Ambati Ranga Rao
Gokare A. Ravishankar *Editors*

Sustainable Global Resources Of Seaweeds Volume 1

Bioresources , cultivation, trade and multifarious applications

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Contents

Chapter 27
Energy and Economic Nexus of Seaweeds

T. V. Ramachandra and Deepthi Hebbale

27.1 Introduction

27.1.1 Macroalgae

Macroalgae, commonly known as seaweeds are multicellular, photosynthetic plants exhibiting wide range of variations in their morphology and reproduction. Multicellular algae consist of haptera (root like), stipes (stem) and blades (leaves). They are devoid of specialized conducting tissues and their reproductive organs are simple cells or masses of cells producing gametes. They lack the embryo and multicellular envelope around sporangia and gametangia, the freshwater charophytes being some exception. They are comparable to higher plants in their biochemical and metabolic pathways, especially in those where chlorophylls constitute as the main photosynthetic pigments (Guiry and Guiry 2008; Pereira and Neto 2014). Algae encompass several phyla and a vast array of forms, ranging from benthic to free-floating forms, from microscopic phytoplankton to minute cells and colonies or filaments epiphytic on larger plants to larger macroalgae or seaweeds. Over the last thirty years', classification of algae has witnessed major transitions while yet to

T. V. Ramachandra (✉)
Energy & Wetlands Research Group, Centre for Ecological Sciences, Bangalore, India

Centre for Sustainable Technologies, Bangalore, India

Centre for infrastructure, Sustainable Transportation and Urban Planning [CiSTUP], Indian Institute of Science, Bangalore, India
e-mail: tvr@iisc.ac.in

D. Hebbale
Energy & Wetlands Research Group, Centre for Ecological Sciences, Bangalore, India

Centre for Sustainable Technologies, Bangalore, India

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Table 27.1 Classification scheme of different algal groups

Kingdom	Phylum	Subphylum	Class
Prokaryota	Cyanophyta		Cyanophyceae
Eukaryota	Glaucophyta		Glaucophyceae
	Rhodophyta	Cyanidiophytina	Cyanidiophyceae
		Eurhophytina	Compsopogonophyceae Poryphyridophyceae Rhodellophyceae Stylonematophyceae Florideophyceae
	Cryptophyta		Cryptophyceae
	Dinotophyta		Dinophyceae
	Haptophyte		Haptophyceae
	Ochrophyta	Khakista	Bacillariophyceae Bolidophyceae
		Phaeista	Chryosophyceae Synurophyceae Eustigmatophyceae Raphidophyceae Dictyochophyceae Pelagophyceae Pinguiophyceae Phaeothamniophyceae Chrysomerophyceae Xanthophyceae Phaeophyceae
	Euglenophyta		Euglenophyceae
	Chlorarachinophyta		Chlorarachinophyceae
	Chlorophyta	Prasinophytina	Prasinophyceae
		Tetraphytina	Chlorophyceae Chlorodendrophyceae Trebouxyophyceae Ulvophyceae Dasycladophyceae
	Charophyta		Coleochaetophyceae Conjugatophyceae Mesotigmatophyceae Klebsormidiophyceae Charophyceae

Source: (Pereira and Neto 2014; Smith 1938)

arrive consensus of an acceptable general scheme. Table 27.1 summarizes a system as per Yoon et al. (2006) for red algae, Leliaert et al. (2012) for green algae, Riisberg et al. (2009) and Yoon et al. (2009) for Ochrophytes, as available from Algaebase (Guiry and Guiry 2008. Seaweeds grow predominantly in marine environment and to lesser extent in brackish waters. Their classification is primarily based on their photosynthetic pigments, which impart them characteristic ranges of colors as well. The Chlorophyta group are green algae, while Phaeophyta are brown and Rhodophyta are red.

27.1.2 Seaweed Structure

Seaweeds consist of thallus which are devoid of roots, stem and leaf. Thallus include superficial leaflike blades, stem-like stipes and often having attaching organs called holdfast or haptera. The ***blades*** have varied shapes ranging from flat, tubular or round depending on taxa. The ***stipe*** is elongated, often-thick stalk of seaweed, superficially resembling stem, keeping the plant erect, while properly exposing the blades to incident light. The ***holdfast*** and ***haptera*** are structures attaching the seaweeds to the substratum. Not all seaweeds (Fig. 27.1) have definite stipe and holdfast, which are characteristic of Laminaria species. Holdfast is a specialized structure, an attaching organ on the base of a seaweed, which anchors the thallus firmly to stable surfaces like rocks. These rhizoidal haptera secrete mucilaginous substance to adhere to the substratum (Hardy and Moss 1979; Moss 1975; Tovey

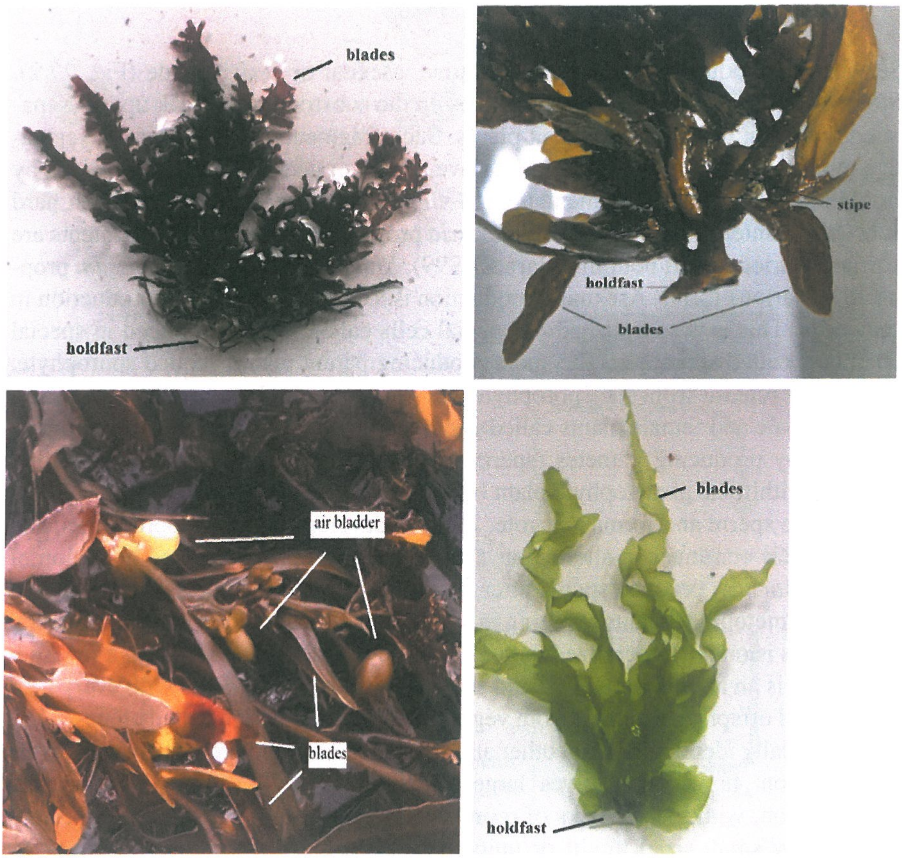

Fig. 27.1 Different structures represented in all Red, Green and Brown seaweed of fragmentation. Fragments after settlement forms one or more adhesive rhizoids and subsequently new filamentous shoots

and Moss 1978). ***Floats*** are inflated vesicles or balloon like structures or parts of the blade itself helping to keep buoyancy in water. The seaweeds absorb mineral nutrients directly from the seawater through their entire surface. The photosynthetic pigments of these algae are located along a membrane system, forming flat vesicles called thylakoids. These thylakoids are free in stroma, the main body of the plastid, remaining in singles or two or more thylakoids remain in groups called lamella. In green algae, thylakoids are in clusters interconnected by other thylakoids forming a compact stack known as grana. In red algae, thylakoids are not grouped and are associated with granules, the Phycobilisomes, where Phycobiliproteins (mainly phycoerythrin and phycocyanin) are contained whereas in brown algae, thylakoids form packs of three surrounded by a band of three thylakoids or a girdle lamella (Guiry 2014; Pereira and Neto 2014).

27.1.3 Seaweed Reproduction

Seaweeds reproduction are either vegetative, asexual or sexual mode (Fig. 27.2). Stoloniferous outgrowths of creeping axes on the substratum, if break up, the separated thalli can live as independent plants. Such fragmentation is a form of vegetative reproduction. Physical forces like wave action, or chemical damages caused by insolation can result in fragmentation. *Gelidium* and *Caulerpa* propagate on hard substrata (Santelices 1990) while *Gracilaria* propagates when thallus fragments are partially buried in soft bottoms (Barnes 1999). *Enteromorpha* and *Sargassum* propagate by various forms. Asexual reproduction is a common mode of reproduction in seaweeds. This is accomplished by special cells called spores produced in special chambers called sporangia. The spore producing parent plant is called sporophyte. After their release from the sporophyte, the spores settle down on the substratum and into male and female plants called gametophytes. The gametophytes reproduce sexually by producing gametes (sperm or eggs). The sperm and eggs are either retained within the gametophyte plant body or released into the water. Egg is fertilized on the sperm and forms a zygote. Zygotes develops and into sporophytes, and the life cycle continues in alternation, the diploid sporophyte (formed by fusion of haploid gametes) produce spores after meiosis; the haploid spores germinate into haploid gametophyte plants resulting in alternation of generations, typical of several algae. This is only a generalized pattern of life cycle in marine algae. In a few species, there is an alternating sexual and asexual reproductive process with every generation. All offspring resulting from vegetative reproduction are called clones. They are genetically identical to each other and the parent seaweed. Vegetative and sexual reproduction, however, involves larger expenditures of resources than asexual reproduction, with greater risks of reproductive failures. Therefore, asexual reproduction, by small-sized, multi or unicellular propagules is an economic way by which population can be increased (Fenner 2012).

