anti-angiogenesis	Oliveira *et al.,* 2019
Sargassum polycystum	Fucoidan fraction-2	Antibacterial	Palanisamy *et al.,* 2019
Sargassum glaucescens	Fucoidan	Hair growth promoting	Huang *et al.,* 2022
Padina pavonioca	Sulphated polysaccharides	Anticancer, antioxidant	Cao *et al.,* 2016
Sargassum angustifolium	Fucoidan	Wound healing	Amiri *et al.,* 2023
L.japonica	Polysaccharides	Antiviral	Cao *et al.,* 2016
Sargassum ilicifolium	Fucoidan	Antioxidant (bone regeneration)	Devi *et al.,* 2022
Sargassum horneri	Alginic acid	Anti-inflammatory	Fernando *et al.,* 2018
Sargassum fulvellum	Sulphated polysaccharide	Anti-inflammatory	Wang *et al.,* 2021

Extract and uses

Different chemicals were extracted out from macro-algae and utilized in the different products of biotechnology, cosmetics and food (Carneiro-daCunha *et al*., 2011; Singh *et al*., 2018; Hu *et al*., 2021). Extract of seaweed used as addition to diet of fish which can increase the lipid metabolism, growth, stress response, physical activity, and carcass quality, disease resistance of different species of fish (Soler *et al*., 2009; Güroy *et al*., 2011). Microalgae also show promise in carbon sequestration, biofuels, wastewater remediation, and algae meal and oils (Khan *et al*., 2008). Recently seaweed farms are inhibited near coast and protected area (Kim *et al*., 2017).

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As reported, algae of marine are enough in biocompounds and nutrients (Vlaisavljevi *et al*., 2021). Phyco-colloids are naturally polysaccharides that obtain from seaweeds and have miscellaneous physicochemical features (Los Ficocoloides en la Industria, 2022). The phycocolloids found in the species named *Sargassum* are laminarin, fucoidan and alginate (Marliana *et al*., 2018). They are known to perform various biological functions e.g neuroprotective effects (Bălas *et al*., 2020), anti-collagenase activity, antitumor potentials and antimicrobial effects (Kalasariya *et al*., 2021), antioxidant activities (Liu *et al*., 2020).

Fucoidans

Fucoidans are considering as the important bioactive compound originate in Sargassum specie, and fucose is chief monomer. The fucoidans composition depends on various factors i.e climate condition, species and geographical area of recovery etc. Antiviral, anti-bacterial properties seen in fucoidans also contain anti-cancer and antioxidant (Marliana *et al*., 2018).

Alginates

Aginic acid salts from alginates are the derivatives. Their main function is give structural composition to the cell wall because of its viscous nature and gel formation physiochemical properties (Bălas *et al*., 2020). It is demonstrated from study that in the body, alginic acid averts the preoccupation of heavy metals. It is examined that derivatives of alginate play role as a curative compound against neurodegenration. Alginic acid is advantageous for health, play role as a dietary fiber and decrease cholesterol level (Holdt, and Kraan, 2011).

Phycocolloid

From different brown seaweed species (Saccharina, Laminaria, Fucus, Laminariaceae and Eisenia) cell wall present linear polysaccharide which is non-toxic and biodegradable named phycocolloid laminarin. This compound has ability to play anti-inflammatory, antioxidant, as prebiotics and antitumor properties (Huang *et al*., 2022).

The industry of food is the largest industry, consumable macroalgae have the ability to form functional food form various years. Researchers made enough effort from 15 years to know their novel way to use in meat products as bioactive compound to enhance its value (Gullón *et al*., 2020). The industries of cosmetics contain biocompound of marine that used as a, gelling agents, viscosifiers and stabilizers (Pradhan *et al*., 2022).

Distribution

In Pakistan 234 species of macro-algae are seen in it 110 seaweed genera are reported on the coast of Balochistan, distributed 57 families widely, 33 orders, 12 classes and 6 divisions (MFF Pakistan, 2016). Variety of marine benthic seaweeds seen on the different coastal waters e.g Manora, Pacha, Cape Monze, Sandpit, Buleji, Nathiagali and Paradise Point (Rizvi *et al*., 2001).

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It is explained that the occurrence of important seaweeds was seen in Buleji and Manora where commonly 20 species were seen e.g *Halymenia porphyroides*, *S.typopodium zonale*, *P.adina pavonica*, *Iyengaria nizamudinii*, *S. boveanum*, *Colpomenia sinuosa*, *Lobophora variegate*, *D. indica*, *Colpomenia sinuosa*, *Jania adherence*, *Stokyia indica*, *Spatoglossum variabile*, *P. gymnospra*, *Cystoseira indica*, *S. vulgare*, *I. stellata*, *S. filifolium*, *D. hauckiana* and *Dictyota dichotoma* were seen abundantly (Bashir *et al*., 2023).

