

Seaweed farming: A perspective of sustainable agriculture and socio-economic development

Ashok S. Jagtap^{a,b} and Surya N. Meena^c

^a*School of Earth, Ocean and Atmospheric Sciences, Goa University, Taleigao, Goa, India,* ^b*Biological Oceanography Division, CSIR-National Institute of Oceanography, Dona Paula, Goa, India,* ^c*Biochemistry Division, Department of Chemistry, Savitribai Phule Pune University, Pune, Maharashtra, India*

Abbreviations

CO ₂	carbon dioxide
FAO	Food and Agriculture Organization
IMTA	integrated multitropic aquaculture
MACR	macroalgal cultivation rig

23.1 Introduction

The ocean covers 71% of the Earth's surface area and provides nutrients (carbon, nitrogen, phosphorus, etc.) required for macroalgae or seaweed growth and photosynthesis (Roleda and Hurd, 2019). The global requirement of seaweed biomass for the production of food and the bio-active compounds are increasing progressively; therefore, the efficient cultivation and utilization of seaweed resources are essential (Keating et al., 2014; Camus et al., 2019; Shannon and Abu-Ghannam, 2019). Seaweeds are promising sustainable bioresource with high productivity compared to terrestrial plant biomass (Gao and McKinley, 1994; Balina et al., 2017). Seaweeds are not competing with terrestrial crops for arable land, fertilizers, pesticides, and insecticides to grow. But it may serve as an alternate source for food, chemical, and fuel generation (Ganesan et al., 2019). Several scientific studies on seaweed have explored various applications in pharmaceuticals, nutraceuticals, cosmeceuticals, animal feed, biomaterials, and biofuels (Zerrifi et al., 2018; Tanna and Mishra, 2018; Shimazu et al., 2019; Pablo et al., 2020).

Seaweed farming is the least environment damaging form of aquaculture. It requires a meager investment to set up aquaculture farms. It helps to preserve the coastal and aquatic environments from some of the impacts of climate change including ocean acidification and de-oxygenation (Chung et al., 2017; Kaladharan, 2018; Meena et al., 2020). The seaweed farming provides three types of ecosystem services. First, it supplies cost-effective

raw materials for the generation of food, feed, and energy (Buschmann et al., 2017). Second, it controls the processes of the environment, such as natural oxygenation cycles, carbon sequestration, food processing, waste purification, and care (Hasselström et al., 2018). Finally, the social programs that support humanity through natural weather interactions, recreational opportunities, and the importance of aquatic biodiversity are need to be explored properly (Langton et al., 2019). So, it can be one of the approaches for coastal countries to contribute toward climate change mitigation (Fig. 23.1).

According to FAO statistics, seaweed production from aquaculture is several times higher than wild harvesting (Ferdouse et al., 2018). Wild harvesting of seaweeds from natural populations can produce various ecological and social consequences if not well managed. For this reason, seaweed farming is an alternative to provide the required amount of seaweed biomass with proper biotic and abiotic interactions (Hasselström et al., 2018). As seaweed farming has ecological and economical importance, still there is a need for advancement of the method of cultivation and challenges associated with aquaculture. This chapter is mainly focused on the ecological and economic importance of seaweed farming and advancement in strategies and techniques to generate void biomass with less environmental impact.

23.2 Seaweed production and its applications

Seaweeds used in daily need by harvesting or collecting from the natural environment is an archaic people's practices in some of the countries in the world, like China, the Korean peninsula, Japan, Philippines, and Thailand (Ohno and Critchley, 1998). Since ancient times, seaweeds have

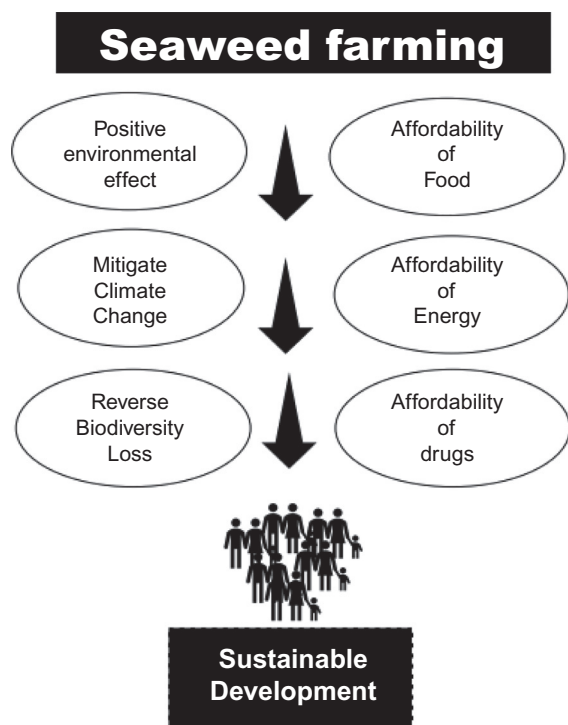


FIG. 23.1 The socio-economic and ecological importance of the seaweed farming leads to a sustainable development of the society.

been consumed as food and medicine in East Asian countries like China, Japan, and Korea. The medicinal benefits of various seaweeds in preventing an individual from various diseases have been reviewed and reported (Brownlee et al., 2012). Over 2000 years ago, brown seaweed *Sargassum* spp. was used in Chinese traditional medicine to treat the goiter (Liu et al., 2012). The high level

of iodine in Japanese individuals showed that the habitual consumption of edible seaweeds such as Kombu, Nori, and Wakame, from the last 50 years (Zava and Zava, 2011).