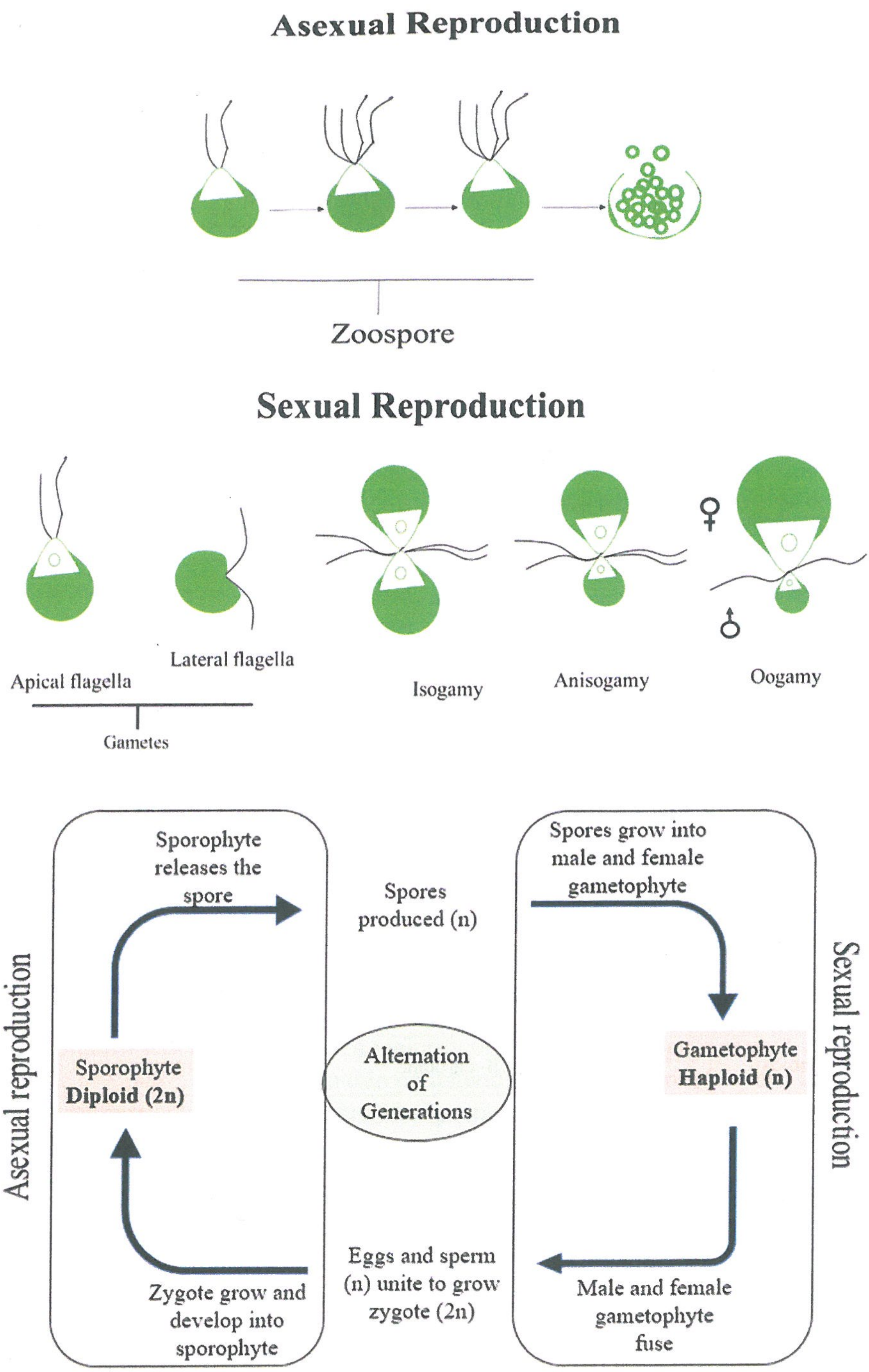

Fig. 27.2 Schematic representation of Alternation of generations observed in Seaweed reproduction

27.1.4 Types of Seaweeds

Seaweeds based on the presence of pigments are categorised into three broad types namely chlorophyta (green), rhodophyta (red) and phaeophyta (brown) and main characteristics of are summarised in Table 27.2 (Borines et al. 2013; Jung et al. 2013; Kjellman 1891; Kumar et al. 2013; Pascher 1914; Percival and McDowell 1967; Smith 1938; Yanagisawa et al. 2013). Chlorophyta have definite geographical

Table 27.2 Detailed characteristics of different types of Seaweed

Characteristics	Green seaweed	Red seaweed	Brown seaweed
Number of species recorded	6032[a]	7105[b]	2039[c]
Habitat	Freshwater and Marine	Strictly marine	Strictly marine
Photosynthetic pigment present	Chlorophyll *a*, *b*, carotene and Xanthophyll	Phycoerythrin	Fucoxanthin
Photosynthetic rate (μmol CO_2 /h) g/dry	30 to 1786	20–1808.7	100–500
Productivity [dry g/(m^2 year)]	7100	3300–11,300	3300–11,300
Nature of cell wall	Cellulose, pectin rarely hemi-cellulose	Cellulose and pectic material with polysulphate esters	Cellulose with alginic acid and fucocinic acid
Sexuality	Isogamy to oogamy	Advanced and complex (oogamous)	Isogamy to oogamy
No. of flagella and their insertion	2 or 4, equal anterior, whiplash	Absent	Only in reproductive cells, 2 unequal, lateral whiplash and tinsel
Phycolibins	Absent	Allophycocyanin,r-Phycoerythrin,r-Phycocyanin	Absent
Carotenoids	α-, β-, γ- carotene	α-, β- carotene	α-, β-, ε- carotene
Xanthophylls	Lutein Prasinoxanthin	Lutein	Fucoxanthin,Violaxanthin, Diadinoxanthin,Heteroxanthin, Vacheriaxanthin
Carbohydrate (%)	30–60	30–50	20–30
Protein (%)	10–20	6–15	10–15
Lipid (%)	1–3	0.5–1.5	1–2
Ash (%)	13–22	5–15	14–28
Photosynthetic reserve* (Stored food)	Starch	Floridean starch (intermediate between true starch and dextrin)	Laminarin and mannitol (hexahydride alcohol)

(*Stored food)

distribution, primarily dependent upon temperature of the water. The plant body (thallus) may be unicellular or multicellular and have either a definite or an indefinite number of cells. In multicellular forms, cells may be arranged in irregular masses, in filaments, as expanded sheets or as solid or hollow cylinders. Cell wall is composed of two concentric portions, the innermost portion wholly of cellulose (Tiffany 1924), and the outer mainly of pectose. The pigmentation of chloroplast is extremely variable and ranges all the way from a quantity sufficient to colour the plastid a brilliant green to an amount so small that there is only a tinge of color. Old cells of many species have the chlorophyll diffused throughout the cytoplasm, but young cells have chloroplast (Smith 1938).

Phaeophyta or brown algae range from microscopic ones to giant kelps, which attain lengths of 50 meters or more. Pigments in the brown algae are similar in chemical composition to those of green plants, but the proportion of chlorophyll *b* is lesser. The unique pigment of the Phaeophyta, fucoxanthin masks the other pigments in the chromatophores. Phaeophyta are known as algae of cold waters, however certain brown algae of orders *Dictyotales* and *Fucales* are distinctly warm-water plants. Cells of the Phaeophyta have a distinct wall and differentiated into an inner firm portion and outer gelatinous portion constituting cellulose and algin respectively. These algin or alginate are extracted from brown algae due to their adhesive property which has many uses in dairy, textile, adhesives, rubber, pharmaceutical, paper industries, etc. Rhodophyta or Red algae are multicellular plants, containing red pigment-*phycoerythrin* in the plastids in addition to chlorophyll, these pigments are present in such quantities as to mask the other pigments and give the plant a distinctive red color. Variation in the proportion of chlorophyll, phycoerythrin and phycocyanin accounts for the diversity of shades and color among Rhodophyceae (Smith 1938).

Algae in Rhodophyta are placed in a single class, the Rhodophyceae. Majority of the red algae are strictly marine, under normal conditions all marine species are sessile and, in most cases, dry up easily if the thallus is detached and free-floating. Rhodophyceae are confined to zones of amplitude of appoximately 5 °C of the summer temperature, but certain species extend over zones representing 10 °C amplitude, and a few are known in zones with an amplitude of 20 °C. Cells of Rhodophyceae lack central vacuole, but those of a majority of species have a large central vacuole and the cytoplasm restricted to a thin peripheral layer next to the cell wall. The cell wall contains cellulose and various other pectic compounds.

27.1.5 Seaweeds Habitat, Ecology and Distribution

Seaweeds occur in a wide range of environment, including fresh, brackish, and marine waters. They require an aquatic environment for reproduction. Seaweeds grow by attaching to a substrate (natural or artificial); the need for a stable anchorage restricts the development of large seaweed beds on rocky substrate (Speight and Henderson 2013). Seaweeds grow well in photic zone at a depth where light reaches.

Benthic seaweeds mostly occupy continental shelf, whereas in much clearer waters they reach up to great depths, like in Caribbean Sea where red algae have been found at depths of over 260 m (Littler et al. 1986). The ability of seaweeds to occur at different depths is closely related to the composition of their photosynthetic pigments. Guiry (2014) observed that in macroalgae, accessory pigments absorb light with specific wavelengths selectively. Light intensity of aquatic ecosystems corresponds to wavelengths of blue-green region of the spectrum. They cover rocky shores in horizontal bands, with the green seaweeds growing along the high-tide line (Supra littoral zone), brown seaweeds found between the high-and low tide lines (littoral zone), and red seaweeds in the waters below the low tide line (subtidal zone).

Green seaweeds have chlorophyll as their light absorbing pigment and are typically found in intertidal or shallow water zone. Red seaweeds have phycoerythrin and phycocyanin pigments, which can efficiently absorb light with wavelengths of photosynthetically active radiation (PAR) that can penetrate seawater to the deep zone, some red algae inhabit the deep sea (over 25 m below the surface) where sunlight availability is limited (Santelices 1991). Whereas, brown seaweeds have fucoxanthin pigment which are efficient in absorbing wavelengths of light not filtered by the water column and can grow in deeper seas. Red and brown seaweeds also contain chlorophyll but are masked by the accessory pigments like phycoerythrin, phycocyanin and fucoxanthin. Substrate, topography, temperature, salinity, humidity, tides, waves, wind, and pollutants can all affect the growth and distribution of the algae, similar to light (Fig. 27.3). Temperature is an important factor for seaweeds, as maximum and minimum temperatures allow seaweeds to survive or complete their reproductive life cycle. Higher biomass and predominance of brown algae is observed in cold and temperate seas (except for few *Sargassum* species) than in warmer seas, where red and green algae are predominant. Some algae prefer the

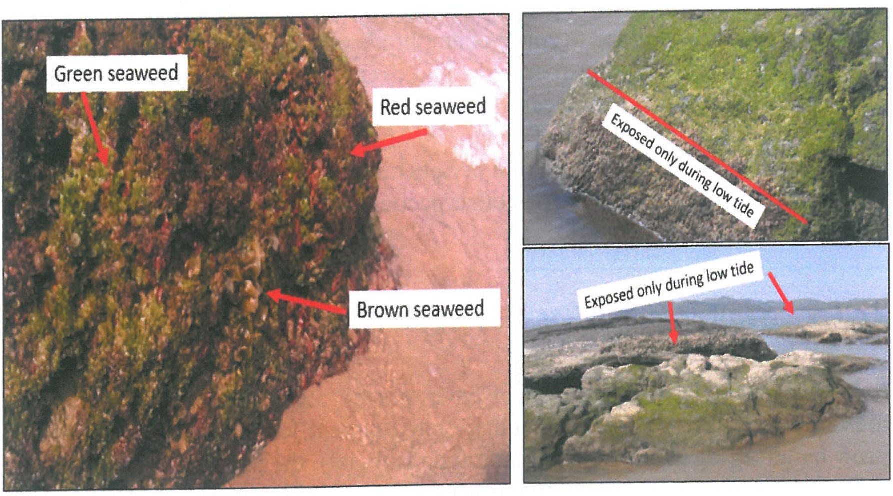

Fig. 27.3 Vertical zonation of seaweeds covering the rocky shores in horizontal bands

areas with strong waves; others prefer calm water or sea bays. Certain seaweed species tolerate drier conditions, hence can grow in the supralittoral fringe; others survive in the extra ordinal environmental changes (dry or wet) in the littoral zone, in which low tide occurs twice daily (Figs. 27.4, 27.5 and 27.6).