14 species of macro algae seen in Hawksbay, Paradise and Sandspit areas e.g *Udotea indica, Colpomenia sinuosa, Iyengaria* sp*., Padina* spp*., Padina* spp*.,* Jania *adherence, Laurencia pinnatifida Caulerpa taxifolia, Cystoseira indica, Dictyota indica, Sargassum* spp*., Gelidium pusillum* while at Mubarak village and Sonehra point the most common found was *Dictyota indica* and *Codium iyengarii*, in the area Chach Jaan Khan K.T. Bandar and at Shahbandar the dominant specie seen was *Enteromorpha flexsousa* (Bashir *et al*., 2023)

Hameed and Ahmed (1999) figured 85 species from Bulegi and explained different micro-habitat linked with algae. It is reported by Saifullah (1973) that 48 species seen in Buleji, Karachi. 36 species of phenophyta seen at the caost of Karachi (Abbas, 2010), it is reported 60 species of algae in Karachi at side of ocean Nathiliagali, 58 species of algae were reported by Nazim *et al*. (2012) at Bulegi, Karachi. Nearly, brown seaweed has 29 genera and 90 species which identified from the coast of Karachi in Pakistan (Shameel and Tanaka, 1992; Aisha and Shameel, 2013).

Cultivation status

In 2019 normally, different five types of seaweed consider 95% present in world among all seaweed cultivation. *Saccharina* and *Laminaria* consider 34.65% of overall world production for consumption purpose, mostly in sauces, condiments and salads. From tropical algae carrageen is taken *Eucheuma* and *Kappaphycus* nearly 32.62%. *Undaria*, *Gracilaria* and *Porphyra* accounted for 7.16%, 10.32% and 8.33% (Zhang *et al*., 2022). It is reported that in 2018 nearly 50 countries appealingly doing seaweed cultivation with representing 32.4 million tons 97.1% in average collectively cultivated and wild (FAO, 2020; Chopin and Tacon, 2021).

It is reported by financial time that the rise in global population to nearly 10 billion by 2050 (Koyande *et al*., 2021). from terrestrial plants algae grow 10 times faster, and contain less than one tenth of land for cultivation by producing same amount of biomass. Algae growth does not content with other plants of land. It inseminates more effectively than terrestrial plants, evades intensive use of water, wasting of fertilizers, eutrophication downstream linked with advanced agriculture (Tzachor, 2019). Sea space around 4 million square kilometers would be used in the culturing of seaweed that based for the formation of biofuels to balance the liquid fuel and its consumption globally (Kite-Powell *et al*., 2022).

Cultivation history

Undaria spp. and Saccharina spp.

From last 50 years different trails for the cultivation of kelp were applied all over the world to gain good results and new methods (Bak *et al.,* 2020). Production of *Saccharina spp*. and *Undaria spp*. are increased due to high demand in the feed of Korea (Hwang *et al.,* 2013).

Neopyropia/Pyropia/Porphyra

From hundred years in Japan cultivation of Neopyropia/Pyropia/Porphyra is performed and it is popular in the industry of aquaculture of China, Japan and Korea (Mumford *et al*., 1988; Pereira and Yarish, 2008). *N. haitanensis*, *N. yezoensis* and *N. tenera* are the commercial species produced (commonly in Japan, China, and Korea) among 138 species taxonomically *Porphyra*, *Pyropia* and *Neopyropia* are accepted (Guiry and Guiry, 2016). Mainly three species (*Py. Haitanensis*, *Py. Tenera* and *Py. Yezoensis*) cultivated commercially, commonly in Japan, Korea and China (99.99% of total production) (FAO, 2017). The method of culturing Porphyra in all these countries with some productive changes (Sahoo and Yarish, 2005; Pereira and Yarish, 2008; Pereira *et al.,* 2015). It is reported that largest blooms of macroalgae in world were originated from grown ulva on the bundle of Porphyra farm in the china Southern yellow sea (Liu *et al.,* 2009; Hu *et al.,* 2010; Zhang *et al*., 2016; Huo *et al*., 2016).

Kappaphycus sp. and Eucheuma sp.

Eucheuma sp., and *Kappaphycus* sp. has been produced in Philippines and Indonesia (FAO, 2014) major source of carrageenan (over 80% of world's carrageenan production) (Hayashi *et al*., 2010). *Eucheuma denticulatum* and *Kappaphycus alvarezii* are mostly farmed where 30 and 6 species are accepted taxonomically of each genus (Kim *et al.,* 2017).

Methods of seaweed cultivation

10,000 seaweed species identified in world but only 145 is being cultured by humans for their texture, culinary versatility and flavor also include *Monostroma*, *Laminaria*, *Caulerpa*, *Hizikia*, *Undaria*, *Porphyra* and *Palmaria* (Baweja *et al*., 2016). Commonly substrates are required to green seaweeds in order to attach themselves that makes slight difference in the process of cultivation in between red and green seaweed. The green seaweed of genus *caulerpa* (sea grapes) requires sand or loamy substratum to attach themselves using rhizoids and elongates and they propagate by their stolon extention (Zubia *et al*., 2020). Many *ulva* species are stored as vegetables and its extensive production of biomass makes it vaible for the cultivation on large scale. The maximized rate of growth of *ulva sp*. per day was notices and reported at 19.2% using offshore cages with fixed tumbling

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and mixing of biomass with air and water exchange (Chemodanov *et al*., 2019).

