Seaweeds: A Promising Source for Sustainable Development

T. Nedumaran and D. Arulbalachandran

Abstract

Macroscopic marine algae, popularly known as seaweeds, form one of the important living resources of the ocean. Seaweeds form an important renewable resource in the marine environment and have been a part of human civilization from time immemorial. Reports on the uses of seaweeds have been cited as early as 2,500 years ago. Seaweed utilization for a variety of purposes has led to the gradual realization that some of their constituents are more superior and valuable in comparison to their counterparts on land. Seaweeds synthesize a wide range of chemicals, some of which are the only natural resources of agar, carrageenan, and alginate. These have been used as food for human beings, feed for animals, natural biofertilizers for plants and source of various chemicals like pharmaceutical values without any side effects, production of biodiesel and wastewater management, etc. In this chapter, utilization of seaweeds has been obviously discussed which are proving and playing a crucial role in sustainable development to became a promising source for human welfare.

Keywords

Biofertilizers • Biofuels • Animal feed • Pharmaceutical value

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1 Introduction

Seaweeds or benthic marine algae are the group of plants that live either in marine or brackish water environment. Like the terrestrial plants, seaweeds contain photosynthetic pigments, and with the help of sunlight and nutrient present in

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the seawater, they photosynthesize and produce food. Seaweeds are found in the coastal region between high tide and low tide and in the subtidal region up to a depth where 0.01 % photosynthetic light is available. Plant pigments, light, exposure, depth, temperature, tides, and the shore characteristics combine to create different environments that determine the distribution and variety among seaweeds (Dhargalkar and Kavlekar 2004). Seaweeds or marine macroalgae are primitive nonflowering plants, without true root, stem, and leaves. They form one of the commercially important marine living renewable resources. Seaweeds occur in the intertidal shallow and deep waters of the sea and also in estuaries and backwaters. They grow on rocks, dead corals, stones, pebbles, solid substrata, and other plants. They require certain environmental conditions for proper growth and establishment in different regions of the coastline. However, the topography, physical nature of the substratum, salinity, currents, tidal action, and other factors of the marine environment vary in different parts of the coastline, and as a result of these fluctuations, marked changes occur in the distribution and abundance of different kinds of seaweeds.

1.1 Seaweed Wealth in India

India has a vast coastline more than 9,000 km long, a number of estuaries, backwaters, and island, rocky, or coral formations occurring in Tamil Nadu and Gujarat states and in the vicinity of Bombay, Karwar, Ratnagiri, Goa, Vizhinjam, Varkala, Visakhapatnam, and few other places like Chilka and Pulicat lakes. India is rich in algal biodiversity country and has large stretches of suitable area for growth. According to Oza and Zaidi (2001), totally 844 species of marine algae available in India belong to different genera and classes as shown below:

	Genera	Species
Chlorophyceae	43	216
Phaeophyceae	38	194
Rhodophyceae	136	434
	217	844

2 Classification of Seaweeds

Based on the type of pigments, external and internal structure, and reproduction, seaweeds are divided in to four broad groups: green, blue-green, brown, and red. Botanist refers to these broad groups as Phaeophyceae, Rhodophyceae, Cyanophyceae, and Chlorophyceae, respectively. Brown seaweeds are usually large and range from the giant kelp; red seaweeds are usually smaller, generally ranging a few centimeters to about a meter in length and they are not always red. They exhibited sometimes purple and even brownish red. Green seaweeds are also small with a similar size range to the red seaweeds.

3 Ecology and Biology of Seaweeds

Seaweeds are ecologically important primary producers, competitors, and ecosystem engineers that play a central role in coastal habitats ranging from kelp forests to coral reefs. Although seaweeds are known to be vulnerable to physical and chemical changes in the marine environment, the impacts of ongoing and future anthropogenic climate change in seaweed-dominated ecosystems remain poorly understood (Harley et al. 2012). Ecological studies have been carried out on the marine algal vegetation of different localities of Indian coast by various workers. They provided data on the seasonal changes and zonation of algae and on the environmental conditions existing in those areas. The changes in the total emergence and submergence, topography of the coast, surf action, and levels at which the plants grow were found to contribute much to the variation in the growth of the algae. Every year fresh plants develop from the reproductive bodies liberated by the plants of the previous generation or from the perennial basal portion of the old plants. The period of regeneration and increase and decline in growth vary from species to species and also from one locality to the other. In some seaweeds, two peak growth periods with a half-yearly growth cycle were observed, while in other seaweeds, only a single peak growth period was observed. In general, maximum growth has been observed in many algae in two seasons of the year, one from June to August and another from November to January. The commercially useful algae should be collected only during their peak growth periods in order to get more quantity of raw material and better yield of finished products with good quality.

Studies on the fruiting periods and relative preponderance of vegetative and reproductive phases of many commercially important seaweeds indicated that the fruiting behavior varies in different seaweeds growing along the Indian coast. Though reproduction was observed throughout the year, two fruiting seasons in a year in many algae and one fruiting season in other algae were found. Information on the spore output from economically important algae was collected. As enormous number of spores was found to be produced from an alga, they can be successfully raised to germlings in the laboratory or nursery and then to harvestable size plants in the sea by transplantation. Periodicity or rhythm in the liberation of spores was observed in some seaweeds, while there was no such periodicity in the shedding of spores in other seaweeds. The spore output season and also the period of maximum sporulation varied from species to species. Information was collected also on the spore germination, survival of germlings, and life cycle of some marine algae. The results of several studies on the growth, fruiting behavior, and sporulation of the economically important marine algae growing in different area paved the way to utilize the available marine algal resources in a rational way for commercial exploitation and cultivation. Studies on the diversity, physiology, biochemistry, and utilization of potentially useful species will be necessary to harness the full potential of seaweed resources and to do so sustainably.

4 Utilization of Seaweeds from Historical Period to Present Day

The earliest record of use of seaweeds dates back to 2700 BC in the compilation on "Chinese Herbs" by Emperor Shen Nung. Seaweeds have been a part of the Japanese diet since 300 BC. Seaweeds are mainly eaten in the oriental countries like Japan, China, Korea, and more recently in the USA, Europe, Philippines, Indonesia, Chile, Taiwan, Vietnam, Russia, Italy, and India. The Republic of Korea has the highest per capita consumption of seaweeds in the world. After human food consumption, the next most valuable commercial use of seaweeds is as a raw material for extraction of phycocolloids like agar, alginate, and carrageenan which are used in several industries. The current phycocolloids (seaweed gels) industry stands at over US $ 6.2 billion. The world production of commercial seaweeds has grown by 119 species since 1984, and presently, 221 species of seaweeds are utilized commercially including 145 species for food and 110 species for phycocolloid production. These have been used as food for human beings, feed for animals or manure for plants, and source of various chemicals. In the recent past, seaweeds have also been gaining new systems for biologist seaweed liquid fertilizer. Seaweed products are used in our daily lives in one way or another (e.g., seaweed polysaccharides are employed in the manufacture of toothpastes, soaps, shampoos, and cosmetic products such as creams and lotions and also as a source for animal nutrition). In addition, it is used in wastewater treatment, paper industry, and medical research (Cruz-Suarez et al. 2010). Recently, seaweed figure prominently debates about the energy and biofuel production. They have been discussed as a potential source against global warming where seaweeds and algae are very efficient carbon sinks which means that they absorb more carbon than their rate emission. Marine algae may also be used as energy collectors, and potentially useful substances may be extracted by fermentation and pyrolysis. The various benefits of different algal species available worldwide are presented in Table 1.