27.1.5.1 Worldwide Seaweed Resources

Tropical seas are characterized by warm waters (>22 °C), having low concentration of inorganic nutrients (i.e. oligotrophic), etc. Seaweeds in these waters are found up to a depth of 268 m (Littler et al. 1986) due to the high incident photon flux density and deeper penetration of light rays (Lobban et al. 1994). Temperate seas are characterized by progressive seasonal cycles of light and temperature resulting in seasonal stratification of water column. Canopy forming large brown seaweed of the orders Fucales and/or Lamninariales dominate the intertidal and subtidal regions. About 33% of seaweeds recorded in this region are endemic communities restricted to sheltered habitats, including crevices. *Ulothrix* spp., *Enteromorpha bulbosa, Acrosiphonia* spp., *Pyropia ediviifolia,*and *Prasiola crispa* dominate this region. The physical conditions of tidal pools differ from those of the adjacent seawater

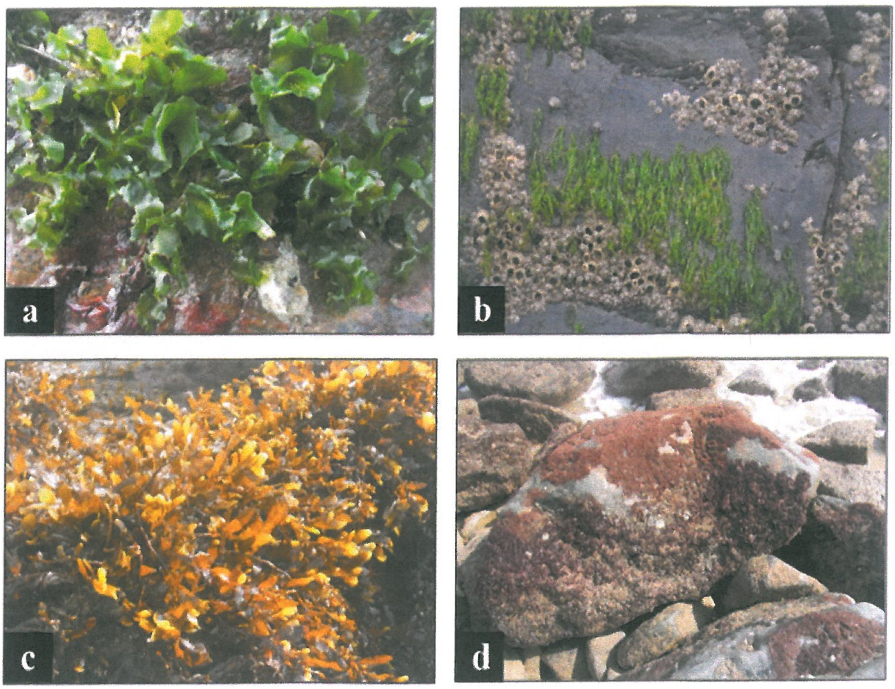

Fig. 27.4 Seaweeds attached to substratum using rhizoidal roots (**a**) *Ulva lactuca,* (**b**) *Enteromorpha intestinalis* (**c**) *Sargassum ilicifolium,* (**d**) *Gracilaria corticata* and *Coralline algae* forming mat on the substratum

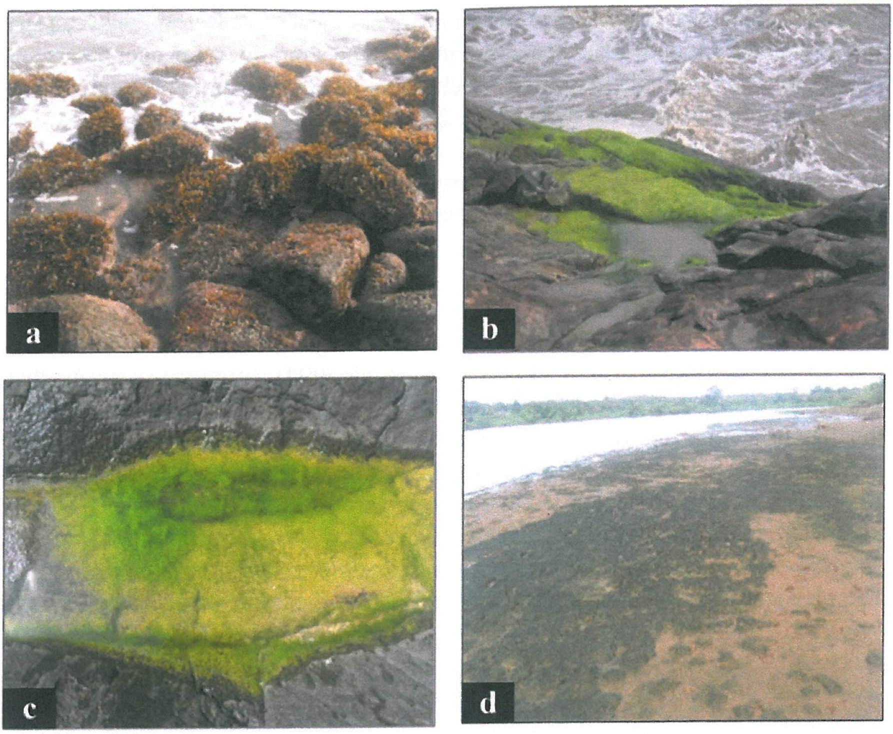

Fig. 27.5 (**a**) *Sargassum sp.* flourishing in Intertidal zone, (**b**) *Enteromorpha sp.* flourishing in supratidal zone (splash zone), (**c**) *Enteromorpha intestinalis.* in tidal pools. (**d**) *Enteromorpha sp.* buried in sediments in estuary

Fig. 27.6 Profuse growth of Ulva and Sargassum species in calm waters, Gulf of Kutch, India

depending on the size of the pool, height on the shore and atmospheric conditions. Tolerant seaweed species like *Enteromoprha (Ulva) intestinalis, Chaetomorpha aerea, Ralfasia verrucosa* (Fig. 27.5) populate these tidal pools which face rapid changes in temperature, salinity, pH, nutrients and oxygen concentrations (Lobban et al. 1994). Seaweed communities in estuary is richest towards the mouth of the estuary, they become progressively poorer with more stress tolerant species towards the head (Lobban et al. 1994; Martins et al. 1999). Seaweeds such as *Enteromorpha* can withstand burial within the sediments and spread on the surface of estuarine mudflats (Martins et al. 1999). Seaweed communities for deep water (>30 m) are well documented for clear tropical waters (Spalding et al. 2003). Mostly coralline algae, and few foliose red seaweeds and geniculate coralline algae are seen populating these waters at depth of 40–55 m (Lobban et al. 1994). Seaweeds that detach from the shore during storms, raft and travel long distance colonizing; mostly brown seaweeds such as *Fucales* for e.g. *Ascophyllum* with buoyant structures and *Druvillaea antarctica* having uniquely inflated medulla (Rothäusler et al. 2012). The Sargasso Sea is famous for its floating population of *Sargassum.* Seaweeds cover rocky shores in horizontal bands, with the green seaweeds growing along the high-tide line (supra-littoral zone), brown seaweeds between the high-and low tide lines (littoral zone), and red seaweeds living in the waters below the low tide line (sub-tidal zone). This zonation is regulated by the light availability and level of sunlight penetration in the seawater. Accessory pigments in macroalgae absorb light with specific wavelengths selectively (Guiry 2014). The Northwest Atlantic Provinces of Canada have well established *Chondrus* spp. One of the richest seaweed resources in the world is believed to be in the Nova Scotia/Gulf of St. Lawrence area. Seaweed resources and their uses are very well established in regions of The Northeast Atlantic region including Norway, Scotland, Iceland, Ireland, France, Spain, Portugal and Denmark. Brown rockweeds particularly abundant on the Iceland's southern coasts, where broad belts of *Ascophyllum* dominates the vast areas of the littoral slopes (Naylor 1976). The coastal seaweed resources of West Central Atlantic are believed to be only moderate; Gulf coast, especially the offshore waters, is found out to be one of the richest centers for seaweeds. Rich algal resources in the Caribbean Sea occurs at a depth of over 260 m (Littler et al. 1986), although possibly the commercially attractive species do not occur in economically adequate quantities. This region includes the floating seaweed resource "Sargasso Sea".

Northeast and Northwest Pacific regions with cold and temperate water seas, show predominance of brown algae (large kelps), in particular Macrocystis and Nereocystis, and the algal biomass in this region is higher than in warmer seas (Pereira and Neto 2014). Seaweeds like *Gracilaria* and the bull-kelp, *Durvillea* are mainly recorded from Southwest Pacific, New Zealand and the southeastern coasts of Australia whereas rich *Gracilaria* and *Macrocystis* occur at Southeast Pacific coastlines of Chile and Peru. Mediterranean seaweed resources are of moderate quantities, Laminaria off the south coast of Spain, *Cladophora* and *Fucus* off coast of southern Italy and *Sargassum* and *Hypnea* off Yugoslavia. Black sea is rich in red algae resources. *Ulva, Eucheuma, Sargassum, Hypnea, Gracillaria, Gelidium, Turbinaria* are spread out along the coasts of Pakistan, India, Sri Lanka, and parts of Australian coastline. Luxurious growth of seaweeds mainly of Bryopsidales, Laminaria, Ulvales, and Siphonales are observed in Antarctic regions, (Fig. 27.7 and Table 27.3).

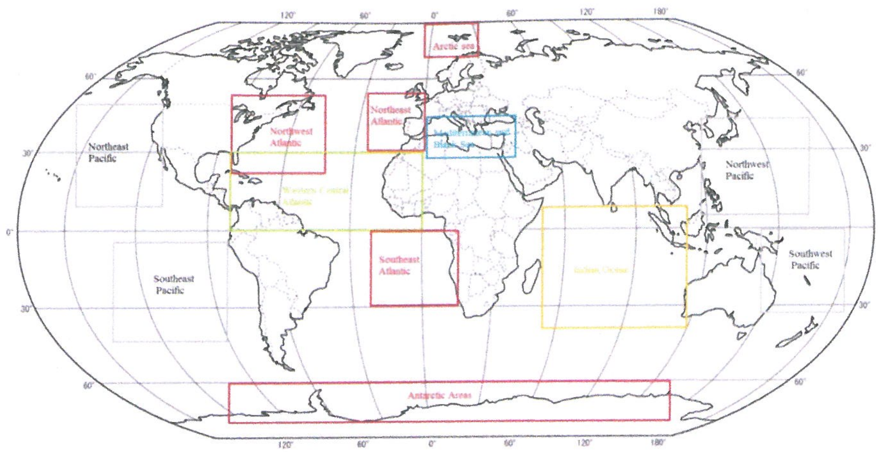

Fig. 27.7 Prominent coastal regions of the world rich in seaweed resources

The Indian coast has an amazing diversity of about 1153 marine algal species, out of which 60 species are commercially important (Chennubhotla et al. 1990; Kaliaperumal and Chennubhotla 1997; Kaliaperumal et al. 1995, 2004). Indian west coast is endowed with the higher seaweed resources, compared to the east coast and the islands due to the availability of suitable substratum in the rocky shore (beach rocks) (Wagle 1990). Rocky beaches, estuaries, mudflats, lagoons and coral reefs are the habitats preferred by macroalgae. Indian coast harbors predominantly inter-tidal and sub-tidal algal communities (Subba Rao and Mantri 2006). Tamil Nadu and Gujarat coasts are richest in seaweeds in the country, while rocky shores along Mumbai, Goa, Karnataka, and Kerala have moderate flora of seaweeds.