Onshore cultivation

In 1970-1980s cultivation of *Chondruscrispus* on-land or onshore started for the extraction of carrageenan (Craigie and Shacklock, 1995). Production take place by applying closed systems (e.g., in raceways, tanks, ponds or lagoons) in it water retained under control condition to provide suspended environment and exposed light for seaweed cultivation (Hafting *et al*., 2012; Currie, 2018).

The key benefits of land based farming are to check the prospects of adjustments used in the cultivation. Input of nutrients can be arranged precisely to enhance the creation of bioactive compounds and reduce the discharge of harmful components (Hafting *et al*., 2015). Monitoring of outflows and inflows done easily, water of sea is impelled and set it according to cultivation needs for seaweed. Addition of nutrients done from efficient methods by forming media under control conditions (Hafting *et al*., 2012; Reid *et al*., 2020).

Main shortcomings of land based farming are the high input cost for infrastructure and maintenance of whole condition of farm. Availability of land with watery area is quite expensive (Hafting *et al*., 2012). Land based cultivation of feedstock biofuel have various drawbacks, it need arable land to be unfocused from production of food, use of different fertilizers with its release footprint of carbon (DeCicco *et al*., 2016), which frequently use in the irrigation which is threatened in various agricultural areas (Rathmann *et al*., 2010; Besharat *et al*., 2020).

Offshore cultivation

Agency-Energy (ARPA-E) of the U.S. Department of Energy for the production of chemicals, fuels, and feeds. Among the possible species mentioned are *Sargassum spp.* in the Gulf of Mexico and the Caribbean, Saccharina in the Northeast (Western Atlantic Ocean), and Northwest (eastern Pacific Ocean of Washington and Alaska) (Kim *et al*., 2017).

The farming of macroalgae for use in the products commercially is not productive in system of pond due its cost above the normal range and the seaweed produced from all these systems used in the formation of high quality products (Hafting *et al*., 2015). Offshore production of seaweed is applied in enough area, around the shore space containing farms for floating and flat cultivation of kelp (Bird, 1987), currently wild farm integrated system started and also practice ring cultivation (Buck and Buchholz, 2004).

Offshore cultivation is a challenging system consider for the growth of epiphytes (Fletcher 1995, Vairappan *et al*., 2008). For all these reasons, species of seaweed selected to farm in open water to reduce the epiphyte growth in the whole season and prevention from local state. The change of climate with the subsequent change of water chemistry and temperature of water that

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could be the reason of decreasing of the cultivation area in ocean (Troell *et al*., 2017; Oyinlola *et al*., 2018).

The previous offshore farming is not still suitable for doing in open area and in deep water, the important aquaculture techniques installed in the protected areas. Generally the recent offshore and onshore farming are not seem good for environmental conditions, they consider unstable economically, fluctuations seen in their production because of biotic and abiotic factors (Sulaiman *et al*., 2012; Peteiro *et al*., 2016; Buschmann *et al*., 2017).

Nearshore cultivation

The cultivation near-shore is an important and mostly applied technique for seaweed cultivation, which were started in estuaries near shore areas (Soto and Wurmann, 2019). This system is also beneficial for not creating hurdles for arable area cultivation, from this it will be protected from the damages promoted from sea storms and agitation of sea. Advantage of this technique is the facilitation provided for bioremediation of river bowls that were polluted from human activities derived from agriculture activities (Zheng *et al*., 2019). As compared to the onshore and offshore production it is not much costly and laborious (Grote, 2019).

IMTA Cultivation

The ancient way of singular cultivation of seaweed is now modified by a combined system named IMTA (integrated multitropic aquaculture) to solve the environmental issues of aquaculture animal e.g, water eutrophication due to excretion and supplementary feed (Granada *et al*., 2016). The integrated multitropic aquaculture is a system used for rearing and culturing different species of various tropic levels close to each other. The waste products inorganic and organic are used and reused in the system provide as a nutrient to other factors (Knowler *et al*., 2020). In integrated multitropic aquaculture (IMTA) technique the excreta (as nutrient) taken from mollusk and fish contain phosphate and dissolved ammonia, from stabilizing the oxygen level, CO2 and PH convert these waste into valuable biomass (Fernand *et al*., 2017; Zheng *et al*., 2019; Knowler *et al*., 2020; Tanaka *et al*., 2020).

Integrated farming

In the cultivation of shrimps, litter remains are the main problem seen that cause toxicity in aquatic environment. In intensive farming of shrimps, the level of nitrogen is high in water which causes somehow problems for the immunity of shrimps. So for balancing the conditions of capacity and yield of stock need to balance the waste assimilation in environment (Neori *et al*.,. 2004).