Table 1 Global utilization of different algal species

Species	Uses	Countries
Chlorophyta		
Acetabularia major	M	Indonesia, Philippines
Capsosiphon fulvescens	F	Korea
Caulerpa spp.	F	Malaysia, Thailand, India
Caulerpa lentillifera	F, M	Philippines
Caulerpa peltata	F, M	Philippines
Caulerpa racemosa	F	Bangladesh, Japan, Philippines South Pacific Islands, Vietnam, India
	M	Philippines, India
Caulerpa sertularioides	F, M	Philippines, India
Caulerpa taxifolia	F, M	Philippines, India
Codium spp.	F	Argentina
Codium bartletti	F	Philippines
Codium edule	F	Philippines
Codium fragile	F	Korea, Philippines
Codium muelleri	F	Hawaii
Codium taylori	F	Israel
Codium tenue	F	Indonesia
Codium tomentosum	F	Indonesia
Colpomenia sinuosa	F	Philippines
Dictyosphaeria cavernosa	Ag	Kenya
	M	Philippines
Enteromorpha spp.	Ag	Portugal, India, Brazil
	F	Bangladesh, France, Hawaii, Myanmar
Enteromorpha compressa	F	Korea, Indonesia
	M	Indonesia, Philippines
Enteromorpha clathrata	F	Korea
Enteromorpha grevillei	F	Korea
Enteromorpha intestinalis	F	Indonesia, Japan, Korea
	M	Indonesia
	Ag	India
Enteromorpha linza	F	Korea
Enteromorpha nitidum	F	Korea
Enteromorpha prolifera	F	Indonesia, Japan, Korea, Philippines
	M	Indonesia
Monostroma nitidum	F	Japan
Scytosiphon lomentaria	F	Korea, France
Ulva spp.	Ag	Italy, Portugal, India, New Zealand
	F, M	Argentina, Canada, Chile, Hawaii, Japan, Malaysia, India
	P	Italy
Ulva lactuca	F, M	Vietnam, Indonesia, India, Japan
Ulva pertusa	M	Philippines
Ulva reticulata	F	Vietnam, India
Rhodophyta		
Acanthophora spicifera	C	Vietnam
	F	Philippines, Vietnam
Ahnfeltia plicata	Ag	Chile
Asparagopsis taxiformis	F	Hawaii, Indonesia
	M	Philippines
Betaphycus gelatinum	F, C	Vietnam
Caloglossa adnata	F	Indonesia
Caloglossa leprieurii	M	Indonesia, Vietnam
Catenella spp.	F	Myanmar
Chondria crassicaulis	F	Korea
Chondrus crispus	C	France, Spain, USA
	F	Ireland, France
Chondrus ocellatus	F	Japan
Eucheuma alvarezii	C	Malaysia, Kiribati, India, Philippines
Eucheuma cartilagineum	F	Japan
Eucheuma denticulatum	C	Philippines, Madagascar
Eucheuma gelatinae	A	India, Malaysia, Vietnam
	C, F	China, Indonesia, Philippines
Eucheuma isiforme	F	Caribbean
Eucheuma muricatum	F, M	Indonesia
Eucheuma striatum	C	Madagascar
Gelidiella acerosa	F, A	Philippines, India, Malaysia, Vietnam
Gelidiella tenuissima	F	Bangladesh
Gelidium anansii	F, M	Korea, Indonesia
Gelidium abbottiorum	A	South Africa
Gelidium capense	A	South Africa
Gelidium chilense	A	Chile
Gelidium latifolium	A	Spain
	F	Indonesia
Gelidium lingulatum	A	Chile
Gelidium madagascariense	A	Madagascar
Gelidium pristoides	A	South Africa
Gelidium pteridifolium	A	South Africa
Gelidium pusillum	F	Bangladesh
Gelidium robustum	A	Mexico
Gelidium rex	A	Chile
Gelidium sesquipedale	A	Morocco, Portugal, Spain
Gelidium vagum	A	Canada
Gigartina canaliculata	C	Mexico

(continued)

Table 1 (continued)

Species	Uses	Countries
Gigartina chamissoi	C	Peru
	C	Chile
Gigartina intermedia	C	Vietnam
Gigartina skottsbergii	C	Argentina, Chile
Gloiopeltis spp.	F	Vietnam
Gloiopeltis furcata	F	Korea
	C	Japan
Gloiopeltis tenax	C	Japan
	F	Korea
Gloiopeltis complanata	C	Japan
Gracilaria spp.	Ag.	Portugal
	C	Malaysia
	F	Myanmar, Thailand, India
	P	Italy
	M	Vietnam
Gracilaria asiatica	A	China, Vietnam
	F	Vietnam
Gracilaria bursa-pastoris	F	Japan
Gracilaria caudata	A	Brazil
Gracilaria changii	F	Thailand
Gracilaria chilensis	A	Chile
	Ag	New Zealand
Gracilaria cornea	A	Brazil
	F	Caribbean
Gracilaria coronopifolia	F	Hawaii, Vietnam
Gracilaria crassissima	F	Caribbean
Gracilaria domingensis	F	Brazil, Caribbean, Chile
Gracilaria edulis	A, F	India
Gracilaria eucheumoides	F	Indonesia, Vietnam
	M	Indonesia
Gracilaria firma	A	Philippines, Vietnam
	C	Philippines
	F	Vietnam
Gracilaria fisheri	A, F	Thailand
Gracilaria foliifera	A	India
Gracilaria gracilis	A	Namibia, South Africa
Gracilaria heteroclada	A	Philippines, Vietnam
	F	Vietnam
Gracilaria howei	A	Peru
Gracilaria lemaneiformis	A	Mexico, Peru
	F	Japan
Gracilaria longa	A	Italy
Gracilaria pacifica	A	Canada
Gracilaria parvispora	F	Hawaii
Gracilaria salicornia	A	Thailand
	F	Thailand, Vietnam
Gracilaria tenuistipitata var.	A	China, Philippines, Thailand, Vietnam
	F	Thailand, Vietnam
Gracilaria verrucosa	A	Argentina, Egypt, Italy, India
	F	France, Indonesia, Japan, Korea
	M	Indonesia
Gracilariopsis lemaneiformis	A	Canada
Gracilariopsis tenuifrons	A	Brazil
Grateloupia filicina	F	Indonesia, Japan
	M	India
Gymnogongrus furcellatus	C	Chile
Halymenia spp.	F, Ag	Myanmar, China, West Indies
Halymenia discoidea	F	Bangladesh
Halymenia durvillaei	F	Philippines
Halymenia venusta	Ag, F	Kenya
Hypnea spp.	F	Myanmar
Hypnea musciformis	C	Brazil, India
Hypnea muscoides	C, F	Vietnam, India
Hypnea nidifica	F	Hawaii
Hypnea pannosa	F	Bangladesh, Philippines
Hypnea valentiae	C, F	Vietnam
Iridaea ciliate	C	Chile
Iridaea edulis	F	Iceland
Iridaea laminarioides	C	Chile
Iridaea membranacea	C	Chile
Kappaphycus alvarezii	C	Philippines, Tanzania, India
	F	Philippines
Kappaphycus cottonii	C, F, M	Vietnam
Laurencia obtusa	F, M	Indonesia
Laurencia papillosa	Ag, F	Kenya, Philippines, India
Laurencia pinnatifida	F	Portugal
Lithothamnion corallioides	Ag	France, Ireland, UK
Mastocarpus papillatus	C	Chile
Mastocarpus stellatus	C	Portugal, Spain
	F	Ireland
Mazzaella splendens	A, F	Canada
Meristotheca papulosa	F	Japan
Meristotheca procumbens	F	South Pacific islands
Nemalion vericulare	F	Korea

(continued)

Table 1 (continued)

Species	Uses	Countries
Palmaria hecatensis	F	Canada
Palmaria mollis	F	Canada
Palmaria palmata	F	Canada, France, Iceland, Ireland, UK, USA
Porphyra spp.	F	Israel, New Zealand, UK, Japan
Porphyra abbottae	F	Alaska, Canada
Porphyra acanthophora	F	Brazil
Porphyra atropurpurea	F, M	Indonesia
Porphyra columbina	F	Argentina, Chile, Peru
Porphyra crispata	F	Thailand, Vietnam
Porphyra fallax	F	Canada
Porphyra haitanensis	F	China
Porphyra kuniedae	F	Korea
Porphyra leucosticta	F	Portugal
Porphyra perforata	F	Canada
Porphyra psuedolanceolata	F	Canada
Porphyra seriata	F	Korea
Porphyra spiralis	F	Brazil
Porphyra suborbiculata	F	Korea, Vietnam
Porphyra tenera	F	Japan, Korea
Porphyra torta	F	Alaska, Canada
Porphyra umbilicalis	F	France, USA
Porphyra vietnamensis	F	Thailand
Porphyra yezoensis	F	China, Japan, Korea
Pterocladia capillacea	A	Portugal
Pterocladia lucida	A	New Zealand
	F	Korea
Scinaia moniliformis	F	Philippines
Solieria spp.	F	Myanmar
Phaeophyta	A	New Zealand
Alaria crassifolia	F	Japan
Alaria fitulosa	Ag, F	Alaska
Alaria marginata	F	Canada
Alaria esculenta	F	Iceland, Ireland, USA
Ascophyllum nodosum	Ag	France, Canada, China, Iceland, USA
	Al	Ireland, Norway, UK
Cladosiphon okamuranus	F	Japan
Cystoseira barbata	Al	Egypt
Desmarestia spp.	RoK	Alaska
Durvillaea antarctica	F	Chile, New Zealand
Durvillaea potatorum	Al	Australia
Ecklonia cava	F	Japan
Ecklonia maxima	Ag	South Africa
Ecklonia stolonifera	F	Korea
Egregia menziesii	F	Canada
Fucus spp.	Ag	France
Fucus gardneri	Ag	Canada
	F, RoK	Alaska
Fucus serratus	Al	Ireland
	F	France
Fucus vesiculosus	Al	Ireland
	Co	Ireland
	F	France, Portugal
Hizikia fusiformis	F	Japan, Korea
Hydroclathrus clathratus	Ag	Philippines
	F	Bangladesh, Philippines
Laminaria angustata	F	Japan, Australia
Laminaria bongardiana	F	Alaska
Laminaria diabolica	F	Japan
Laminaria digitata	Al	France, Ireland
	F	Ireland
Laminaria groenlandica	F	Canada
Laminaria hyperborean	Al	Ireland, Norway, Spain, UK
Laminaria japonica	Al	China
	F	China, Japan, Korea
Laminaria longicruris	F	USA
Laminaria longissima	F	Japan
Laminaria ochroleuca	Al	Spain
Laminaria ochotensis	F	Japan
Laminaria religiosa	F	Japan, Korea
Laminaria saccharina	F	Alaska, Canada, Ireland
	RoK	Alaska
Laminaria setchellii	F	Canada
Laminaria schinzii	Ag	South Africa
Lessonia nigrescens	Al	Chile, Peru
Lessonia trabeculata	Al	Chile
Macrocystis integrifolia	Al	Peru
	RoK	Alaska, Canada
Macrocystis pyrifera	Ag	Australia
	Al	Chile, Mexico, Peru, USA
	F	Argentina
	RoK	Alaska, USA
Nemacystis decipiens	F	Japan
Nereocystis luetkeana	Ag	Alaska, Canada
	F	USA
Pelvetia siliquosa	F	Korea
Postelsia spp.	F	USA
Sargassum aquifolium	F	Indonesia
Sargassum crassifolium	Al	Vietnam
	F	Thailand