27.1.6 Biochemical Composition of Seaweeds

Macroalgae and terrestrial plants have different carbohydrate profile, both the group contains hemicelluloses-heterogeneous polysaccharide composed of pentoses, mainly xylose (Daroch et al. 2013) associated with the cell wall and intercellular spaces (Pereira and Neto 2014) (Figs. 27.8 and 27.9). Seaweed polysaccharides show range of structures and fulfil a variety of functions, most such constituents are also present in neutral sugars and sugar acids of land plants (Table 27.4). Certain seaweeds also contain acidic half ester sulphate groups attached to hydroxyl group of sugars. Hexose sugars such as, glucose, galactose and mannose found in these polysaccharides have identical chemical formula but their constituent atoms have different spatial arrangements and linkages, resulting in vast array of polysaccharides in different shapes and having diverse properties.

Table 27.3 Worldwide distribution of seaweed resources

Red Algae	
Gelidium	Japan, Spain, Portugal, Morocco, Algeria, Senegal, U.S.A., Mexico, Ireland, Chile, India, Philippines, Madagascar
Gracilaria	South Africa, Japan, Philippines, coastal areas of South China Sea, India, Sri Lanka, Australia, Chile, Peru, Brazil, Argentina, Adriatic, U.S.A. (Florida), Canada (British Columbia)
Chondrus	Canada (Nova Scotia, Newfoundland), Portugal, France (Brittany), U.K. (Scotland), Republic of Korea, Japan
Gigartina	South Africa, New Zealand, Portugal
Hypnea	U.S.A. (Florida), north Brazil, South Africa, Gulf of Oman
Eucheuma	Indonesia, Philippines, Malaysia, East Africa
Iridea	U.S.A. (California), Japan, Chile, South Africa
Furcellaria	Denmark, Baltic, Canada
Brown Algae	
Macrocystis	Northeast Pacific, California, Mexico, Peru, Chile, Argentina, South Africa, New Zealand, Tasmania
Alaria	Alaska, Japan
Laminaria	Northwest Atlantic, Greenland, Iceland, Norway, Ireland, Scotland, France, Spain, Morocco, Japan, U.S.S.R. (White Sea, Murmansk, Kamchatka, Okhotsk Sea)
Nereocystis	Northeast Pacific
Ecklonia	South Africa, Japan, Australia, New Zealand
Eisenia	Japan
Fucales order	Northeast and Northwest Pacific, Northeast and Northwest Atlantic, Chile, Murmansk, White Sea, New Zealand, Australia, Gulf of Oman
Green algae	
Bryopsidales	Eastern Atlantic (Africa canaries), Western Atlantic, Indo-Pacific, North Pacific Ocean, Caribbean, Gulf of Mexico, Federal Republic of Somalia, Gulf of Mexico, Indian Ocean, Kenya, Madagascar, North Atlantic Ocean, Republic of Mauritius, Seychelles, Tanzania, Venezuela.
Cladophorales	Gulf of Mexico, Caribbean Sea, Puerto Rico, Australia
Ulvales	Australia, North Pacific Ocean, Belgium, Federal Republic of Somalia, France, Gulf of Mexico, Indian Ocean, Ireland, Kenya, Madagascar, Mediterranean Sea, North Atlantic Ocean, Seychelles, South Africa
Siphonales	Western Atlantic, Indo-Pacific, North Pacific Ocean, Caribbean, Brazil, Gulf of Mexico, Gulf of Mexico, Indian Ocean, Kenya, Madagascar, North Atlantic Ocean, Southeast pacific

Carbohydrate formation in brown algae is comparable to that in sugar storing vascular plants rather than to the starch storing ones. These sugars are stored in dissolved form; very small amount of simple sugars is found in brown algae as these simple sugars are converted immediately to complex carbohydrates. One of the widely distributed of these is the dextrin-like polysaccharides known as ***laminarin.*** Laminarin can accumulate sufficient quantity constituting 7–35% of the dry weight of the plant. Gradual increase in the amount of laminarin throughout the growing season and the diminution at the time of reproduction or when new parts are

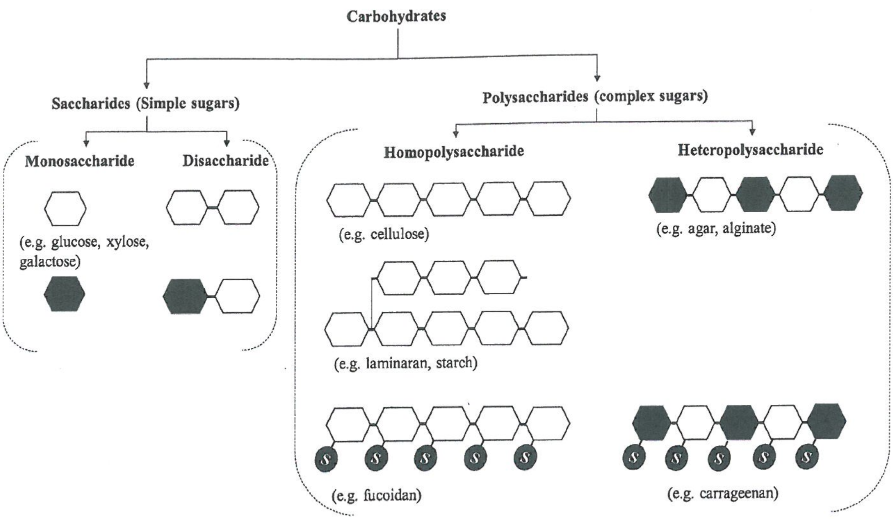

Fig. 27.8 Different types of sugars occurring in macroalgae

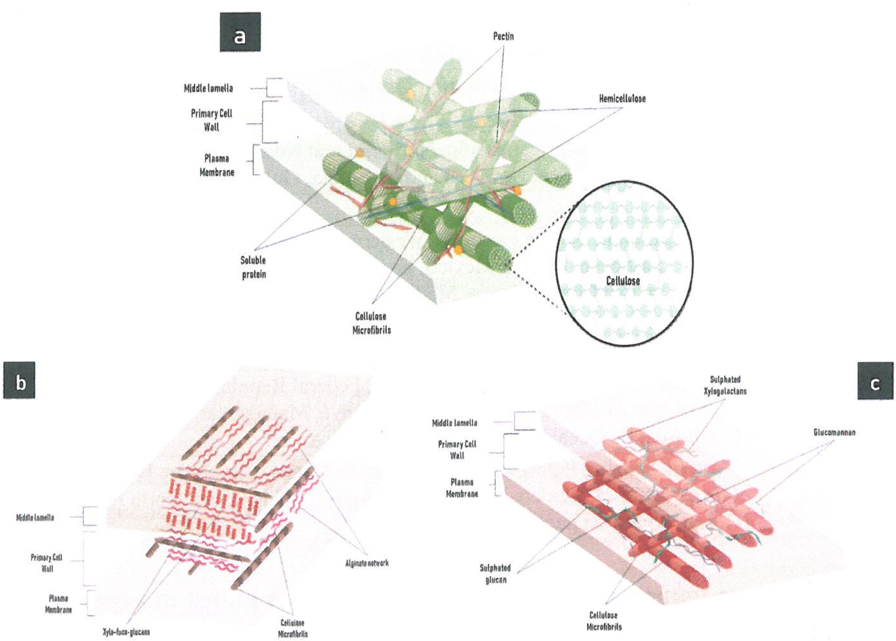

Fig. 27.9 Schematic representation of cell wall of green (**a**), brown (**b**) and red (**c**) macroalgae

regenerated shows that it serves as a reserve food (Adams et al. 2011; Guiry 2014; Mautner 1954). ***Mannitol*** a hexahydride alcohol is another widely distributed carbohydrate of Phaeophyta (Smith 1938). Major polysaccharide of brown algae is alginic acid (i.e., alginate), which accounts for up to 40% dry wt. as a principal

Table 27.4 Carbohydrate profile of seaweeds

Seaweeds	Carbohydrate reserve	Polysaccharides	Monosaccharides	Sugar alcohols	Sugar acids
Chlorophyta	Starch	Starch, Cellulose, Ulvan, Mannan	Glucose, Mannose, Rhamnose, Xylose	–	Uronic acid, Glucuronic acid
Rhodophyta	Floridean starch	Agar, Carrageenan, Cellulose, lignin	Glucose, Galactose, Agarose	–	
Phaeophyta	Laminarin	Laminarin, Alginate, Fucoidan, Cellulose	Glucose, Galactose, Fucose, Xylose	Mannitol	Uronic acid, mannuronic acid, Glucuronic acid. Alginic acid

Source: (Percival and McDowell 1967; Sudhakar et al. 2016; Yanagisawa et al. 2013)

material of the cell wall (Draget et al. 2005). Alginate is composed of uronic acids: mannuronic acid blocks, glucuronic acid blocks, and alternative blocks of mannuronic and glucuronic units (Lobban and Wynne 1981). Alginate tends to become gel due to its high affinity for divalent cations such as calcium, strontium, barium, and magnesium (Draget et al. 2005). Various brown algae tend to have their respective alginate structure (Fig. 27.9) and proportions of mannuronic and glucuronic acids in alginate (Lobban and Wynne 1981). Brown algae also have fucoidan, which is a sulphated complex polysaccharide consisting of fucose and a linear backbone of sulfate monosaccharides (Holtkamp et al. 2009). *Fucus vesiculosus* is used to produce relatively pure fucoidan (Duarte et al. 2001). In addition, brown algae have glucose and glyoxylic acid in small amounts (Mautner 1954).

Carbohydrate reserves of red algae are usually stored in the form of small grains that lie in the cytoplasm outside the algal plastids, the chromatophores. These plastids turn light brown to wine red, when treated with iodine, instead of taking the deep-blue colour characteristic of the iodine-starch reaction. On this account, the insoluble carbohydrate reserve of red algae has been called floridean starch (intermediate between true starch and dextrin). Floridean starch is an α-1,4-glucosidic linked glucose homopolymer and accounts for up to 80% of the cell volume (Yu et al. 2002). During the production of agar and carrageenan by using thermophilic α-amylase treatment, floridean starch is removed as an impurity, as it has a property to weaken gel strength (Yu et al. 2002). The major polysaccharide constituents of red algae are galactans such as carrageenan (up to 75% dry wt.) and agar (up to 52%), which are the most commercially important polysaccharides from red algae (Lobban and Wynne 1981; McHugh 2003). Carrageenan consists of repeating D-galactose unit and an-hydrogalactose, which may or may not be sulfated (Lobban and Wynne 1981). By dissolving red seaweeds into an aqueous solution carrageenan can be readily extracted (McHugh 2003), which are later purified and used for forming thick solution or gel (Lobban and Wynne 1981). Commercial carrageenan have been extracted from *Chondrus, Gigartina, and Eucheuma sp.* (Vera et al. 2011).

Agar, another major constituent, is made up of alternating β-D-galactose and α-L-galactose with scarce sulfations (Lobban and Wynne 1981). Agar cannot make a gel structure (Lobban and Wynne 1981), when these galactose compounds are highly sulfated.