Seaweed used as bioremediators in biofloc system to treat the waste formed from organisms. Different species of Gracilaria present naturally in seaside area of Brazil that used in the effluent of shrimps. Use seaweed as biomediator, the advanced eutrophic condition of farming ponds (Samocha *et al*., 2015).

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Shrimp are exposed to disease easily bacterial and viral, like *V. parahaemolyticus* and WSSV (White Spot Virus Syndrome). This combined farming might be suitable for controlling the pathogenic organisms (Brito *et al*., 2016).

Rate of survival is a main issue seen in farming of shrimp. An experiment performed on diseased shrimp with bacterial pathogen, that culture with seaweed show good survival and immunity against disease control. These macroalgae contain antiviral and antibacterial capacity beside immuno-stimulating characteristics that can alleviate its survival chances (Thanigaivel *et al*., 2016). In integrated culture of shrimp and seaweed, shrimp take seaweed as supplementary feed. From this enhance enzymatic activity and immunity. Due to this reduce oxidative stress because of antioxidant and bioactive compound taken from macroalgae and reduce pathogenic activities. The bioactive compounds are phenolic, sulfated, antioxidant and polysaccharides (Anaya *et al*., 2019).

Role of women in culture

In seaweed agriculture and the value chain, women frequently hold important leadership positions (Msuya, 2013). Seaweed farming was first and primarily adopted by women in India because it provided them with a safe and secure source of income (Krishnan and Narayanakumar, 2013). Women in the United Republic of Tanzania are leaders in seaweed cultivation and value addition, having taken the initiative in this field (Msuya, 2013). Women were heavily involved in seaweed farming in the Philippines, particularly in seeding and post-harvest treatments; they made up roughly 44% of the regular seaweed farming workforce and were the primary source of casual labor (Hurtado, 2013).

Growing seaweed significantly promotes women's empowerment and community cohesion (Valderrama *et al*., 2015; Suyo *et al*., 2020; Suyo *et al*., 2021). Many homes with limited resources or vulnerable people can participate in seaweed production due to its labor-intensive, low-capital, and easy farming technology. This is especially true for the tropical species Kappaphycus/Eucheuma (Needham and Lentisco, 2013).

Maintainable culture of macroalgae to contribute in the creation of jobs and for the well-being of society, firstly i.e hatcheries, processing and grow-out operations secondly supplying goods from industries, provide services to mariculture such as equipment and feed, thirdly providing the jobs associated with it i.e directly or indirectly employment in the culture of seaweed (Pinfold, 2013).

Uses

In 20 years, the bioactive compounds from micro and macroalgae are commonly used in the industry of cosmetic. Algae as compared to terrestrial crops contain various new and exclusive components e.g terpenoid, polyphenols, sterol, halogen, polysaccharides and unsaturated fatty acids additionally protein, vitamin, trace

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element and minerals (López-Hortas *et al*., 2021). Seaweed is used to enhance beauty. Many countries in South East Asia, including Japan, China, Korea, Malaysia, Thailand, Indonesia, and the Philippines, use seaweed because of its high protein content. Soups, salads, and curries are prepared using seaweeds such as *Ulva* sp*., Enteromorpha* sp*., Caulerpa* sp*., Codium* sp*., Monostroma* sp*., Sargassum* sp*., Hydroclathrus* sp*., Laminaria* sp*., Undaria* sp*., Macrocystis* sp*., Porphyra* sp*., Gracilaria* sp*., Eucheuma* sp*., Laurencia* sp., and *Acanthophora* sp, (Kolanjinathan *et al*., 2014).

Seaweed cultivation role in economics

Seaweed's upstream and downstream operations have benefited various sectors by fostering innovation and boosting economic development (Chen *et al*., 2020; Felaco *et al*., 2020; Padam and Chye, 2020; Wang *et al*., 2020). Additionally, seaweed offers vital resources such as food, renewable energy, and raw materials, and contributes to cultural value through recreation, learning, heritage conservation, and scientific exploration (Hasselström *et al*., 2018).

Around 221 species of seaweed in which Chlorophytes 32, Phaeophytes 64 and Rhodophytes 125 that are using in development at commercial level among all these 24 utilize in medicinal products, 25 species used in animal feed, compost and in agriculture, 145 species are used as a food (White, 2015). Macroalgae are used as compost to enhance fertility of soil and better production of plants. Seaweed also used as an organic fertilizer in farming recompenses the shortage of plant nutrients e.g phosphorous, nitrogen and potassium (Soares *et al*., 2020).

Seaweed also used as enhancer of beauty due to good amount of protein and used in various areas e.g China, Japan, Korea, Indonesia, Thailand, South east Asia and Philippines. Seaweeds like *Enteromorpha sp., Codium sp., Sargassum* sp*., Laminaria* sp*., Macrocystis* sp*., Gracilaria* sp*., Acanthophora* sp. *Ulva* sp*., Caulerpa* sp*., Monostroma* sp*., Hydroclathrus* sp*., Undaria sp., Porphyra* sp*., Laurencia* sp. and *Eucheuma* sp. are used in the formation of curry, salad and soup (Kolanjinathan *et al*., 2014) (Fig. 4).