(continued)

Table 1 (continued)

Species	Uses	Countries
Sargassum spp.	Ag	Brazil, Vietnam, India, China, South Africa, Australia
	Al	Vietnam
	F	Bangladesh, Hawaii, Malaysia, Myanmar, Philippines, Thailand, Vietnam
	M	Brazil, Vietnam
Sargassum filipendula	F	Egypt
Sargassum graminifolium	Al	Vietnam
Sargassum henslowianum	Al	Vietnam
Sargassum horneri	F	Korea
Sargassum ilicifolium	Al	India
Sargassum mcclurei	Al	Vietnam
Sargassum myriocystum	Al	India
Sargassum oligosystum	F	Thailand
Sargassum polycystum	F	Indonesia, Thailand
	AL, M	Vietnam
Sargassum siliquosum	Al	Vietnam
	F, M	Indonesia
Sargassum wightii	Al	India
Sargassum vachelliannum	Al	Vietnam
Turbinaria spp.	Ag	Vietnam
	M	Philippines
Turbinaria conoides	Al	India
Turbinaria decurrens	Al	India
Turbinaria ornata	Al	India
Undaria pinnatifida	F	Australia, China, France, Japan, Korea
Undaria peterseniana	F	Korea, Japan, China

F food, *A* agar, *C* carrageenan, *Al* alginate, *M* medicine, *RoK* roe on kelp, *Ag* agricultural, *P* paper (Zemke-White and Ohno 1999)

5 Seaweeds for Industrial Applications

5.1 Agar–Agar Production

Agar is the major constituent of the cell walls of certain red algae especially members of the Gelidiaceae and Gracilariaceae. Agar is widely used in paper manufacturing, culture media, packaging material, photography, leather industry, plywood manufacturing, cosmetics, and pharmaceutical industry.

5.1.1 Method of Agar Production from Seaweed

A brief account of the extraction of agar from *Gracilaria*/*Gelidium* is given below (McHugh 2003). Collected and dried seaweeds are washed with water to remove adhering mud and sand. It is soaked in acidified water (0.5 N HCl) for 24 h. It is then washed, taken, and introduced into boiling potable water at 100 °C. The ratio of seaweed to water is 1:40. The pH at the beginning of the extraction is adjusted to slightly acidic after introducing seaweeds. This will facilitate easy extraction of the gel. Extraction was carried out at 100 °C for 1 h at this temperature, and then the liquid is allowed to simmer for another hour. Finally, the extract is left in a warm chamber to cool gradually, permitting the sedimentation of suspended particles. The clear supernatant liquid was separated, kept at ambient temperature for some time, and then cooled. The gel is formed and is slightly warmed to melt. Or the gel is removed, melted in water, and poured in to enamel trays to form the gel again. Upper layer of the gel is sufficiently scored using a cutter to increase the surface area to enable to freeze immediately. It is frozen at temperature between 0 and −5 °C for 24 h and it is allowed to thaw at room temperature. The process is repeated till complete water is removed. It is then drained off; the gel is placed on plastic screen and then in galvanized wire netting and is dried either in shade or in hot air at 65 °C in most of the agar manufacturing plants, and it is bleached using mild chlorine water when it is thawed. It is washed free of chlorine using potable water. The dried agar is powdered and packed in polyethylene bags. Agar can also be packed in the form of agar shreds. The agar obtained is of good quality, and the yield is about 13–15 % of the dry seaweeds. The processing method is slightly different when the bacteriological grade is manufactured. Gel solution is filtered using a filter press and drying is done at a low temperature. It is pulverized using a pulverizer fine mesh. Gel strength is the most important criterion for the quality of agar. High gel strength is a must for the bacteriological grade of agar. Commercial agar obtained from the Indian *Gracilaria* by acid treatment process has got very low gel strength in the range of 200–250 g/cm^2. As the gel strength of agar produced is very low, it fetches very low price.

5.1.2 Carrageenan

Carrageenans obtained from various red algae like *Chondrus*, *Gigartina*, *Eucheuma*, and *Hypnea* are employed in food industries. It is valuable in the manufacture of "sausages," meatballs, ham, preparations of poultry and fish, chocolates, desert gel, ice creams, juice, textiles, toothpastes, hair shampoos, sanitary napkins, fungicides, etc. There are three main types of carrageenan such as lambda, kappa, and iota each having their own gel characteristics. Previously, the use of carrageenan was restricted because of the availability of natural resources of *Chondrus crispus* (common name: Irish moss) from Canada, Ireland, Portugal, Spain, and France and *Gigartina*/*Iridaea* from South America and Southern Europe (Trono 1997). *Chondrus* contains a mixture of two types (lambda and kappa) that could not be separated during commercial extraction. Limited quantities of wild *Chondrus* are still used; attempts to cultivate *Chondrus* in tanks have been biologically successful but uneconomic as a raw material for carrageenan (McHugh 2003). These sources now only contribute 20 % of the total processed material. Supplies for this phycocolloid are dominated by *Eucheuma* which are cultivated in Indonesia and the Philippines and recently very successfully in India and Tanzania (Trono 1997).

5.1.2.1 Production of Carrageenan

Washed sun-dried seaweed is boiled in a digester by passing a team and treating with 10 % KOH (caustic potash). The bleached seaweed is sun-dried or dried indoor on sieve plates below which hot air is passed. Then, the bleached and dried seaweed is grinded in a pulverizer to make into powder. Carrageenan is extracted from this crude (semi-processed) carrageenan similar to that of agar extraction by large-scale industry method, except treating the seaweed with 5–10 % sodium hydroxide solution before the hot extraction (Bixler 1996).

5.1.3 Alginate

Alginate is a polysaccharide extracted from brown seaweeds such as *Sargassum*, *Turbinaria*, *Dictyota*, and *Padina* generally growing in cold water areas worldwide and also occurring in the Indian waters. Alginate is used in the preparation of various pharmaceutical food and rubber products, textile productions, and others. This can readily form nontoxic gels (Chapman 1970). Alginates find their uses in varied industries, but the most important consumers are textile (50 %) and food (30 %) industries. As with other phycocolloids, various grades of alginate are available for specific applications and associated prices, e.g., sodium alginate in both pharmaceutical and food grade (McHugh 1987).

6 Medicinal Uses of Algae

Seaweeds were considered to be of medicinal value in the early as 3000 BC. Chinese and Japanese used them in the treatment of goiter and other diseases. Romans used the seaweeds for healing wounds, burns, and rashes. Though the importance of different seaweed products in pharmacology is known, the development of antibacterial, antifungal, and antiviral substances from seaweeds is still in the growing stages of research and development. Iodine is the most important element to enable the thyroid glands to secrete the thyroxin which contains 60 % iodine. It controls the general development of the animal. Seaweeds are the best source of iodine for human beings. Several important seaweed medicinal preparations are prepared in various countries, i.e., Kelpeck is prepared from kelps in Chicago, Burbank vegetable tablets are seaweed preparations from the USA, Kelpamalt is a seaweed medicinal preparation from New York (USA), Isokelp is prepared in California, and Parakelp and Manamar are other medicinal seaweeds (Chennubhotla et al. 2013).

Gelidium cartilagineum has been found to be against influenza B and mumps viruses. Among the seaweeds, red algae have been the major producer of bioactive secondary metabolites. Isolation of polysaccharides and other compounds with antiviral activity against enveloped viruses increased interest in algae as a source of antiviral compounds; subsequently, polysaccharides from extracts of red algae were to inhibit herpes simplex virus (HSV) and other viruses. Extracts from the California red algae *Schizymenia pacifica* contained a sulfated polysaccharide in the r-carrageenan family, which selectively inhibited HIV reverse transcriptase (Iwashima et al. 1999).