Agar is produced from *Gracilaria, Gelidium,* and *Pterocladia sp.* by treating them with acid/heat or alkali (McHugh 2003). In Green algae polysaccharides proportions are small (1–4% for starch; and 0–6% for lipids) (Burton et al. 2009). Lahaye and Robic (2007) reported the insoluble cellulose (38–52% dry wt.) and water-soluble ulvan in the cell walls of *Ulva* and *Enteromorpha sp.* Ulvan, a distinctive carbohydrate of green algae, is composed mainly of D-glucuronic acid, D-xylose, L-rhamnose, and sulfate (Lobban and Wynne 1981).

27.1.7 Economic Utilization of Seaweed Resources

27.1.7.1 Food

Seaweeds are being used as sources of food, which can be traced back to the fourth century AD in Japan and the sixth century AD in China. These two countries and the Republic of Korea are the largest consumers of seaweed as food. However, as nationals from these countries have migrated to other parts of the world, the demand for seaweed for food has followed them, for example, in some parts of the United States of America and South America, *Ulva* (Chlorophyta), *Poryphyra* (Rhodophyta), *Undaria, Laminaria, Himanthalia* and *Saccharina* (Phaeophyta) are direct sources of food (Pereira and Neto 2014; Shama et al. 2019) Food products for human consumption, mainly associated with the Asian market, account for 83 to 95% of the total value of macroalgae. China is leading country in world market in seaweed production, followed by North Korea, South Korea, Japan, Phillippines, Chile, Norway, Indonesia, USA and India, altogether contributing upto 95% of world's commercial seaweed volume (Khan and Satam 2003; Roesijadi et al. 2010) (Table 27.5). The cultivation industries are producing more than 90 percent of the market's demand with increase in research into the life cycles of these seaweeds. Fresh seaweeds as vegetables and in salads are being used traditionally in an informal market that exists among coastal dwellers in some developing countries (McHugh 2003).

27.1.7.2 Hydrocolloid

Seaweeds are the only source of hydrocolloids, viz., agar-agar, algin and carrageenan. Hydrocolloids extraction from seaweeds dates to 1658, when the gelling properties of agar, extracted with hot water from a red seaweed, were first discovered in Japan. Extracts of Irish moss, another red seaweed, contain carrageenan and

Table 27.5 Different edible seaweed with their common names

Species	Type	Country	Local name/ product
Laminaria	Brown	Japan	Kombu
		China	Hai Dai
Porphyra	Red	Japan	Nori/amanori/hoshi-nori / Yaki-nori
		China	Zicai
		Korea	Kim
		UK (wales)	Purple laver/Laver bread
Hizikia fusiforme	Brown	Republic of Korea	Hoshi hiziki
Cladosiphon okamuranus	Brown	Japan	Mozuku
Alaria esculenta	Brown	Ireland	Winged kelp
		Scotland	
		Iceland	
		Hawaii	Limu
Undaria stipes *Undaria pinnatifida*	Brown	Japan	Wakame
		China	Quindai cai
Rhodymeni palmata *Palmaria palmate*	Red	Scotland	Dulse
		Ireland	Dillisk
		Iceland	Sol
		Canada	Sea parsley
Chondrus crispus	Red	Europe	Irish Moss/Carragenan
Callophyllis variegate	Red	Chile	Carola
Gracillaria spp.	Red		Ogo,ogonori or sea moss
Asparogopsis taxiformis	Red	Hawaii	Limu kohu
Caulerpa lentillifera, Caulerpa. Racemosa	Green	Phillipines	Sea grapes or green caviar
Monostroma spp and Enteromorpha spp.	Green	Japan	Aonori or green laver
Ulva spp.	Green	Japan	Sea lettuce

Source: (Chapman and Chapman 1980; Khan and Satam 2003; McHugh 2003)

were prevalent as thickening agents in the nineteenth century. Alginates were produced commercially in late 1930s, extracted from brown seaweeds, containing alginate and sold as thickening and gelling agents. Industrial uses of seaweed extracts extended rapidly after the Second World War, but were sometimes restricted by the availability of raw materials (McHugh 2003) (Table 27.8). These phytochemicals are widely used in various industries like food, confectionary, textile, cosmetics, paper, pharmaceutical, dairy, paint etc., as gelling, stabilizing and thickening agents (Table 27.6) (Roesijadi et al. 2010).

Table 27.6 Estimated global value of seaweed products per annum as reported in 2003 by McHugh

Product	Value
Human Food (Nori, aonori, kombu, wakame, etc.)	$5 billion
Algal hydrocolloids	
Agar (Food ingredient, pharmaceutical, biological/microbiological)	$132 million
Alginate (Textile printing, food additive, pharmaceutical, medical)	$213 million
Carrageenan (Food additive, pet food, toothpaste)	$240 million

27.1.7.3 Bioactive Compounds

Seaweeds are well known for their broad spectrum of bioactive compounds that are useful for formulation of cosmetics, function food and pharmaceuticals (such as antimicrobial, antiviral, anti-allergic, anticoagulant, anticancer, antifouling and antioxidant activities) (Table 27.7) (Pereira and Neto 2014). Chemically active metabolites such as alkaloids, polyketides, sterols, quinones, lipid and glycerol are released by macroalgae as an aid to protect themselves against other organisms, these metabolites having a broad range of biological activities and have found place in pharmaceutical industries as well. Macroalgae *Ulva lactuca* and *Enteromorpha intestinalis* have been studied for their antioxidant and antimicrobial activities, showcasing very promising antimicrobial activity against numerous bacterial, fungal, human, animal and plant pathogens, mycotoxin producers, and food spoilage agents (Kosanić et al. 2015). Sulphated polysaccharides, sodium alginate, laminarin have been explored for medical and pharmaceutical uses (Torres et al. 2019).

27.1.7.4 Biofertilizers

Seaweeds are rich in minerals and trace elements due to which they are preferred as fertilizers for plants (Table 27.7). High fiber content of macroalgae aids in retaining moisture in the soil and improve soil conditioning. Fresh seaweeds are mechanically pressed to extract sap, which is used as liquid fertilizers, sprayed to the plants as growth stimulants. Dried seaweeds are powdered and used as micronutrients for plants. Fertilizers from macroalgae act as biostimulant and biofungicide also by improving the plant yield and quality. It is seen to affect composition of essential oils i.e. rosemary oil, α- phellandrene, β-pinene, α-thujene etc. in medicinal plants (Tawfeeq et al. 2016; Torres et al. 2019).

27.1.7.5 Feed

Macroalgae rich in essential nutrients, minerals, soluble and insoluble fiber, vitamins and trace elements are utilized as feed for farm animals, poultry and aquaculture. Enormous amounts of brown seaweeds are washed ashore along the coasts of

Table 27.7 Seaweeds species used for extraction of various bioactive compounds

Seaweeds	Antimicrobial	Antifungal	Antiviral	Antitumor
Turbinaria conoides	+			
Padina gymnospora	+			
Sargassum tenerrimum	+			
Codium decorticatum		+		
Caulerpa scalpelliformis		+		
Sargassum wightii		+		
Acanthophora spicifera		+		
Dictyota mertensii			+	
Lobophora variegate			+	
Spatoglossum schroederi			+	
Fucus vesiculosus			+	
Grateloupia sp.			+	
Undaria pinnatifida			+	
Sargassum muticum				+
Sargassum vulgare				+

Source: Modified from Pereira and Neto, 2015

Table 27.8 Biofuel potential of seaweeds

Seaweeds	Fermentation yield (%)	Methane yield (m^3 kg^{-1} VS)	H2 yield (L kg^{-1} TS)	HV (MJ kg^{-1})	Biochar (%, at 500 °C)	Bio-oil (%, at 500 °C)
Alaria crassifolia	38					
Ascophyllum nodusum		0.18		21.2	21.4	
Chaetomorpha linum	39					
Cladophora glomerata					40	30
Codium fragile			49			
Cystoseira barbata					0.21	0.32
Ecklonia stolonifera			43			
Enteromorpha clathrata				12–12.1		41.2–45
Eucheuma denticulatum	47					
Eucheuma spinosum	40					
Fucus vesiculosus		0.12				
Fucuss serratus						11

(continued)

Table 27.8 (continued)

Seaweeds	Fermentation yield (%)	Methane yield ($m^3\ kg^{-1}$ VS)	H2 yield (L kg^{-1} TS)	HV (MJ kg^{-1})	Biochar (%, at 500 °C)	Bio-oil (%, at 500 °C)
Gelidia dura	46					
Gelidiella acerosa	47					
Gelidium amansii	50		34–53			
Gelidium elegans	38					
Gelidium pusillum	47					
Gracilaria gracilis					28	65
Gracilaria verrucosa	48		46			
Hizikia fusiforme			10			
Kappaphycus alvarezii	47					
Laminaria digitata	38	0.36	26	23.1		17
Laminaria hyperborea	29					
Laminaria japonica	41	0.17	28–110	10.3–33.5		29–37.5
Padina tetrastromatica			16–1000			
Porphyra tenera			16	29.7		47.4
Saccharina latissima	13	0.22				
Sargassum fusiforme					38.3	
Sargassum muticum		0.11				
Ulva fasciata	45					
Ulva lactuca		0.25	10			
Ulva ohnoi					50	
Ulva pertusa	38					
Ulva rigida	50	0.63				
Undaria pinnatifida			13–23		67.7	39.5

UK, which are utilized as fertilizers. Seaweed incorporated meal in feed has resulted in several benefits such as increased milk production in cows, increased iodine content in eggs in poultry and increased wool production in lambs (Kraan and Guiry 2006). Sodium alginate fed poultry saw reduction in ceacal *salmonella* spp., that infected the birds (Yan et al. 2011) (Table 27.8).