Used in animal food

Seaweed also used as a food to the animals of farm e.g poultry, cattle etc. Macro-algae provide disease resistance and contain balanced amount of micronutrients. They also help in reducing the cow fever and mastitis. It also enhances iodine content and fat amount in milk and their products. Seaweed enhances yolk color of eggs and aids in increasing fertility and rate births in animals (CMFRI, 2010). From species *Sargassum*, *Gelidiella*, *Gracilaria* and *Hypnea* feed were prepared and used in culturing of prawns and fishes. The feed was balanced amino acids, minerals, carbohydrates that can also maintain quality of water in aquaculture (Chapman 2012).

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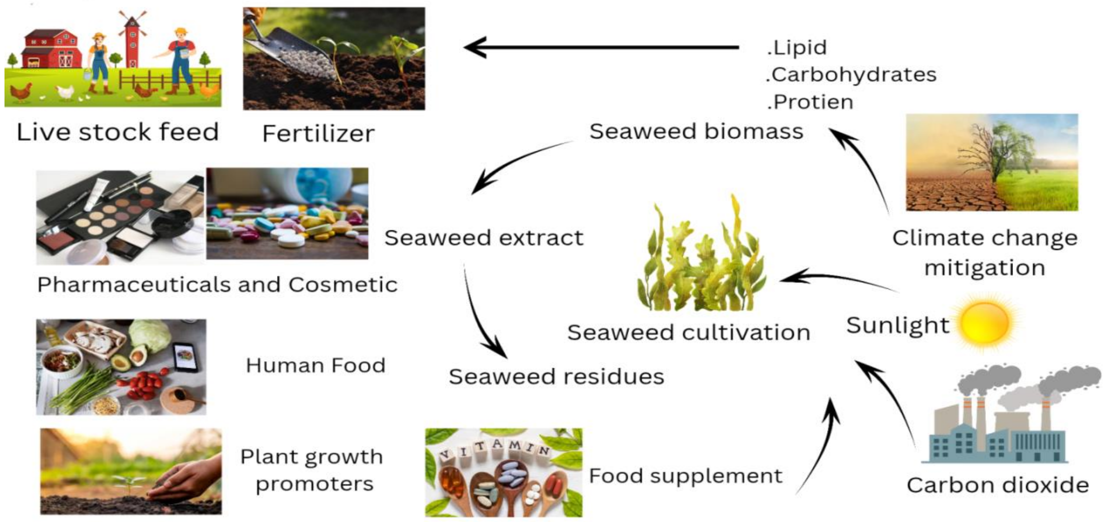

Figure 4: Various uses of seaweed.

Findings confirmed that from cattle decreasing emission of methane when give seaweed feed (Li *et al*., 2016; Duarte *et al*., 2017). Supplementation of seaweed in poultry, aquaculture feed and livestock were given from decades and show good results in meat quality, health of animal (Vijn *et al*., 2020). In case of addition of brown seaweed (*Ascophyllum nodosum* and *Undaria pinnatifida)* in the feed of sheep and pigs to enhance the health of animal's intestine and with the use of some percent red seaweed (*Eucheuma denticulatum*) in fishmeal enhance quality of meat of Japanese flounders by extending the omega-3 fatty acid in muscles (Shimazu *et al*., 2019).

del Olmo *et al*. (2018), examined a noteworthy development in physiochemical eminence of hard cheese when given as a supplementary with macroalgae e.g *Undaria pinnatifida, Laminaria ochroleuca, Porphyra umbilicalis, Ulva lactuca,* and *Himanathalia elongate* species. It is founded from research that microbiota of intestine were enhance in mice because of the use of polysaccharides of seaweed (Ulva prolifera and Porphyra haitanensis) as oral supplementary feed (Zhang *et al*., 2022)

Food additive

Due to high level of vitamins minerals and protein in seaweed it is highly used as food for long time mainly in East Asia (Sho, 2001). They are also good source of animal feed and as supplements. *A. nodosum* brown seaweed was used in the feed of animals by the Canadian company to enhance the microbial invasion and immunity (Allen *et al*., 2001; Saker *et al*., 2001).

More than hundred seaweed species are used by Japanese. *A. nodosum* is used in the diet of people who are overweight to decrease the energy intake after feasting (Hall *et al*., 2012). From species of *porphyra* derived R-phycoerythrin (Suganya *et al*., 2016) also used as a food of color (Dumay *et al*., 2014).