6.1 Medicinal Values of Red Algae

- *Alsidium helminthocorton*, *Digenea simplex*, and *Corallina officinalis* – vermifuge
- *Chondrus crispus* and *Gigartina stellata* – cough, chest, and stomach ailments
- *Porphyra* sp. and *Palmaria palmata* – antiscorbutic

6.2 Medicinal Values of Brown Algae

- *Fucus vesiculosus* – scrofula
- *Fucus evanescens* – stomach ailments
- *Laminaria* and other kelps – iodine source (cures goiter), stipes used to open wounds and in cervical dilation

6.3 Medicinal Values of Green Algae

- *Ulva* spp. – burn treatment
- *Acetabularia major* – bladder and kidney ailments

6.4 Antitumor Activity of Seaweeds

The anticancer property of different types of marine algae was extensively reviewed by Lee et al. (2013). An antitumor activity was tested on the different fraction of red alga *Porphyra telfairiae*. It was shown that the petroleum ether fraction showed an obvious inhibition effect on Sarconema 180 (S sub (180)), hepatic carcinoma (hep A), and enrich carcinoma (ECA) under the dose-dependent relation in the range of 125–500 mg kg^{-1}, whereas the inhibitory effects on tumor did not affect the increase of the body weight of mice. In addition, the petroleum fraction showed some cell toxicity HeLa cells and HL-60 cells. The chloroform and butanol fraction had a less effect compared with the petroleum ether fraction and water fractions and strong activity. Five compounds were isolated from petroleum ether fraction, and structures of four were elucidated as beta-sitosterol, stearic acid, Tetra triacontanol stearate, and beta-sitosterol palmitate on the basis of chemical and spectral evidence.

6.5 Sulfated Polysaccharides from Seaweeds

Fucan, a family of sulfated polysaccharides present in brown seaweeds, has several biological activities. Their use as drugs would offer the advantage of no potential risk of contamination with viruses or particles such as prions. A fucan prepared from *Spatoglossum schroederi* was tested as a possible inhibitor of cell–matrix interactions using wild-type Chinese hamster ovary cells (Cho-k1) and the mutant type deficient in xylosyltransferase (Cho-745). The efficient polymer on adhesion properties with specific extracellular matrix components was studied using several matrix proteins as substrates for cell attachment treatment with the polymer inhibiting the adhesion of fibronectin to both Cho-k1 (2 × 10.) and Cho-745 (2 × 10.) and 5 × 10. cells. No effect was detected with laminin using the cell types. On the other hand, adhesion to vitronectin was inhibited in Cho-k1 cells and adhesion to type -1 collagen was inhibited. The fucan did not affect either cell proliferation or cell cycle (Rocha et al. 2001).

6.6 Antihypercholesterolemic Activity

In the right and left sides of the peritoneal cavity, levels of total cholesterol and low-density lipoprotein decreased to 37 % and 24 % due to seaweed. For histochemical changes, hepatic tissues obtained at 40 h after injection of the triton and the *Porphyra yezoensis* extract were fixed in from calcium solution. The number of lipid drops and cholesterol particles decreased in the portal space of the hepatic cytoplasm. This indicated that the accumulation of lipid, including cholesterol, caused by triton was prevented by the antihypercholesterolemic effect of extract from the seaweed *P. yezoensis* (Hong et al. 1998).

6.7 Anticoagulant Substances from Seaweeds

An anticoagulant isolated from the marine green alga *Codium pugniformis* was composed mainly of glucose with minor amounts of arabinose and galactose. It was highly sulfated (326 μ mg polysaccharide) and contained protein (52 μ mg polysaccharide) and was thus a proteoglycan. The anticoagulant properties of the purified proteoglycan were compared with those of heparin by studying the activated partial thromboplastin time (APTT), prothrombin time (PT), and thrombin time (TT) using normal human plasma. The proteoglycan showed similar activities to heparin, but was weaker than heparin. On the other hand, the proteoglycan did not affect PT even at the concentration at which APTT and TT were prolonged. The anticoagulation mechanism of this proteoglycan was due to the direct inhibition of thrombin and the potentiation of antithrombin III. Ethanol extracts from a group of 53 marine organisms were evaluated for their antimicrobial and antiparasitic activity. The activity against *Staphylococcus aureus*, *Streptococcus faecalis*, *Bacillus subtilis* (Gram-positive), *Escherichia coli* (Gram-negative and Gram-positive), *Escherichia coli* (Gram-negative), and *Candida albicans* (yeast) was determined by the diffusion agar method. From this group, 15 ethanol extracts were tested against *Entamoeba histolytica*, and *Giardia lamblia*, *Lithothamnium crassiuscula*, *Geodia* sp., *Pacifigorgia* sp. showed significant activity against *Entamoeba histolytica*, while *Myxilla incrustans* and *Muricea appressa* were active against *Giardia lamblia. Lithothamnium crassiuscula* showed activity against both trophozoites (Matsubara et al. 2000).

6.8 Immunosuppressive Activity from Seaweeds

Water extracts of marine algae with immunosuppressive activity were investigated for in vivo activity using murine models of collagen-induced arthritis and skin transplantation. Eleven (three brown and eight red algae) of them had suppressive activity on the collagen-induced mouse arthritis model. Of these, *Eisenia bicyclis*, *Sargassum sagamianum*, *Amphiroa aberrans*, and *Gracilaria verrucosa*, in particular, showed high activity. On the other hand, treatment with extracts from *Codium fragile*, *C. intricatum*, *C. divaricatum*, and *Liagora* sp. prolonged the allograft survival time on the murine skin rejection model. One of these algal extracts, those from *Liagora* sp., markedly prolonged the allograft survival time. These results suggest that bioactive compounds with immunosuppressive activity may be contained in these algae (Mizukoshi et al. 1995).

6.9 Antiulcer Substance from Seaweeds

Porphyran inhibits Gram-negative bacterium *Helicobacter pylori* colonization. This substance can eliminate specifically *H. pylori* from the stomach and used in the prevention or treatment of gastritis, gastric ulcers, duodenal ulcers, and gastric cancer. Oral administration of porphyran prevents the adhesion of the urease on the *H. pylori* cells so as to prevent several diseases associated with it (Bhatia et al. 2003).

6.10 Agglutination, Coagulation, and the Stimulation of Cell Migration Properties

Macromolecule recognition processes are common in cells and their specificity is their most important characteristic. Many research programs exploit recognition events, and these have become the focus areas of research in biology, chemistry, medicine, and pharmacology. Biological reactions that involve recognition events include processes such as cell agglutination and coagulation, the stimulation of cell migration, and fertilization. Lectins, sometimes referred to as hemagglutinins or agglutinins, are glycoproteins with an ability to agglutinate red blood cells (Boyd and Reguera 1949). Various polysaccharides are present on cell surfaces and as a result many cells including microbes and yeasts. Tumor cells (Hori et al. 1986) and erythrocytes are selectively agglutinated by lectins (Chen et al. 1995).

Lectins are inhibited by sugars of the same type as those on the surface of the cells being agglutinated (Sharma and Sahni 1993). They are useful in exploring properties of biological structures and processes and have found applications in biology, cytology, biochemistry, medicine, and food science and technology. Lectins from *Codium* sp. have been developed into commercially available reagents and are routinely used in biochemical studies. Lectins with hemagglutinating properties occur in a verity of red, green, and brown algae (Rogers and Hori 1993; Shanmugam et al. 2002). They react with a wide array of erythrocytes including human blood group types. Agglutination reactions with human blood groups have led to their use in assays for blood typing. Lectins are also used to characterize cell-surface polysaccharides or to examine cell-binding patterns in lectinosorbent assays (Wu et al. 1998). Lectins from *Codium fragile* subspecies *tomentosoides* have been developed into a histochemical reagent by coupling them to colloidal gold, forming a lectin-gold conjugate. This conjugate is useful for studies of the surface topography of cells of animal tissues (Griffin et al. 1995).

6.11 Antilipemic, Hypocholesterolemic, Hypoglycemic, Hypotensive, and Related Activities

High plasma cholesterol levels and high blood pressure are the causes of cardiovascular disease. Some macroalgal polysaccharides and fibers such as alginate, carrageenan, funoran, fucoidan, laminaran, porphyran, and ulvan have been noted to produce hypocholesterolemic and hypolipidemic responses due to reduced cholesterol absorption in the gut (Panlasigui et al. 2003). This is often coupled with an increase in the fecal cholesterol content and a hypoglycemic response (Dumelod et al. 1999). Others have reported lowering of systolic blood pressure (antihypertensive responses) and lower levels of total cholesterol, free cholesterol, triglyceride, and phospholipid in the liver (Nishide and Uchida 2003). Evidence suggests that ulvan as a dietary fiber plays a protective role in the rate such that it modulates the stimulatory effect of mucin secretion by goblet cells into the colon (Barcelo et al. 2000). A crude methanolic extract from *Pelvetia babingtonii* showed potent α-glucosidase inhibitory activity which could make it effective in suppressing postprandial hyperglycemia (Ohta et al. 2002).

Hypolipidemic activities have been identified in ethanolic extracts of *Solieria robusta*, *Lyngarisa stellata*, *Colpomenia sinuosa*, *Spatoglossum asperum*, and *Caulerpa racemosa*, as shown by decreases in the total serum cholesterol, triglyceride, and low-density lipoprotein cholesterol levels in rats (Ara et al. 2002). PGE2 from *Gracilaria lichenoides* has antihypertensive properties when administered intravenously to hypertensive rats. Some of these substances, most notably the fibers, are likely to be exploited by nutraceutical companies that market them as health products.

6.12 Antioxidants from Seaweeds

Marine algae are constantly exposed to various environmental conditions including freezing, carbon limitation, water stress, and heat stress.