27.1.7.6 Biofuels

Seaweed species are explored for their potential as third generation feedstock for biofuel production (Table 27.8), due to the limitations of land availability encountered by the first- and second-generation feedstocks. Several macroalgal biomass have been explored for biogas, biodiesel, bioethanol and biobutanol productions (Mohammad et al. 2019; Hessami et al. 2019). Macroalgal biomass are potential candidate for bioethanol production, achieved by conversion of their polysaccharides by fermentation process. The conversion process of macroalgal biomass to bioethanol involves (i) pretreatment or hydrolysis of complex sugars to simpler forms and (ii) fermentation of these simple sugars (Fig. 27.10). Pretreatment

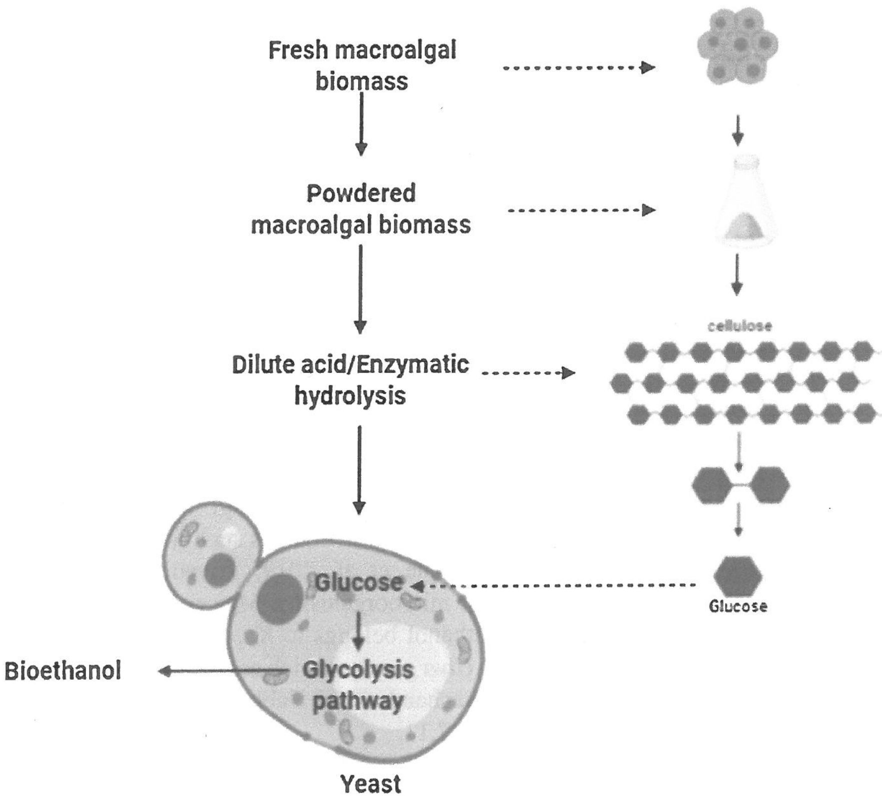

Fig. 27.10 Production of bioethanol from macroalgal biomass

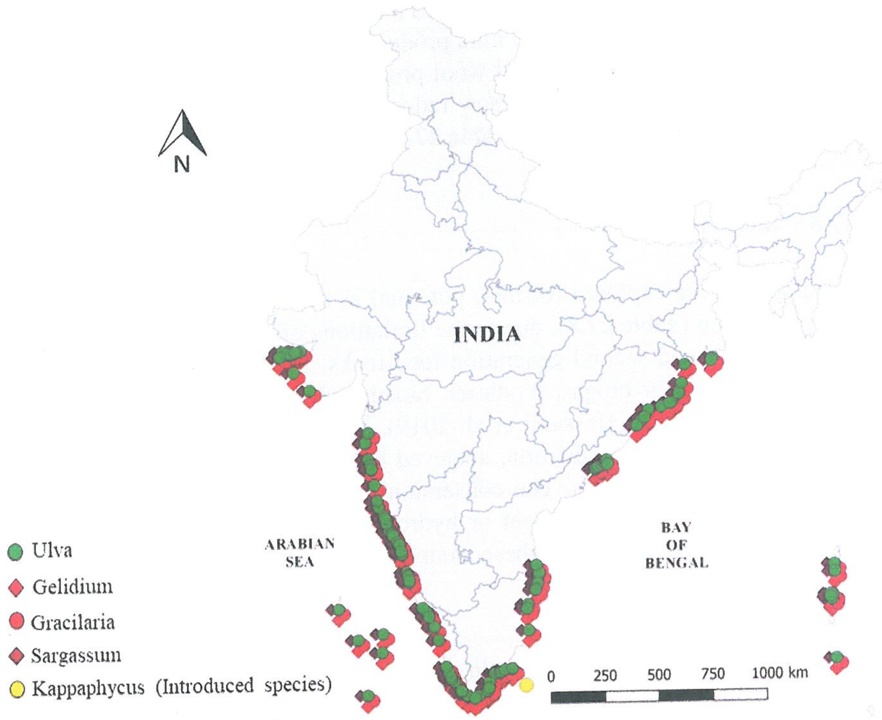

Fig. 27.11 Distribution of potential macroalgal feedstock of Indian coast

involves breaking down of complex polysaccharides to simple fermentable sugars by employing physical, chemical or biological agents. Pre-treatment with H_2SO_4 at different temperature and incubation period, is one of the most widely used procedures for seaweed cell wall depolymerization. Apart from cellulose, there are certain polymers such as alginate, mannitol and fucoidan present in cell wall of macroalgae, which requires additional processing like pre-treatment and enzyme hydrolysis before fermentation. Enzymatic hydrolysis involves dilute-acid pre-treatment followed by enzyme for further saccharification of seaweed polysaccharide. Enzymes are mostly extracted from terrestrial fungi sources such as *Trichoderma, Penicillum, and Aspergillus,* bacterial sources such as *Bacilus subtilis, Vibrio paraheamolyticusi* etc. (Hebbale et al. 2019; Trivedi et al. 2011). Fermentation is carried out using yeast microorganisms. Majority of macroalgal species utilized for production of bioethanol belongs to *Kappaphycus, Gelidium, Gracilaria, Sargassum, Laminaria* and *Ulva* genera, which are recorded abundantly from Indian east and west coast (Ramachandra and Hebbale 2020; Mohammad et al. 2019; Hessami et al. 2019) in Fig. 27.11.

27.1.8 *Biothanol Prospects of Seaweed in the West Coast: Energy and Economic Nexus*

Twenty-five macroalgal species were recorded from West coast of Karnataka, among which eight species were available in extractable amounts from the rocky shores and were selected as potential source for bioethanol production. Based on the biochemical compositions, seasonality studies and euryhaline nature of the species two green macroalgae; *Enteromorpha intestinalis* and *Ulva lactuca* were prioritized as suitable feedstock for bioethanol production. The production of bioethanol from seaweeds (Fig. 27.12) involves two major steps, which are described below:

27.1.8.1 Hydrolysis (Acid or Enzyme) of the Biomass to Release Fermentable Sugars

Reducing sugar (RS) from dilute acid hydrolysis (DAH) of *E. intestinalis* (**DAH:** 5% w/w, 0.7 N H_2SO_4 at 121 °C for 45 min, **RS:** 239.94 ± 1.3 mg/g) and *U. lactuca* (**DAH:** 5% w/v, 0.5 N H_2SO_4 at 121 °C for 45 min, RS: 214.67 ± 0.9 mg/g). Cellulose degrading bacteria were isolated from wide-ranging sources including marine habitats, herbivore residues and gastrointestinal region. *Vibrio parahaemolyticus* (Hebbale et al. 2019) isolated from marine environment is capable of hydrolysing CMC as well as *E. intestinalis* and *U. lactuca* pretreated biomass, highlighting cellulolytic activity of enzyme capable of hydrolysing structural polysaccharide (cellulose) in green seaweed. Pre-treated macroalgal biomass produced one-fold higher reducing sugar in enzymatic hydrolysis (EH) *E. intestinalis* (**EH:** pH 6 at

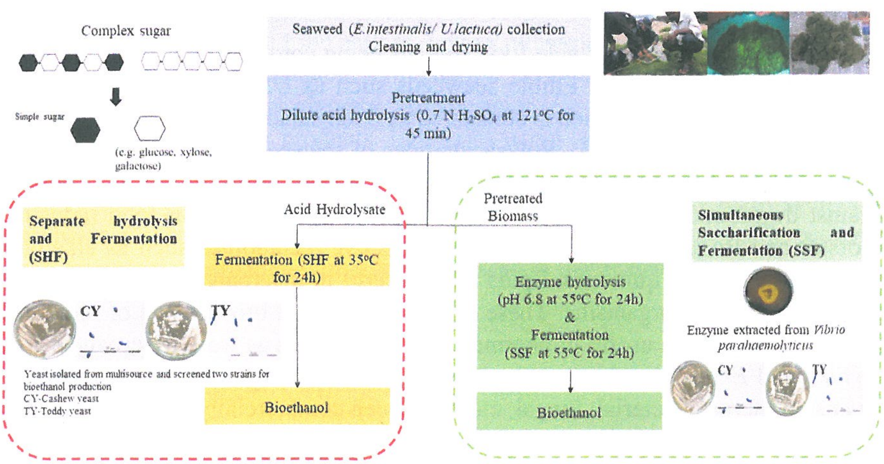

Fig. 27.12 Bioethanol production from macroalgal biomass

50 °C for 24 h, **RS:** 289.89 ± 2.4 mg/g) and *U.lactuca* (**EH:** pH 6 at 50 °C for 24 h, **RS:** 261.76 ± 0.9 mg/g) as compared to the dilute acid hydrolysis.

27.1.8.2 Fermentation by Microorganisms

Marine macroalgae contain low amounts of polysaccharides composed of glucose. Production of ethanol, therefore, needs to be from carbohydrates including sulphated polysaccharides, sugar acids and sugar alcohols. However, the major hurdle is the inability of microorganisms in fermenting all sugars present in seaweeds. Therefore, exploration of yeast strains that can ferment both pentose (C5) and hexose (C6) sugars is crucial for higher ethanol yield. Yeast strains were isolated from various fruit sources and fermented products and 19 strains were prioritized based on the performance in glucose and xylose media, with the carbohydrate fermentation capabilities. Yeast strains Meyerozyma *caribbica* (Cashew yeast: CY) and *Pichia kudriavzevii* (toddy yeast: TY) were chosen based on longer exponential growth, maximum conversion efficiency with respect to glucose and macroalgal sugar fermentation (**F**) apart from being tolerant to temperature and ethanol (ETOH). Separate hydrolysis and fermentation (SHF) (**DAH:** 0.7 N H_2SO_4 121 °C for 45 min, **F**: 35 °C, 100 rpm for 24 h, **ETOH**: 0.16 g) yielded higher ethanol conversion efficiency of 51% using *Pichia kudriavzevii* for *Enteromorpha intestinalis*. Simultaneous Saccharification and Fermentation (SSF) (**DAH:** 0.5 N H_2SO_4 121 °C for 45 min, **F**: 35 °C, 100 rpm for 24 h, **ETOH**: 0.14 g) yielded higher ethanol conversion efficiency of 80.9% using enzyme extracted from *Vibrio parahaemolyticus* and *Pichia kudriavzevii* for *U. lactuca* biomass. Wild yeast strain *Pichia kudriavzevii* exhibited higher fermentation capabilities using macroalgal biomass.