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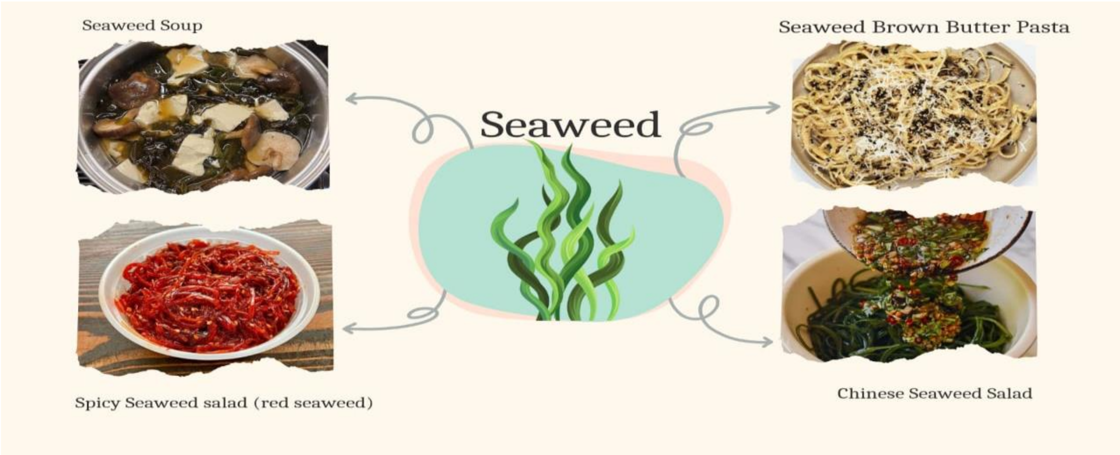

Figure 5: Uses in food.

High value macroalgae product is phycobiliproteins (approximately $5000/g) (Suganya *et al.*, 2016). Although their lower constancy in light and heat, phycobiliproteins also play role in cosmetics (phycoerythrin and phycocyanin) and food natural colorant (Griffiths *et al*. 2016). Seaweed has enough fiber content, which can complicate the digestion phenomenon in humans, while ruminants have designed enzymes in their system that are helpful in their digestion and enhance the accessibility of nutrients (Holman and Malau, 2013) (Table 4).

Table 4: Edilble species of macro-algae.

Edible species of Seaweeds		
Brown Algae	**Green Algae**	**Red Algae**
Durvillaea Antarctica	*Caulerpa* spp	*Chondrus crispus*
Alaria esculenta	*Codium* spp	*Eucheuma denticulatum*
Eisenia bicyetis	*Enteromorpha* spp	*Gracitaria edutis*
Ascophyllum nodosum	*Ulva lactuca*	*Champia compressa*
Fucus vesiculosus	*Ulva* spp	*Gelidiella acerosa*
Fucus serratus	*Ulva pertusa*	*Porphyra spp*
Laminaria hyperborean	*Monostroma* spp	*Porphyra columbina*
Laminaria digitata	*Ulva australis*	*Porphyra umbiticatis*
Himanthatia elongate	*Entromorpha* spp	*Porphyra laciniata*
Sargassum swartzii		*Gracilariopsis tongissima*
Sargassum fusiforme		*Palmaria palmate*
Sarrgassum vulgare		*Osmundea pinnatifida*
Sarrgassum muticum		*Mastocarpus stellatus*
Undaria undarioides		*Solieria robusta*
Undaria pinnatifida		
Stoechospermum marginatum		

Fleurence, 2022; Pandey *et al.,* 2020

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Heavy metals absorption

From seawater absorb heavy metals that depends on different factors e.g season, species, wave exposure, location, light intensity, temperature, PH, age of the plant, nitrogen availability and salinity (Griffiths *et al*., 2016). Chen *et al*. (2018), explain the metalloids and metal Se, Mn, As, Hg, Al, Cr, Ni, Cu, Cd, and Pb that are absorb by red seaweeds. Mainly the concentrations of heavy metal in seaweed are low than preserving toxic limit. But the bioaccumulation level of lead, cadmium and arsenic are consider the culture of seaweed hazardous that can cause hyperpigmentation, allergies and cancer. Arsenic is consider as hazardous chemical compound carcinogenic in nature, it is taken as food by seaweeds and it is seen high level of arsenic present in seaweed as in organic form (Taylor *et al*., 2017). In coastal defense aquatic seaweed play role by decreasing the hydrodynamics energy of waves by normalizing high bed tides, and protecting the area of tides from erosion (Christianen *et al*., 2013, Ondiviela *et al*., 2014).

The photosynthetic activity of seaweeds and microalgae can clean wastewater, lessen ocean acidification, reduce eutrophication, and capture carbon dioxide by removing nutrients (phosphorus and nitrogen) from nearby waters and absorbing carbon dioxide (Muraoka, 2004).

Pharmaceutical use

Natural commercially formed product named InSea2 available in different countries which is used to control metabolism of carbohydrates and blood sugar. The product InSea2 is formed from two seaweeds natural extracts *A. nodosum* and *F. vesiculosus*. These extracts have inhibitory factors called α-glucosidase and α-amylase (Roy *et al*., 2011).