These conditions are the main causes for the formation of ROS and contribute to the photoinhibition of photosynthesis. The brown alga *Fucus evanescens* produced ROS due to freezing, high light, and desiccation stress (Collén and Davison 1999, 2001) which was detected with fluorescent dyes (Collén and Davison 1997). *Mastocarpus stellatus*, a red alga, showed higher antioxidant activity other than red seaweed *Chondrus crispus,* because of its daily exposure to high air temperature in the lower intertidal zone. The activities of enzymatic and nonenzymatic antioxidants increase with tidal height and also with temperature. In the high tidal levels, the marine algae are continuously exposed to both visible and ultraviolet radiation, resulting in higher ROS production.

7 Utilization of Seaweed as Fertilizer

The use of seaweeds as manure in farming practice is very ancient and was prevalent among the Romans and also practiced in Britain, France, Spain, Japan, and China (Thirumaran et al. 2009). Seaweed manure is a slow but long-activating fertilizer, and its application is well suited to light sandy soils, which are generally deficient in potash. Physical condition of these light soils also improves (crumb structure) on account of the gelatinous nature of seaweeds. This is attributed to the high content of polysaccharides and its consequent capacity for holding of water. Seaweed extracts are used extensively in agriculture as plant growth supplements and seaweed meal takes months to become fully effective in the soil as a plant nutrient. Seaweed concentrates are known to cause many beneficial effects on plants as they contain growth-promoting hormones (IAA and IBA, cytokinins) trace elements (Fe, Cu, Zn, Co, Mo, Mn, and Ni), vitamins, and amino acids (Challen and Hemingway 1965). Hence, large quantities of seaweeds can be used as manure in all parts of the country, either directly in the form of compost. Seaweed fertilizer application improves the fertility of soils in cultivated fields particularly the brown seaweeds because of their alginate content, which helps in conditioning the soil facilitating aeration, moisture retention, and absorption of nutrient elements. Seaweed liquid fertilizer (SLF) application (spraying) sometimes reduces the incidence of insect attack, and sugar beet and potato leaves treated with seaweed extract had significantly fewer levels infested with aphids (20 %) than the untreated leaves (83 %). The application of SLF to improve the growth of terrestrial plants is fast becoming an accepted practice. In general, the reported beneficial effects of seaweeds are improvement of overall plant vigor, yield, quality, and quantity of different plant parameters which is able to withstand any adverse environmental conditions (Balakrishnan et al 2007). Unlike, chemical fertilizers, extracts derived from seaweeds are biodegradable, nontoxic, nonpolluting, and nonhazardous to humans, animals, and birds (Anandhan and Sorna kumari 2011).

7.1 Methods of Application

The seaweed fertilizers can be prepared by the methods of manure (or) compost, crude manure, and liquid preparation. Generally, seaweed extracts are applied in small dosages. It is clear that the active ingredients in seaweed extracts are effective in low concentrations with Hoagland solution protocol followed by Epstein (1972).

7.1.1 Manure (or) Compost

Seaweeds have been used as a food and manure for plantation crops by coastal people in many countries (Kaliaperumal et al. 1987). Recent research suggests that application of seaweed extract as seed treatment and/or foliar spray helps significant growth of plants. The extract contains micronutrients, auxins and cytokinins, and other growth-promoting substances (Spinelli et al. 2010). Seaweed and its derived products are used as fertilizer in the coastal areas throughout the globe. In India, it is used for coconut plantations especially in Tamil Nadu and Kerala (Kalimuthu et al. 1987). The high amount of water-soluble potash and other mineral and trace elements present in seaweeds is readily absorbed by plants and they control nutrient deficiency in plants. Carbohydrates and other organic matter present in seaweeds alter the nature of the soil and improve its moisture retaining capacity. Hence, large quantities of seaweeds including sea grasses such as *Cymodocea*, *Diplanthera*, *Enhalus*, and *Halophila* are used as manure in all parts of the country either directly or in the form of compost.

7.1.2 Seaweed Liquid Fertilizer (SLF)

Seaweed extracts exhibit growth-stimulating property on crop plants. Hence, its formulation can be used as a bio-stimulant in agriculture. The bio-stimulant present in seaweed extract increases the vegetative growth (10 %), the leaf chlorophyll content (11 %), the stomata density (6.5 %), the photosynthetic rate, and the fruit production (27 %) of the plant (Spinelli et al. 2010). In spite of the proven capability of SLF on growth and yield promotion of various crops, the extraction procedure from seaweeds, its concentration, and mode of application have not been standardized. The liquid seaweed extracts from seaweeds are usually prepared by hydrolyzing the material under pressure; however, the preparation may vary from species to species depending upon the amount of dried material available. The method of extraction significantly differs from person to person and also the mode of application to crops. Seaweed extracts are used in several ways, such as drench in soil during transplantation, during field preparation (Lingakumar et al. 2002), seed treatment (Immanuel and Subramanian 1999), or as foliar application.

Foliar applications of liquid fertilizer supply the plant with nutrients more rapidly than methods involving uptake by root due to seed/root treatment. Growers, therefore, can apply SLF as foliar treatment to quickly correct nutrient deficiencies. Foliar treatment has some drawbacks, mainly due to the structure of the leaf and the temporary nature of the nutrient supply. Leaves, particularly those with thick cuticle, have low absorption rates. Therefore, multiple applications of liquid fertilizers are necessary to supply a sufficient quantity of the nutrients to the plants. Further, once applied, foliar nutrients may be washed off by rain or irrigation water before the plant absorbs them. To counter this loss, surfactants can be used to increase the efficiency of penetration of the leaf surface and the duration of the sprays on the leaf be increased depending upon the situation. At certain cases, application of high nutrient concentrations in foliar spray causes severe leaf damage due to phytotoxicity. To avoid this situation, repeated applications of dilute formulations, therefore, is necessary to supply the plant's nutrient requirements without damaging the foliage. Since there are different types of seaweed extracts available in the market, it is important for the farmer/grower to know the type of species used in preparation of SLF and how to properly use it for specific crops. The timing, dosage, and frequency of application are very important when dealing with seaweed extract. Application rate and frequency may vary based on location, time of season, soil type, and crop. Proper application is important because higher concentration of seaweed extract may damage the plant resulting to loss in yields (Spinelli et al. 2010).

7.2 Present Status of Seaweed Fertilizer Usage

Though seaweed and its derived product are increasingly used in the production of agricultural crops, the mechanism of action of seaweed extract on enhancement of productivity is still unknown. The recent challenge in sustainable food production is due to the increasing occurrence of biotic and abiotic stress due to climate change, which may lead to the reduction of agricultural productivity globally. Under this situation, SLF may work as a good inducer for sustainability in agricultural production coupled with maintenance of soil health. In India, seaweeds are not used extensively except for production of phycocolloids. However, being a rich source of vitamins, minerals, and growth promoters, they can be of immense help to the coastal farmers for their use as a source of organic fertilizer. Hence, there is a need for popularizing the use of seaweed as health food and liquid organic fertilizer through mass scale field trials and organization of public awareness programs (Mohanty et al. 2013).

8 Utilization of Seaweeds as Food

Seaweeds are considered as a food supplement in the twenty-first century because they contain proteins, lipids, polysaccharides, minerals, vitamins, and enzymes. In general, seaweeds are rich in vitamins A, E, C, and niacin with similar contents in green algae (Chlorophyta), brown algae (Phaeophyta), and red algae (Rhodophyta). The concentration of vitamins B12, B1, pantothenic acid, and folic and folinic acids is generally higher in greens and reds than in browns (Madlener 1977). The brown algae possess organic iodine in greater amounts, whereas in green algae, this micronutrient is found generally in low quantity. For example, one tablespoon of cooked hijiki (*Hizikia fusiforme*), a brown algae, is approximately equivalent in calcium to one glass of whole milk. On the other hand, tea made from *Fucus vesiculosus* (bladder wrack) is called "slimming tea" because the high iodine content in the plants will act as a stimulator of the thyroids that regulates the metabolism, and there is no better way to provide the body with a full complement of trace elements than consuming these kinds of sea vegetables. Marine algae are similar to oats in protein and carbohydrate values. The red and green algae appear higher in crude protein far tested about 2–4 %. For example, the blue-green algae *Nostoc* species have around 20 % protein content, which is similar for the green algae *Enteromorpha linza* (20 %) and the brown algae *Analipus japonicus* (22 %). The protein values of red algae *Porphyra* are higher than rice or soybeans and very close to horsemeat meal (Madlener 1977).

All algae contain high content of carbohydrates (sugars and starches) in polysaccharide biochemical structure which is a natural nontoxic colloidal substance that has been used as mucilaginous material referred to as gel. However, this structure cannot be broken by the digestive enzymes in several organisms, and therefore their use for human consumption is nutritionally limited (Madlener 1977). Fat content in sea vegetables ranges from 1 % in *Laminarias* to 8 % in *Pelvetia canaliculata*.