27.1.8.3 Economic Nexus

Macroalgae are readily available food sources being consumed by coastal communities, particularly in Asia. Edible seaweeds such as *Ulva* species are popularly known as “Sea lettuce”, which is consumed as fresh salads or cooked as vegetables along with rice (WHO 2003). Polysaccharides of seaweeds are used as thickening agents in sweet and savoury sauces and condiments, stabilizing food products against degradation, staling and heating, and for replacing fat in food industries (Forster and Radulovich 2015). Chemically active metabolites such as alkaloids, polyketides, sterols, quinones, lipids and glycerol in macroalgae aid in protecting them against other organisms. These metabolites with a broad range of biological properties have been useful in pharmaceutical industries as well. Macroalgae *Ulva lactuca* and *Enteromorpha intestinalis* with the promising antimicrobial activities against numerous bacterial, fungal, etc. have been commercially used as mycotoxin producers and food spoilage agents (Kosanić et al. 2015; Pereira and Neto 2014). Carrageenans – the water-soluble polysaccharide present in red algae are extracted using water, alkali or acid treatment. Major portion of carrageenan and agar

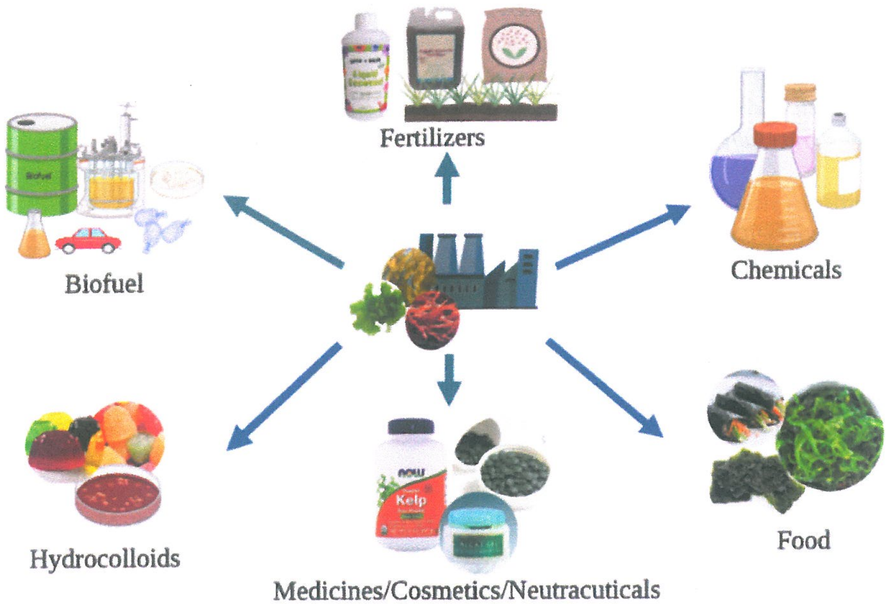

Fig. 27.13 Economic nexus of macroalgal biomass

extraction is done using cultivated red algae, whereas alginate (from brown algae) is mostly obtained from natural populations. These have been used to make jellies and milk puddings (Blanc mange) (from *C. crispus* and *G. stellata*) as well as utilization of carrageenan granules (from *K. alvarezii*) as raw material for bioethanol production (Khambhaty et al. 2012; Stanley 1987; Tuvikene et al. 2006). These phytochemical compounds constitute a part of healthy balanced diet, as protein content in seaweeds is higher than other food materials such as cereals, eggs and fish they are also excellent sources of vitamins A, Bl, B12, C, D and E, riboflavin, niacin, pantothenic acid and folic acid as well as minerals such as Ca, P, Na, K. Apart from production of bioethanol, fermentation of algal hydrolysate also produces many by-products, such as glycerol, organic acids (e.g., acetate, succinate), biomass protein, and other minor products. Industries using seaweed as feedstock for production of bioethanol will be economical with the simultaneous utilization of the fermentation by-products, similar to the petroleum industry where many such products besides gasoline are profitable (Fig. 27.13). Cultivation prospects for economically important macroalgal biomass is discussed in the next section.

27.1.9 Macroalgal Cultivation in India

The seaweed industry in India (Table 27.9) is still at infant stage, functioning more as a cottage industry. Agar and algin yielding seaweeds are collected from the from the natural stock along the coast (Khan and Satam 2003). However, this type of

Table 27.9 Distribution of Agar, Carrageen yielding and edible seaweeds in India

Seaweed species	Culture Location
Agar yielding	
Gelideilla acerosa	Gulf of Manner and Palk Bay near Mandapam
Gracilaria edulis	Gulf of Mannar and Palk Bay
	Krusadai Island (Mandapam) and Karvaratti Island (Lakshadweep)
Carrageen yielding	
Hypnea musciformis	Krusadai island, Lakshadweep
Acanthophora spicifera	Hare Island near Mandapam
Kappaphycus alvarezii	Saurastra and Mandapam region, Narakkal (Cochi) and Calicut
Edible seaweed	
Enteromorpha Flexuosa	Okha (Gujarat)

Source: (Subba Rao and Mantri 2006)

collection is not sustainable and not favoring the stability of an industry. More attention must be paid for bridging the gap between demand and supply that is possible only through cultivation of various seaweeds as raw materials for food production and for other seaweed-based industries. Cultivation can ensure improved yield, continuous supply, and conserve the natural seaweed beds.

Few genera namely, *Laminaria, Undaria, Sargassum, Poryphyra, Eucheuma* (*Kappaphycus*), *Gracilaria, Gelidium* and *Ulva* are mostly focused on the aquaculture production as they are potential source for production of various raw materials. Red seaweeds such as *Kappaphycus, Gelidium, Gracilaria,* and brown seaweeds including *Sargassum,* and *Laminaria* are mostly utilized for extraction of hydrocolloid (agar, algin and carrageenan). Green seaweed (such as *Ulva*) serves as direct source of food (e.g. Salads) (Pereira and Neto 2014), and support a well-established multi-billion-dollar industry in Asia (Milledge et al. 2014). Currently, these seaweeds are also the leading feedstock for bioethanol production (Trivedi et al. 2013, 2015).

India's mainland coastline of 5422.6 km endows several major and minor estuaries along east and west coast. Indian estuarine area of 3.9 million ha, of which 1.2 million ha are salt-affected lands dedicated for brackish water shrimp cultivation, which covers about 15% for aquaculture purpose. as potential sites the rest 85% of the land serves as potential sites for cultivation of macroalgae. These salt-affected aquaculture ponds are known as *gazni* (Karnataka), *pokkali land* (Kerala), *kharland* (Maharashtra), *bheri* (West Bengal), *gheri* (Odisha) across Indian states. The stagnant water in these ponds are conducive for macroalgal cultivation as it prevents the algae from drying out.

Seaweed cultivation along the coast is a challenging task due to wave action, epiphyte fouling, ice-ice disease and algae feeding fishes.Off-shore macroalgal cultivation has been explored in India along 10 km stretch of Palk Bay, Mandapam, where red seaweed *Kappaphycus alvarezii* and *Hypnea musciformis* were cultivated in an area of 100 ha through contract farming system involving the local

Fig. 27.14 Estuaries and Lagoons in Indian

communities. These two species other than serving as raw materials for industries are also explored for bioethanol production potential. However, drifting of broken algal fragments from the rafts were a hindrance as they attached to the nearby hard corals (in Mandapam Marine National Park), growing profusely by vegetative propagation, thereby affecting the growth of the coral. Such difficulties can be overcome by cultivating seaweeds in enclosed ponds, lagoon systems, or in coastal brackish water *gazni* rice fields, which experience sufficient inflow of seawater to keep the seaweeds from drying out. Figure 27.14 represents estuaries and lagoons of India, which serves as potential sites for macroalgal cultivation.

Coastal and marine livelihoods include a wide range of stakeholders, who are dependent completely or partially on the direct use of the goods and services generated from coastal and marine areas. Most of these coastal resources are utilized for "self- subsistence", although market forces have strongly come into the fishery sector. The entire economy of coastal areas is intimately linked to the earnings generated from the use of those resources (Townsley 2004). Land based macroalgal cultivation integrated with shrimp cultivation is a beneficial process as it caters to employment of coastal women, who, with little effort can contribute significantly to the household income and supports the livelihood of the fisherman's family during any failure in shrimp cultivation. Labour from the fishing community and skill from estuarine farming community will provide a perfect platform for launch of seaweed cultivation in estuaries. Estimated production potential of one million tons of dried seaweeds from India can generate employment to 200 thousand families with annual earnings of around 0.1 million per family (Radhika et al. 2014). Setting up of a small-scale viable seaweed bio refinery, brings economy and employment to the coastal communities residing in the region. Seaweed cultivation can be taken up in these estuaries where suitable sea conditions prevail, advocating full-time or part-time large-scale job opportunities in coastal rural sector. Therefore, such estuarine backwaters can serve as suitable site for Seaweed cultivation at large scale.

27.1.10 Conclusion

Macroalgae are multicellular, photosynthetic algae occurring in marine and brackish environment. Broadly classified into three types as chlorophyta, rhodophyta and phaeophyta based on the presence of pigment. Seaweeds are rich in carbohydrates. Polysaccharides from red and brown algae are natural source of hydrocolloids such as agar, algin and carrageenan. Seaweeds are utilized as food source and for production of biofertilizers, feed, biofuel, cosmetics etc. Production of bioethanol from seaweeds is regarded as promising and sustainable option. Major unit operations involved in bioethanol productions are pretreatment or hydrolysis of macroalgal biomass and fermentation of sugars released. Cultivation of economically important native species of macroalgae in abandoned aquaculture ponds along estuaries is a sustainable and income generating option. The prospects visualized here is for fetching a value for these seaweeds which can become feedstock for biofuel production, so much so such 'sea-weeds' of today could be easily transformed into 'sea-wealth'. Bioethanol production not only ensures the strategic energy security of the nation, but also helps in mitigating GHG footprint, judicious use of feedstock, lowering import burdens, empowers rural women with the sustainable livelihood through integrated approaches in fishery, etc.

27.1.11 Prospects of Macroalgae in India

Seaweed biomass are promising resources for production of various products catering to industries related to food, fertilizers, cosmetics, biofuel, pharmaceuticals. Future direction towards economic utilization of macroalgal biomass should focus mainly on:

(i) biorefinery approach which is profitable with production of multi products including bioethanol.
(ii) Optimization of process parameters to obtain high yield of bioethanol production.
(iii) Innovative macroalgal cultivation technologies on land-based aquaculture ponds for achieving higher biomass productivity.
(iv) Development of decentralised seaweed-based industries in coastal regions of India where resources are abundantly available.
(v) To contribute to the growth of maritime sectors by improving existing infrastructures for fisherman and training the fisher folks in large scale ocean farming of seaweeds.
(vi) Seaweed cultivation as a notable future enterprise can open up platform for establishing seed hatcheries, seeding units and processing units and enhance employment opportunities in rural coastal area.

References

Adams JMM, Toop TA, Donnison IS, Gallagher JA (2011) Seasonal variation in laminaria digitata and its impact on biochemical conversion routes to biofuels. Bioresource Technol 102(21):9976–9984. https://www.sciencedirect.com/science/article/pii/S0960852411011205 (January 3, 2019)

Barnes H (1999) Oceanography and marine biology. CRC Press

Borines MG, de Leon RL, Cuello JL (2013) Bioethanol production from the macroalgae sargassum spp. Bioresour Technol 138(1):22–29. https://doi.org/10.1016/j.biortech.2013.03.108

Burton, T., Lyons, H., Lerat, Y., Stanley, M., & Rasmussen, M. B. 2009. "A review of the potential of marine algae as a source of biofuel in Ireland"

Chapman VJ, Chapman DJ (1980) Sea Vegetables (Algae as Food for Man). In: Seaweeds and Their Uses. Springer, pp 62–97

Chennubhotla VS, Najmuddin M, Ramalingam JR, Kaliaperumal N (1990) Bulletin 44. In: CMFRI Bulletin-national symposium on research and development in marine fisheries sessions III & IV, vol 1987, pp 442–446

Daroch M, Geng S, Wang G (2013) Recent advances in liquid biofuel production from algal feedstocks. Appl Energy 102:1371–1381. https://doi.org/10.1016/j.apenergy.2012.07.031

Draget KI, Smidsrød O, Skjåk-Bræk G (2005) Alginates from Algae. Biopolymers Online: Biol Chem Biotechnol Applicat 6

Duarte MER, Cardoso MA, Noseda MD, Cerezo AS (2001) Structural studies on fucoidans from the brown seaweed *sargassum stenophyllum*. Carbohydr Res 333(4):281–293