Alginate is used to enhance the texture of paper. It is being used as a reactive foundation for textile reactive dye printing, a stabilizer for ice cream, and a possible additive for frozen foods. Alginates are also frequently employed as stabilizers in the pharmaceutical industry (Krishnamurthy 2005). Approximately 13000 years, marine macro algae were subjugated by anthropogenic activities in the field of food and medicine. In Chile at late Pleistocene settlement findings of seaweed based presence seen at Jomon period and Monte Verde in Japan (Ugent and Tindall, 1997), an archeological implication from earlier sites macro algae used in three different purpose of medical, from 400BC Ayunvedic medicine formed (Misra and Sinha, 1979) (Fig. 6).

Anti inflammatory activity

Methanol extract taken from *Ulva linza* and *Undaria pinnatifida* used due their anti-inflammation function, have actively participated in the resistant of inflammation while used against mouse erythema and ear edema. Edema was inactive by the species of macro-algae *Ulva linza* and *Undaria pinnatifida* (Mohammed *et al*., 2008).

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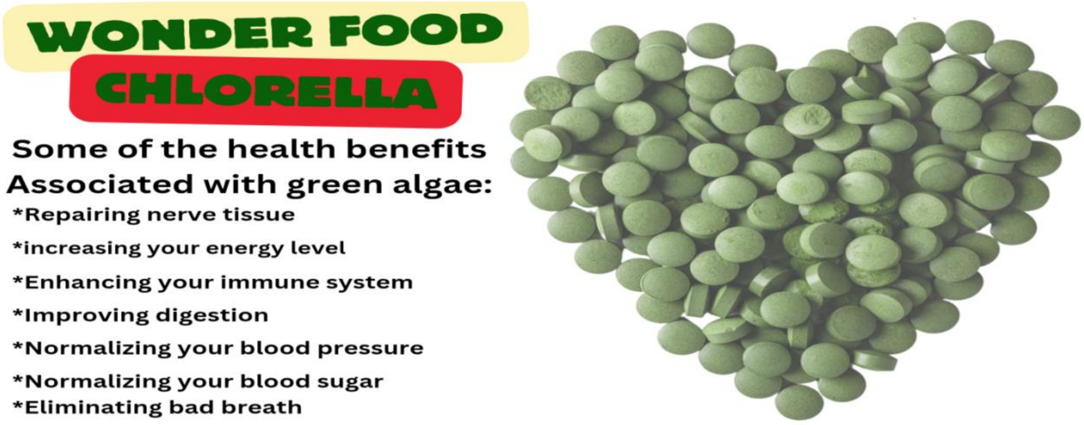

Figure 6: *Chlorella*.

During in-vivo study extract of methanol from *Ulva linza* and *Undaria Pinnatifida* seaweeds which play role of anti-inflammation (Khan *et al*., 2008). Extract of methane from Dictyota dichotoma was consider as noteworthy against β-lactamases by constraining GES-22 which can be effective in controlling the emergence condition of antibiotic resistance of bacteria in humans (Houchi *et al*., 2018)

Bioactive compounds

Seaweeds are known for their natural richness in especial sulfated polysaccharides, bioactive molecules such as polyunsaturated fatty acids, proteins, lipids, natural pigments, carbohydrates, and minerals such as iron, potassium, sulfur, iodine, vitamins (Plaza *et al*., 2008; Kraan, 2013). Different studies noticed that various seaweed contain good amount of polyphenols that are antioxidant in nature (Gómez *et al*., 2018).

In red seaweed found carrageenans which are composed of D-series of 4-linked α-galactose residues. Polysaccharides called agarans are extracted from red seaweed, which have L-series of 4-linked α-agalactose remains (Knutsen *et al*., 1994). These are the molecules contain broad spectrum of antiviral, anticancer activities and anticoagulant (Jiao *et al*., 2011; Mayer *et al*., 2011).

Effect on climate and soil

The autotrophic seaweed mass production can help in enhancing the effect in change of climate. Seaweeds are considered as a good carbon sinks which help in absorbing the carbon dioxide from the environment to avert the atmosphere from acidification (Fernández *et al*., 2019). *Sargassum, Ascophyllum, Laminaria* are the species used as organic manure, which is by nature non-toxic, non-hazardous, biodegradable and non-polluting to birds animals and humans. Apart from this it enhance moisture holding ability and fertility of soil (Pati *et al*., 2016).

Seaweed enhance the soil nutritional profile e.g K, P, N and all the nutrients necessary for growth of plant (Nabti *et al*., 2017). In seaweed the elements composition seen in the species of

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Karachi coast are Zn, Pb, Na, Cd, Ca, Cu, Cr, Mg, Fe, k and Co. Most abundant elements are K, Mg, Ca, Na and Fe (Rizvi *et al*., 2001).

Use in Cosmetics

Pakistan is known for different emporium of seaweed that is used in cosmetics. Shameel and Tanaka (1992) reported 177 genera and 475 species of benthic algae and marine planktonic present the aquatic environment. Among all seaweed, various used in the products of cosmetics formation. Commonly seen macro alga at the coast of Pakistan are *Gracilaria gracilis, Hypnea musciformis, Laurencia obtusa, Gelidium usmanghanii, Scinaia saifullahii, Gracilaria corticata, Botryocladia leptopoda* that used in the formation cosmatics products by exploitation of agar (Afaq-Husain *et al*., 2001).