8.1 Food Source from Green Seaweeds

The green seaweeds *Monostroma*, *Enteromorpha*, *Ulva*, *Caulerpa*, and *Codium* are commonly known as source of food. In Japan, dried fronds of edible *Monostroma* are used in preparation of "nori-jam" and soup. Edible *Monostroma* and *Enteromorpha* are called "Aonori" in Japanese (Ohno 1997); in some Pacific regions, *Enteromorpha* is being known as "ele ele" (Hawaii), "Iulua," "lumi boso" (Fiji), and "Nalumlum malekesa" (Vanuatu). This alga is being eaten by humans as edible raw, dried, or cooked (Novaczek 2001). *Codium geppiorum* is a favorite dish with fish cooked in milk by many Pacific islanders. *Caulerpa* is known as "sea grapes," "green caviar," or "green sea feather." It is commonly sold in markets and is important to the economy of many Pacific regions. *Caulerpa lentillifera* is being consumed as a salad in the Philippines and some parts in Indonesia (Trono and Toma 1997), and *C. sertularioides*, *C. peltata*, and *C. bikinensis* are being consumed with coconut milk (Payri et al. 2000).

8.2 Food Source from Brown Seaweeds

Laminaria "kombu" and *Undaria* "wakame" are edible and important resources in Japan. They are consumed raw, boiled, or dried material with sweetened green beans, jelly, crushed ice, and coconut milk in Southern Vietnam (Tsutsui et al. 2005). *Cladosiphon okamuranus* is consumed as salad in Japan (Toma 1997). *Sargassum* is known as horsetail, and it is eaten as soup or dressed with soybean sauce, after being processed in Korea (Madleners 1977) and in Hawaii (Novaczek 2001). In the Pacific region, *Rosenvingea* or slippery cushion and *Turbinaria* or spiny leaf are eaten as soup or omelet; *Colpomenia* or papery sea bubble as chop soup, stew, or salad; and *Hydroclathrus* or sea colander, *Dictyota* or brown, and Padina or sea fan ribbon weeds as a food dressing, soup, or stew (Novaczek 2001).

8.3 Food Source from Red Seaweeds

Acanthophora or spiny sea plant, *Asparagopsis* or supreme limu, *Callophyllis* or large wire weed, *Hypnea* or maidenhair, *Halymenia* or red sea lettuce, *Laurencia* or flower limu, and *Scinaia* or tender golden weed are eaten fresh or raw; chopped and cooked, especially with coconut milk, or sprinkled as a spice in salads; used to make pudding and jellies; and dried and rehydrated in the Pacific regions (Novaczek 2001).

Gracilaria or sea moss is being used as homemade agar, garnish for sashimi, used for commercial agar, or fresh as a salad (Madlener 1977; Novaczek 2001). *Gelidiella* or little wire weed is eaten after being simmered as a jelly in Japan and Vietnam (Madlener 1977; Novaczek 2001; Tanaka and Nakamura 2004). *Rhodymenia palmata* or dulse is the most common of edible seaweeds in Europe and North America. *Alaria fistula*, *Chordaria flagelliformis*, and *Porphyra umbilicalis* are also used as food, while *Porphyra* or purple lever is being consumed fresh or dried in Japan, China, Korea, Vietnam, North America, and Europe (Madlener 1977; Tanaka and Nakamura 2004; Tsutsui et al. 2005). *Eucheuma* and *Kappaphycus* or thorn grass, elkhorn (*Eucheuma*), and brown licorice algae tambalang (*Kappaphycus*) are being eaten with coconut milk and sugar in Indonesia and Vietnam (Tsutsui et al. 2005).

8.4 Seaweed Recipes

It is known that about 100,000 tones of seaweeds are eaten annually in Japan in the name nori, kombu, and hakama. Seaweeds are rich in proteins, vitamins, amino acids, growth hormones, minerals, and other trace elements. Hypothyroidism (goiter) can be controlled by the intake of iodine-rich seaweeds like *Asparagopsis taxiformis*, *Sarconema* spp., etc. Indian seaweed can be best consumed as follows: *Caulerpa sertularioides*, *Codium*, *Gracilaria confervoides*, *Hydroclathrus clathratus*, *Laurencia papillosa*, and *Hypnea valentiae* as seaweed salad; *Ulva lactuca* as seaweed masala; *Gracilaria edulis* as seaweed pickle, seaweed wafer, and seaweed jelly; and *Ulva lactuca* as seaweed jam (Chennubhotla et al. 1981).

8.5 Production of Vegetable Oils from Microalgae

Most current research on oil extraction is focused on microalgae to produce biodiesel from algal oil. The biodiesel from algal oil in itself is not significantly different from biodiesel produced from vegetable oils. Dilution, microemulsification, pyrolysis, and transesterification are the four techniques applied to solve the problems encountered with high fuel viscosity. Of the four techniques, transesterification of oil into its corresponding fatty ester (biodiesel) is the most promising solution to the high viscosity problem. This is accomplished by mixing methanol with sodium hydroxide to make sodium methoxide. This liquid is then mixed into vegetable oil. The entire mixture then settles and glycerin is left on the bottom while methyl esters, or biodiesel, is left on top. Biodiesel can be washed with soap and glycerin using a centrifuge and then filtered. Kinematic viscosities of the fatty acid methyl esters vary from 3.23 to 5.61 mm/s (Knothe 2005). Methanol is preferred for transesterification because it is less expensive than ethanol (Graboski and McCormick 1998). For production of biodiesel, macroalga (*Cladophora fracta*) and microalga (*Chlorella protothecoides*) samples were used (Demirbas 2008). The higher heating value of *Chlorella protothecoides* (25.1 MJ/kg) is also higher than that of *Cladophora fracta* (21.1 MJ/kg). Most vegetable oils are unsaturated. The properties of the various individual fatty esters that comprise biodiesel determine the overall fuel properties of the biodiesel fuel. The average polyunsaturated fatty acids of *Chlorella protothecoides* (62.8 %) are also higher than those of *Cladophora fracta* (50.9 %). Algae generally produce a lot of polyunsaturates, which may present a stability problem since higher levels of polyunsaturated fatty acids tend to decrease the stability of biodiesel. However, polyunsaturates also have much lower melting points than monounsaturates or saturates; thus, algal biodiesel should have much better cold weather properties than many other bio-oils (Demirbas 2008). A large amount of microalgal oil was efficiently extracted from the heterotrophic cells using n-hexane and then transmuted into biodiesel by acidic transesterification (Xu et al. 2006).

9 Seaweeds Used as Animal Feed

Seaweeds had been used for many years directly for human consumption and animal feed. It is also an ingredient for the global food and cosmetics industries and is used as fertilizer and as an animal feed additive. Also, seaweeds are valuable sources of food, micronutrients, and raw materials for the pharmaceutical industry. Seaweed has plenty of essential nutrients, especially trace elements and several other bioactive substances that explains why seaweeds are considered as a food supplement in the twenty-first century and as source of proteins, lipids, polysaccharides, mineral, vitamins, and enzyme (Rimber 2007). Interestingly, the best known component of the seaweed-derived industry is that of the phycocolloids, the gelling, thickening, emulsifying, binding, stabilizing, clarifying, and protecting agents known as carrageenans, alginates, and agars (Chopin 2007). Total annual use by the global seaweed industry is about 8 million tones of wet seaweed (McHugh 2003).

9.1 Seaweed Used as Fish Feed

In fish farming, wet feed usually consists of meat waste and fish waste mixed with dry additives containing extra nutrients all formed together in a doughy mass. When thrown into the fishponds or cages, it must hold together and not disintegrate or dissolve in the water. A binder is needed; sometimes a technical grade of alginate is used. It has also been used to bind formulated feeds for shrimp and abalone. However, the use of finely ground seaweed meal made from brown seaweeds is cheaper.

There is also a market for fresh seaweed as a feed for abalone. In Australia, the brown seaweed *Macrocystis pyrifera* and the red seaweed *Gracilaria edulis* have been used. In South Africa, *Porphyra* is in demand for abalone feed, and recommendations have been made for the management of the wild population of the seaweed. Pacific dulse (*Palmaria mollis*) has been found to be a valuable food for the red abalone, *Haliotis rufescens*, and development of land-based cultivation has been undertaken with a view of producing commercial quantities of the seaweed. The green seaweed, *Ulva lactuca*, has been fed to *Haliotis tuberculata* and *H. discus* (McHugh 2003). Feeding trials showed that abalone growth is greatly improved by high protein content, and this is attained by culturing the seaweed with high levels of ammonia present.

9.2 Seaweed Used as Feed for Farm Animals

Seaweeds are cheap sources of minerals and trace elements besides vitamins, growth hormones, and phycocolloids. Hence, meals prepared from seaweeds can be given as supplements to the daily rations of the cattle, poultry shrimps, and fishes. Seaweed meal can be mixed with fish meal and used as poultry feed. Dave et al. (1977) assessed the possibility of seaweeds being used as supplementary animal feed and they reviewed the feeding trails of animals with seaweeds conducted in Japan, Germany, the UK, Norway, and other countries.

9.3 Seaweed Utilization in Integrated Aquaculture

Cultivation of *Gracilaria* started in Taiwan Province of China in the 1960s as a source of raw material for its agar industry. At first cultivation was on ropes in ditches containing fishpond effluents, but in 1967, it was moved into the fishponds themselves. This had the twofold benefit of the seaweed using the fish waste material as fertilizer and the fish eating the epiphytes, such as *Enteromorpha* species, that would otherwise become serious pests for the seaweeds. Control with tilapia (*Oreochromis mossambicus*) and milkfish (*Chanos chanos*) was satisfactory as long as the fish were removed before they started to eat the *Gracilaria*; larger fish were periodically removed and replaced by small fish. This concept of polyculture, or integrated aquaculture to use the more recent terminology, has since been utilized in many situations where the effluent from the aquaculture of one species, potentially threatening environmental damage, can be utilized by another species to its advantage, with a reduction in pollution. Various strategies have been tried. Seaweed cultivation around the outside of fish cages has led to significantly better growth of seaweed but was only partly successful in removing the large amount of nutrients coming from the fish cages. Unattached *Gracilaria* has been grown in the effluent from shrimp ponds. Semi-enclosed or land-based systems have been suggested, but the higher capital investment has been a deterrent (McHugh 2003).