Fenner MW (2012) Seed ecology. Springer Science & Business Media

Forster J, Radulovich R (2015) Seaweed and food security. In: Seaweed sustainability: food and non-food applications (October), pp 289–313

Guiry MD (2014) The seaweed site: information on marine algae, Seaweed. ie

Guiry MD, G M 2013 Guiry (2008) AlgaeBase. AlgaeBase

Hardy FG, Moss BL (1979) Attachment and development of the zygotes of pelvetia canaliculata (L.) Dcne. et Thur.(Phaeophyceae, Fucales). Phycologia 18(3):203–212

Hebbale D, Bhargavi R, Ramachandra TV (2019) Saccharification of macroalgal polysaccharides through prioritized cellulase producing bacteria. Heliyon 5(3):e01372. https://linkinghub.elsevier.com/retrieve/pii/S2405844018374954

Hessami MJ, Cheng SF, Ranga Rao A, Yin YH, Phang SM (2019) Bioethanol production from agarophyte red seaweed, *Gelidium elegans* using a novel sample preparation method for analysing bioethanol content by gas chromatography. Biotech J 9(1):25

Holtkamp AD, Kelly S, Ulber R, Lang S (2009) Fucoidans and fucoidanases—focus on techniques for molecular structure elucidation and modification of marine polysaccharides. Appl Microbiol Biotechnol 82(1):1

Jung KA, Lim SR, Kim Y, Park JM (2013) Potentials of macroalgae as feedstocks for biorefinery. Bioresour Technol 135:182–190. https://doi.org/10.1016/j.biortech.2012.10.025

Kaliaperumal N, Chennubhotla VSK (1997) Sea weed distribution and resources in Kerala coast. Seaweed Res Ulіln 19(1):29–32

Kaliaperumal N, Kalimuthu S, Ramalingam JR (2004) Kaliaperumal, kalimuthu, ramalingam - 2004 - present scenario of seaweed exploitation and industry in India. Seaweed Res Utiln 26(1 & 2):47–53

Kaliaperumal N, S Kalimuthu, Ramalingam J (1995) Economically important seaweeds 1–44

Khambhaty Y et al (2012) *Kappaphycus alvarezii* as a source of bioethanol. Bioresour Technol 103(1):180–185

Khan SI, Satam SB (2003) Seaweed mariculture: scope and potential in India. Aquaculture Asia VIII (4):26–29. http://aquaticcommons.org/205/1/AquacultureAsia_8_4_2003.pdf#page=28

Kjellman FR (1891) Phaeophyceae (Fucoideae). Die Naturlichen Pflanzenfamilien I Teil 2:176–192

Kosanić M, Ranković B, Stanojković T (2015) Biological activities of two macroalgae from adriatic coast of montenegro. Saudi J Biol Sci 22(4):390–397. http://www.sciencedirect.com/science/article/pii/S1319562X14001417

Kraan S, Guiry MD (2006) The seaweed resources of Ireland. ETI, Amsterdam, Seaweed resources of the worldm, A CD-rom project

Kumar S et al (2013) Bioethanol production from gracilaria verrucosa, a red alga, in a biorefinery approach. Bioresour Technol 135:150–156. https://doi.org/10.1016/j.biortech.2012.10.120

Lahaye M, Robic A (2007) Structure and function properties of ulvan, a polysaccharide from green seaweeds. Biomacromolecules 8(6):1765–1774

Leliaert F et al (2012) Phylogeny and molecular evolution of the green algae. Crit Rev Plant Sci 31(1):1–46

Littler MM, Littler DS, Blair SM, Norris JN (1986) Deep-water plant communities from an uncharted seamount off san salvador Island, Bahamas: distribution, abundance, and primary productivity. Deep Sea Research Part A Oceanographic Research Papers 33(7):881–892

Lobban CS, Harrison PJ, Harrison PJ (1994) Seaweed ecology and physiology. Cambridge University Press

Lobban CS, Wynne MJ (1981) The biology of seaweeds, vol 17. Univ of California Press

Martins I, Oliveira JM, Flindt MR, Marques JC (1999) The Effect of Salinity on the Growth Rate of the Macroalgae *Enteromorpha Intestinales* (Chlorophyta) in the Mondega Estuary (West Portugal). Acta Oecol 20(4):259–265

Mautner HG (1954) The chemistry of brown algae. Econ Bot 128:174–175

McHugh DJ (2003) FAO. Fisheries technical paper A guide to the seaweed industry. Food and Agriculture Organization of the United Nations Rome. http://www.fao.org/documents/card/en/c/24efc5c0-d2fe-55b3-ade9-6bdffee4e66e/

Milledge JJ, Smith B, Dyer PW, Harvey P (2014) Macroalgae-derived biofuel: a review of methods of energy extraction from seaweed biomass. Energies 7(11):7194–7222

Mohammad JH, Ranga Rao A, Ravishankar GA (2019) Opportunities and challenges in seaweeds as feed stock for biofuel production. In: Ravishankar GA, Rao AR (eds) Handbook of algal technologies and phytochemicals: volume-II phycoremediation, biofuels and global biomass production. CRC Press, USA, pp 39–50

Moss B (1975) Attachment of zygotes and germlings of *Ascophyllum nodosum* (L.) Le Jol. (Phaeophyceae, Fucales). Phycologia 14(2):75–80

Naylor J (1976) Production, trade and utilization of seaweeds and seaweed products. In: FAO Fisheries Technical Papers (FAO). Documents Techniques FAO sur les Peches (FAO)-Documentos Tecnicos de la FAO sobre la Pesca (FAO), p 159

Organization, World Health (2003) 916 Diet, nutrition, and the prevention of chronic diseases: report of a joint WHO/FAO expert consultation. World Health Organization

Pascher A (1914) Uber flagellaten und algen. Ber Deutschen Bot Ges 32:136–160

Percival E, McDowell RH (1967) Chemistry and enzymology of marine algal polysaccharides

Pereira L, Neto JM (2014) Marine algae: biodiversity, taxonomy, environmental assessment, and biotechnology. CRC Press

Ramachandra TV, Hebbale D (2020) Bioethanol from macroalgae: prospects and challenges. Renew Sustainable Energy Rev 117:109479. https://linkinghub.elsevier.com/retrieve/pii/S1364032119306872 (October 18, 2019)

Riisberg I et al (2009) Seven gene phylogeny of heterokonts. Protist 160(2):191–204

Roesijadi G, Jones SB, Zhu Y (2010) Macroalgae as a biomass feedstock: a preliminary analysis. Analysis:1–50. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19944.pdf

Rothäusler E, Gutow L, Thiel M (2012) Floating seaweeds and their communities. In: Seaweed Biology. Springer, pp 359–380

Santelices B (1991) Production ecology of gelidium. In: International workshop on gelidium. Springer, pp 31–44

Santelices B (1990) Patterns of reproduction, dispersal and recruitment inseaweeds. Ocearrogr A Mar Biol 471h Rez 28:177–276

Shama A, Joyce SG, Mari FD, Ranga Rao A, Ravishankar GA, Hudaa N (2019) Macroalgae and microalgae: novel sources of functional food and feed. In: Ravishankar GA, Rao AR (eds) Handbook of algal technologies and phytochemicals: volume-I: food, health and nutraceutical applications. CRC Press, USA, pp 207–219

Smith GM (1938) Cryptogamic botany. volume I. In: Algae and fungi

Spalding H, Foster MS, Heine JN (2003) Composition, distribution and abundance of deep-water (>30m) macroalgae in central California. J Phycol 39(2):273–284

Speight MR, Henderson PA (2013) Marine ecology: concepts and applications. John Wiley & Sons

Stanley N (1987) Production, properties and uses of carrageenan. production and utilization of products from commercial seaweeds. In: FAO fisheries technical paper, vol 288, pp 116–146. http://www.fao.org/3/x5822e/x5822e05.htm (September 16, 2019)

Subba Rao PV, Mantri VA (2006) Indian seaweed resources and sustainable utilization: scenario at the dawn of a new century. Curr Sci 91(2):164–174

Sudhakar MP, Ravel Merlyn K, Arunkumar, and K. Perumal. (2016) Characterization, pretreatment and saccharification of spent seaweed biomass for bioethanol production using baker's yeast. Biomass Bioenergy 90:148–154. https://doi.org/10.1016/j.biombioe.2016.03.031

Tawfeeq A, Culham A, Davis F, Reeves M (2016) Does fertilizer type and method of application cause significant differences in essential oil yield and composition in rosemary (*Rosmarinus Officinalis L.*)? Ind Crop Prod 88:17–22

Tiffany, Lewis Hanford. 1924. "A physiological study of growth and reproduction among certain green algae"

Torres MD, Kraan S, Domínguez H (2019) 18 Reviews in environmental science and biotechnology. Seaweed Biorefinery

Tovey DJ, Moss BL (1978) Attachment of the haptera of *laminaria digitata* (Huds.) lamour. Phycologia 17(1):17–22

Townsley P (2004) Review of coastal and marine livelihoods and food security in the Bay of Bengal large marine ecosystem region. Bay of Bengal Large Marine Ecosystem Programme

Trivedi N, Gupta V, Reddy CRK, Jha B (2013) Detection of ionic liquid stable cellulase produced by the marine bacterium *pseudoalteromonas* Sp. Isolated from brown alga sargassum polycystum C. Agardh. Bioresour Technol 132:313–319. https://doi.org/10.1016/j.biortech.2013.01.040

Trivedi N, Reddy CRK, Radulovich R, Jha B (2015) Solid State Fermentation (SSF)-derived cellulase for saccharification of the green seaweed ulva for bioethanol production. Algal Res 9:48–54. https://doi.org/10.1016/j.algal.2015.02.025

Trivedi N et al (2011) An alkali-halotolerant cellulase from bacillus flexus isolated from green seaweed ulva lactuca. Carbohydr Polym 83(2):891–897. https://doi.org/10.1016/j.carbpol.2010.08.069

Tuvikene R, Truus K, Vaher M, Kailas T (2006) Extraction and quantification of hybrid carrageenans from the biomass of the red algae furcellaria lumbricalis and coccotylus truncatus. Proc Estonian Acad Sci Chem 55(1):40–53

Vera J, Castro J, Gonzalez A, Moenne A (2011) Seaweed polysaccharides and derived oligosaccharides stimulate defense responses and protection against pathogens in plants. Mar Drugs 9(12):2514–2525

Wagle BG (1990) 10 Beach rocks of the central west coast of India. https://link.springer.com/content/pdf/10.1007%2FBF02431028.pdf (December 26, 2018)

Yan GL et al (2011) Sodium alginate oligosaccharides from brown algae inhibit salmonella enteritidis colonization in broiler chickens. Poult Sci 90(7):1441–1448

Yanagisawa M, Kawai S, Murata K (2013) Strategies for the production of high concentrations of bioethanol from seaweeds. Bioengineered 4(4):224–235

Yoon HS, Andersen RA, Boo SM, Bhattacharya D (2009) Stramenopiles. In: Encyclopedia of microbiology. Elsevier Inc., pp 721–731

Yoon HS et al (2006) Defining the major lineages of red algae (RHODOPHYTA) 1. J Phycol 42(2):482–492

Yu S et al (2002) Physico-chemical characterization of floridean starch of red algae. Starch-Stärke 54(2):66–74