Biofuel production

By Using and applying seaweed in the industries of agriculture and energy. Convert seaweed into biofuel e.g biodiesel and bio-alcohols (butanol and ethanol) by adopting the process of microbial fermentation and the breakdown of phytochemical components (Ashokkumar *et al*., 2017; Ra *et al*., 2019). Biofuel yeild from different seaweeds species, after the fermentation of various microorganisms, by using different technology which can help in the efficient conversion that would be more effective for the production of biofuels on commercial scale (Tabassum *et al*., 2017; Ra *et al*., 2019). *Ulva sp*. the green seaweed used to produce polylactic acid from feedstock (Helmes *et al*., 2018).

Use to cure Cancer

The species of seaweed Fucus spp in brown algae has shown resistant against breast cancer and colorectal. Seaweed has various anticancer effects on breast and colon of human (Moussavou *et al*., 2014). In past, Chinese used Laminaria sp. for cancer treatment (Loeser, 1956). It is documented that various seaweed has anticancer effect against breast and colon cancer in human beings. Different macroalgae play defensive role from cancer by decreasing the formation of cancer cells. Due to good anti-oxidant ability of macroalgae as a defensive agent against heart diseases (Sharma *et al*., 2016). Macroalgae also used against diabetes. Administration of extract of Ulva faciata orally that decrease the glycosylated hemoglobin level and blood glucose as compared to other in-vivo standard of medicines (Abirami and Kowsalya, 2013).

Reproductive function

Macro-algae raise the amount of fat and iodine in milk and milk products and it improves the yolk color of eggs and increases animal fertility and birth rates. Fish and prawn culture are fed the food made from the species of *Sargassum*, *Gracilaria*, *Gelidiella*, and *Hypnea* (Gómez *et al*., 2018). The feed's mineral, amino acid, and carbohydrate enrichment helps to maintain aquaculture's water quality (Kaladharan *et al*., 1998). In aquaculture system it is used to prevent the waste from the culture of shrimp, which decrease the chances of eutrophication. The Gracilaria verrucosa specie of red seaweed have good efficacy to eliminate level of BOD and COD whereas Ulva fasciata a green macroalgae have higher efficacy for the ammonia removal (Sasikumar and Rengsamy, 1994).

Difficulties and challenges

Apart from benefits, many of difficulties seen in the propagation of seaweed that includes the lack of significant protocols for the gaining of callus induction, axenic cultures and the whole plant regeneration by using regulators for plant growth. For commercialization, hybridization is another technique used in the production and growth enhancement of macroalgae (Kopprio *et al*., 2021). New hybrid strain *K. alvarezii* and *E. denticulatum* with new carrageenan composition and good growth rates was formed by using cell-cell fusion technique and fusion of protoplast (Cheney *et al*., 1998; Bindu and Levine 2011).

External challenges

The problems of environment seen due to the evolvement of algae's processing and breeding. Halogenated hydrocarbons released from various algae that can cause effect on ultraviolet rays and on ozone. The mass of growing area is a suitable platform for the addition of new species. The equipment of breeding is the base of attachment for green macroalgae. Within the rise of temperature the production rate of green seaweed increases that will be added in ocean and cause the green tides (Yu *et al*., 2020).

Internal challenges

Macroalgae processing and production technology does not meet to its cultivation need. Recently the production of macroalgae is mostly established in low developed areas. Some counties, mainly China know the importance of large-scale offshore production, industrial seed raising, automated harvesting and maintain industrial chain for sale different products. Most of the countries, done basic productions and their practices for processing and harvesting are common. From the value addition in the products are squat due to the use of low techniques for purification and extraction (Pérez *et al*., 2016). In the open ocean the barriers seen for seaweed culture include insufficient technology that ropes the operational purpose and cultivation in open environment and professed possibility for aquatic (marine) mammal predicaments. Forming structures of aquaculture that can be viable economically and bear-up the hurdles of open sea area and the engineering difficulties faced for the advancement of tools, analysis and demonstration of complete system (Moscicki *et al*., 2024).

Conclusion

Seaweeds are an increasingly significant and highly valued marine asset, with

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expanding and varied uses across a wide range of industries, particularly in aquaculture. This is largely attributed to their rich nutritional content and the presence of numerous biologically active compounds. The integration of seaweed into aquaculture diets has yielded significant benefits, such as faster fish growth, strengthened immune systems, and a natural source of critical minerals and pigments. The escalating global demand for seaweed and its by-products is driving the advancement of sustainable, environmentally responsible, and efficient farming techniques. To fully tap into seaweed's potential while ensuring both ecological and economic resilience, it is imperative to focus on maximizing nutrient yield, breeding durable and climate-resilient strains, and promoting the development of integrated multi-trophic aquaculture systems.

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