Integrated aquaculture is developing as solutions are sought to problems of environmental sustainability, including the management of coastal areas and the disposal of effluents from large-scale aquaculture activities. Animal aquaculture techniques affect adversely the environment in one way or another (Ackefors and Enell 1990). They generate increased sedimentation, biochemical oxygen demand, nutrient loadings, etc., inherent to highly intensive stocking and feeding. Wastewater contains a large amount of nitrogen excreted by the animals as particulate or in the dissolved state (del Rio et al. 1996). The worldwide increase during the last few years on mono-species aquaculture has generated severe environmental problems and is a matter of great concern. Haglund and Pedersén (1993) investigated the potential of the red seaweed *Gracilaria tenuistipitata* when cocultivated with *Oncorhynchus mykiss* (rainbow trout) for the removal of nitrogen and phosphorus from the pond. Integrated management of seaweed in shrimp aquaculture ponds is a common practice in China and Taiwan since it attributes the following: (1) the seaweeds could be a suitable shelter for the animals especially during the day; (2) the oxygen evolved during photosynthesis by seaweed helps the aerobic bacteria to accelerate the degradation of complex organic substances to simple elements; (3) ammonia, urea, and other nutrients present in the excreta of the animals are being utilized by the seaweed for its productivity thereby reducing the nutrient loading; (4) the polysaccharides and other products obtained from the seaweed while grown in aquaculture farms exhibit good quality since the ambient water is enriched with nutrients; (5) the shrimp farmers benefited not only from the animals but also from the seaweeds; and (6) the level of oxygen during the day is increased due to photosynthesis. However, both animals and plants compete for oxygen during night. Therefore, maintenance of stocking density of seaweed in the pond is a prerequisite for integrated aquaculture practice (Kavitha and Rengasamy 2002).

10 Utilization of Seaweed Biomass for Fuel

Continued use of petroleum sourced fuels is now widely recognized as unsustainable because of depleting supplies and the contribution of these fuels to the accumulation of CO_2 in the environment. Renewable, carbon-neutral transport fuels are necessary for environmental and economic sustainability (Chisti 2007). Biodiesel can be carbon neutral and produced intensively on relatively small areas of marginal land. The quality of the fuel product is comparable to petroleum diesel and can be incorporated with minimal change into the existing fuel infrastructure. Innovative techniques, including the use of industrial and domestic waste as fertilizer, could be applied to further increase biodiesel productivity (Campbell 2008). Similar to higher plants like corn, soybeans, sugar cane, wood, and other plants, algae also used photosynthesis to convert solar energy into chemical energy. They store this energy in the form of oils, carbohydrates, and proteins. The plant oil can be converted into biodiesel; hence, biodiesel is a form of solar energy.

Algae are among the fastest growing plants in the world, and about 50 % of their weight is oil. This lipid oil can be used to make biodiesel for cars, trucks, and airplanes. Microalgae have much faster growth rates than terrestrial crops. The per-unit area yield of oil from algae is estimated to be between 20,000 and 80,000 L/acre/year; this is 7–31 times greater than the next best crop, palm oil (Chisti 2007). It is possible that US demand for liquid fuel could be achieved by cultivating algae in one tenth the area currently devoted to soybean cultivation (Scott and Bryner 2006). The lipid and fatty acid contents of microalgae vary in accordance with culture conditions. Most current research on oil extraction is focused on microalgae to produce biodiesel from algal oil. Algal oil can be processed into biodiesel as easily as oil derived from land-based crops.

The production of microalgal biodiesel requires large quantities of algal biomass. The algae that are used in biodiesel production are usually aquatic unicellular green algae. This type of algae is a photosynthetic eukaryote characterized by high growth rates and high population densities. Under good conditions, green algae can double their biomass in less than 24 h (Schneider 2006; Chisti 2007). Additionally, green algae can have huge lipid contents, frequently over 50 % (Schneider 2006; Chisti 2007). This high-yield, high-density biomass is ideal for intensive agriculture and may be an excellent source for biodiesel production. A one ha algae farm on wasteland can produce over 10–100 times as much oil compared to any other known source of oil crops. While a crop cycle may take from 3 months to 3 years for production, algae can start producing oil within 3–5 days, and thereafter oil can be harvested on a daily basis. Algae can be grown using sea water and non-potable water on wastelands where nothing else grows. Algae farming for biofuels is expected to provide a conclusive solution to the food vs. fuel debate. The production of biodiesel has recently received much attention worldwide. In order to resolve the worldwide energy crisis, seeking for lipid-rich biological materials to produce biodiesel effectively has attracted much renewed interest. Algae have emerged as one of the most promising sources for biodiesel production. It can be inferred that algae grown in CO_2-enriched air can be converted into oily substances. Such an approach can contribute to solving the major problems of air pollution, resulting from CO_2 emissions and future crises due to a shortage of energy sources (Sharif Hossain et al. 2008).

The process for producing microalgal oils consists of a microalgal biomass production step that requires light, CO_2, water, and inorganic nutrients. The latter are mainly nitrates, phosphates, iron, and some trace elements. Approximately half of the dry weight of microalgal biomass is carbon, which is typically derived from CO_2. Therefore, producing 100 tons of algal biomass fixed roughly 183 tons of CO_2. This CO_2 must be fed continually during daylight hours. It is often available at little or no cost (Chisti 2008). The optimal temperature for growing many microalgae is between 293 and 303 K. A temperature outside this range could kill or otherwise damage the cells. There are three well-known methods to extract oil from algae: (1) expeller/press, (2) solvent extraction with hexane, and (3) supercritical fluid extraction. A simple process is to use a press to extract a large percentage (70–75 %) of the oils from algae. Algal oil can be extracted using chemicals. The most popular chemical for solvent extraction is hexane, which is relatively inexpensive. Supercritical fluid extraction is far more efficient than traditional solvent separation methods. Supercritical fluids are selective, thus providing the high purity and product concentrations (Paul and Wise 1971). This method alone can allow one to extract almost 100 % of the oils. In supercritical fluid CO_2 extraction, CO_2 is liquefied under pressure and heated to the point where it has the properties of both a liquid and a gas. This liquefied fluid then acts as the solvent in extracting the oil. The lipid and fatty acid contents of microalgae vary in accordance with culture conditions. Algal oil contains saturated and monounsaturated fatty acids. The fatty acids exist in algal oil in the following proportions: 36 % oleic (18:1), 15 % palmitic (16:0), 11 % stearic (18:0), 8.4 % isolinoleic (17:0), and 7.4 % linoleic (18:2). The high proportion of saturated and monounsaturated fatty acids in this alga is considered optimal from a fuel quality standpoint, in that fuel polymerization during combustion would be substantially less than what would occur with polyunsaturated fatty acid-derived fuel (Sheehan et al. 1998). Oil levels of 20–50 % are quite common (Chisti 2007; Carlsson et al. 2007; Demirbas 2009). After oil extraction from algae, the remaining biomass fraction can be used as a high protein feed for livestock (Schneider 2006; Haag 2007). This gives further value to the process and reduces waste. Moreover, according to the biodiesel standard published by the American Society for Testing Materials (ASTM), biodiesel from microalgal oil is similar in properties to standard biodiesel and is also more stable according to their flash point values.

10.1 Economics of Biodiesel Production

There are small numbers of economic feasibility studies on microalgae oil (Richardson et al. 2009). Currently, microalgae biofuel has not been deemed economically feasible compared to the conventional agricultural biomass (Carlsson et al. 2007). Critical and controversial issues are the potential biomass yield that can be obtained by cultivating macro- or microalgae and the costs of producing biomass and derived products. The basis of the estimates is usually a discussion of three parameters: photosynthetic efficiency, assumptions on scale up, and long-term cultivation issues. For microalgae, the productivity of raceway ponds and photobioreactors is limited by a range of interacting issues. Typical productivity for microalgae in open ponds is 30–50 t/ha/year (Benemann and Oswald 1996; Sheehan et al. 1998). Several possible target areas to improve productivity in large-scale installations have been proposed (Benemann and Oswald 1996; Grobbelaar 2000; Suh and Lee 2003; Torzillo et al. 2003; Carvalho et al. 2006). Harvesting costs contribute 20–30 % to the total cost of algal cultivation, with the majority of the cost attributable to cultivation expenses. Genetic engineering, development of low-cost harvesting processes, improvements in photobioreactor, and integration of coproduction of higher-value products/processes are other alternatives in reducing algal oil production costs (Chisti 2007). The harvested algae then undergo anaerobic digestion, producing methane that could be used to produce electricity. In commercial photobioreactors, higher productivities may be possible. Typical productivity for a microalga (*Chlorella vulgaris*) in photobioreactors is 13–150 (Pulz 2001). Photobioreactors require ten times more capital investment than open pond systems. The estimated algal production cost for open-pond system is $ 10/kg and photobioreactors are from $ 30 to $ 70/kg. The cost of algal production is two to three orders of higher magnitude than conventional agricultural biomass (Carlsson et al. 2007). Assuming that biomass contains 30 % oil by weight and carbon dioxide is available at no cost (flue gas), Chisti (2007) estimated the production cost for photobioreactors and raceway ponds at $ 1.40 and $ 1.81/L of oil, respectively. However, for microalgal biodiesel to be competitive with petrodiesel, algal oil should be less than $ 0.48/L (Chisti 2007).

It is useful to compare the potential of microalgal biodiesel with bioethanol from sugar cane, because on an equal energy basis, sugarcane bioethanol can be produced at a price comparable to that of gasoline (Bourne Jr. 2007). Bioethanol is well established for use as a transport fuel (Gray et al. 2006), and sugarcane is the most productive source of bioethanol (Bourne Jr. 2007). For example, in Brazil, the best bioethanol yield from sugarcane is 7.5 m^3/ha (Bourne Jr. 2007). However, bioethanol has only ~64 % of the energy content of biodiesel. Therefore, if all the energy associated with 0.53 billion m^3 of biodiesel that the USA needs annually (Chisti 2007) were to be provided by bioethanol, nearly 828 million m^3 of bioethanol would be needed. This would require planting sugarcane over an area of 111 million ha or 61 % of total available US crop land. Recovery of oil from microalgal biomass and conversion of oil into biodiesel are not affected by whether the biomass is produced in raceways or photobioreactors. Hence, the cost of producing the biomass is the only relevant factor for a comparative assessment of photobioreactors and raceways for producing microalgal biodiesel.

If the annual biomass production capacity is increased to 10,000 t, the cost of production per kilogram reduces to roughly $ 0.47 and $ 0.60 for photobioreactors and raceways, respectively, because of economies of scale. Assuming that the biomass contains 30 % oil by weight, the cost of biomass for providing a liter of oil would be something like $ 1.40 and $ 1.81 for photobioreactors and raceways, respectively (Chisti 2007). Biodiesel from palm oil costs roughly $ 0.66/L, or 35 % more than petrodiesel. This suggests that the process of converting palm oil into biodiesel adds about $ 0.14/L to the price of oil. For palm oil-sourced biodiesel to be competitive with petrodiesel, the price of palm oil should not exceed $ 0.48/L, assuming no tax on biodiesel. Using the same analogy, a reasonable target price for microalgal oil is $ 0.48/L for algal diesel to be cost competitive with petrodiesel.

10.2 Improving Economics of Microalgal Biodiesel

Algae are among the fastest growing plants in the world, and about 50 % of their weight is oil. That lipid oil can be used to make biodiesel for cars, trucks, and airplanes. Algae will someday be competitive as a source of biofuel. Only renewable biodiesel can potentially completely displace liquid fuels derived from petroleum. The economics of producing microalgal biodiesel need to improve substantially to make it competitive with petrodiesel, but the level of improvement necessary appears to be attainable (Demirbas 2008). Biodiesel has great potential; however, the high cost and limited supply of renewable oils prevent it from becoming a serious competitor with petroleum fuels. As petroleum fuel costs rise and supplies dwindle, biodiesel will become more attractive to both investors and consumers. For biodiesel to become the alternative fuel of choice, it requires an enormous quantity of cheap biomass. Using new and innovative techniques for cultivation, algae may allow biodiesel production to achieve the price and scale of production needed to compete with, or even replace, petroleum (Campbell 2008).

It has been estimated that 0.53 billion m^3 of biodiesel would be needed to replace current US transportation consumption of all petroleum fuels (Chisti 2007). Neither waste oil nor seed oil can come close to meeting the requirement for that much fuel; therefore, if biodiesel is to become a true replacement for petroleum, a more productive source of oil such as algal oil is needed (Scott and Bryner 2006; Chisti 2007). The cost of producing microalgal biodiesel can be reduced substantially by using a biorefinery-based production strategy, improving capabilities of microalgae through genetic engineering and advances in photobioreactor engineering. Like a petroleum refinery, a biorefinery uses every component of the biomass raw material to produce usable products (Chisti 2007).

11 Utilization of Seaweeds in Wastewater Treatment

11.1 Seaweeds in Sewage Treatment

Wastewater stabilization ponds are designed for anaerobic and aerobic bacteria and algae to decompose waterborne organic wastes efficiently. Ludwig et al. (1951) studied the role of algae in the treatment of sewage by photosynthetic oxygenation in waste stabilization ponds. Indian coastal waters are constantly polluted with industrial and domestic wastes. Domestic sewage is rich in nutrients such as NH_4-N, NO_2-N, NO_3,-N, PO_4-P, K, etc. The discharge of sewage into the coastal waters is estimated to be 35 Km^3/year (Qasim and Sen Gupta 1988). Addition of such enormous quantities of pollutants into the coastal water affects its water quality and cause eutrophication. Therefore, treatment of wastewaters before their discharge into the sea is essential. Red seaweeds like *Chondrus crispus*, *Gracilaria foliifera*, and *Neoagardhiella baileyi* when grown in the aquaculture system considerably removed the nutrients (Ryther et al. 1979). Dhargalkar (1986) observed that *Ulva fasciata* and *G. verrucosa* showed better growth in 5 % sewage seawater mixture. The biomass of *Ulva sp.* and *Enteromorpha sp.* increased when they were grown near the vicinity of discharge of domestic effluent. The use of *Ulva* sp. as biofilters has been suggested as an efficient method to recover large amount of dissolved inorganic nitrogen (Vandermeulen and Gordin 1990). Some seaweeds are used to remove heavy metals to clean up wastewater. Milled, dried species of the brown seaweeds *Ecklonia*, *Macrocystis*, and *Laminaria* were able to adsorb Cu, Zn, and Cd ions from the solution. In another laboratory-scale trial, *Ecklonia maxima*, *Lessonia flavicans*, and *Durvillaea potatorum* adsorbed Cu, Ni, Pb, Zn, and Cd ions, though to varying extents depending on the seaweed type and metal ion concentration. After the extraction of alginate from brown seaweeds, there is an insoluble waste product, mostly cellulose, and the adsorbing properties of this have been tested and found to equal some of the brown seaweeds. Using such a waste material is obviously more attractive than using the dried seaweed itself. Another waste product, from the production of Kelpak, and liquid fertilizer previously mentioned, has also been tested and found that it adsorbs Cu, Cd, and Zn just as effectively as the seaweed from which it is derived. So, there is the potential to use either seaweed or residues remaining from seaweed extraction. It is a matter of whether this is the most economical way to do so, depending on their availability and cost at the source of the wastewater (McHugh 2003). There are two main areas where seaweeds have the potential for use in wastewater treatment. The first is the treatment of sewage and some agricultural wastes to reduce the total nitrogen- and phosphorus-containing compounds before the release of these treated waters into rivers or oceans. The second is for the removal of toxic metals from industrial wastewater.

11.2 Treatment of Wastewater to Reduce Nitrogen- and Phosphorus-Containing Compounds

The rapid expansion of aquaculture has contributed to the excessive increase of nutrients, especially nitrogen and phosphorous, in aquatic ecosystems (Beveridge 1996). These nutrients generally originate from pond fertilization, feed, and metabolic residues of the cultivated animals. In this sense, the major challenge has been to develop nonpolluting strategies that minimize the negative effects of this activity. The most practical and economical approach to reduce the concentration of nutrients in aquaculture areas is to treat the effluents before it reaches the sea. A potentially feasible alternative is the biological treatment of effluents, using macroalgae for nutrient removal (Chopin et al. 2001; Neori et al. 2004). Heavy metals like Fe, Zn, Ca, and Mg have been reported to be of bio-importance to man and their daily medicinal and dietary allowances (Duruibe et al. 2007). Even for those having bio-importance, dietary intake has to be maintained at regulatory limits, as excesses will result in poisoning or toxicity, which is evident by certain reported medicinal symptoms that are clinically diagnosable (Fosmire 1990; Nolan 2003). Methods for removing metal ions from aqueous solution mainly consist of physical, chemical, and biological technologies. Seaweeds are presented as very good sorbents, because the cell wall of green and brown algae contains alginate with its carboxyl and hydroxyl groups (Davis et al. 2003; Vieira and Volesky 2000). Worse sorptive properties are suggested for red algae owing to its carrageen, exposing hydroxyl and sulfonate groups (Tsezos and Volesky 1981).

12 Conclusions

Ecological and commercial seaweeds are important as a potential source as food supplement in the twenty-first century because they serve as sources of proteins, lipids, polysaccharides, minerals, vitamins, and enzymes. The use of seaweeds in the development of pharmaceuticals, nutraceuticals, and cosmetics and as source of pigments, bioactive compounds, and antiviral agents is extensively discussed. They are being used for food, medicine, industry, and others such as integrated aquaculture with fishes, biofuel, and in removing the heavy metal in cleaning wastewater. Hence, seaweeds are the promising and versatile source for maintaining green environment in a sustainable manner.

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