Seaweeds are the marine plant divided into three groups: red, brown, and white, with around 7500 of red, 2000 of brown, and 1800 of white species. Worldwide, 145 species used in human food and 110 species used for hydrocolloid (gelling agent) production. Seaweeds are pervasive in the coastal waters exhibiting species composition, diversity, and richness (Romdoni et al., 2018; Mantri et al., 2020). Despite bountiful species diversity, only a few genera and some species provided more than 80% of the world's seaweed production (Table 23.1). Top intensively cultivated brown seaweeds are *Laminaria japonica*, *Undaria pinnatifida*, and *Sargassum fusiforme* (Ferdouse et al., 2018). Red seaweeds *Porphyra* spp., *Eucheuma* spp., *Kappaphycus alvarezii*, *Gracilaria* spp. and green seaweeds *Enteromorpha clathrata*, *Monostroma nitidum*, and *Caulerpa* spp. are used for hydrocolloids and human food applications (Radulovich et al., 2015; Rhein-Knudsen et al., 2015).

World's seaweed cultivation and harvesting have reached a new milestone with 31.2 million tons year⁻¹ production (95% accounts to farming) with a market worth US\$ 11.7 billion. The increment of 2.5 folds within the last decade, 11,561 million tons in 2005 to 28,952 million tons in 2016. As per Ferdouse et al. (2018), China and Indonesia are the major seaweed producers and generated 26,018 thousand tons of seaweed biomass in 2016 contributing 86.6% of global seaweed production (Table 23.2).

In East Asian countries including China, Japan, and the Republic of Korea, seaweed is found to be used as food products either consumed directly or processed into food products. Carrageenan from red and alginate from brown

TABLE 23.1 Top cultivated seaweeds and increment in cultivation across the world (FAO, 2018).

Seaweed species	World seaweed production (thousand tons, live weight)							
	2005	2010	2011	2012	2013	2014	2015	2016
<i>Eucheuma</i> spp.	987	3481	4616	5853	8430	9034	10,190	10,519
<i>Laminaria japonica</i>	4371	5147	5257	5682	5942	7699	8027	8219
<i>Gracilaria</i> spp.	933	1691	2171	2763	3460	3751	3881	4150
<i>Undaria pinnatifida</i>	2440	1537	1755	2139	2079	2359	2297	2070
<i>Kappaphycus alvarezii</i>	1285	1888	1957	1963	1726	1711	1754	1527
<i>Porphyra</i> spp.	703	1072	1027	1123	1139	1142	1159	1353
<i>Porphyra tenera</i>	584	564	609	691	722	674	686	710
<i>Eucheuma denticulatum</i>	172	259	266	288	233	241	274	214
<i>Sargassum fusiforme</i>	86	78	111	112	152	175	189	190
Total	11,561	15,717	17,769	20,614	23,883	26,786	28,457	28,952

TABLE 23.2 Top countries producing seaweed through wild and farming (94% contribution by top 10 countries) (FAO, 2018).

Country	Metric tons per year	% total seaweed production
World	2,165,675	100
China	698,529	32
France	616,762	28
United Kingdom	205,500	9
Japan	123,074	6
Chile	109,308	5
Philippines	95,912	4
North Korea	71,435	3
South Korea	67,050	3
Indonesia	46,894	2
Norway	40,632	2

seaweeds are used as gelling agents in confectionaries, bakery products, ice-creams, dairy products, and clarifying agents for beers and wines. They are also used in pharmaceuticals as binders, emulsifier, and stabilizers (Ferdouse et al., 2018).

23.3 Need of seaweed farming

The global population is increasing progressively, and as it grows, the requirement of food grain production is increasing, and therefore the efficient utilization of natural resources is essential (Jhariya et al., 2019a,b; Raj et al., 2020; Banerjee et al., 2020). The restricted agricultural land makes limited production of food from terrestrial resources. The amount of food production decreased because fertile land is used for building township, commercial establishments, industrial developments, and infrastructural facilities (Khan et al., 2020a,b, 2021a,b). So, there is a need to focus on alternative bioresource, which could have food and pharmaceutical applications (Le Mouél and Forslund, 2017). The ocean is the sink for the nutrients required for the growth of algae present in the sea, such as seaweeds (Roleda and Hurd, 2019). Seaweed is a renewable feed-stock, which acts as a source of food, feed, bioenergy, and bioactive compounds. The hydrocolloids from seaweeds provide valuable raw material for industries like health food, drugs, textiles, fertilizers, animal feed, etc. These hydrocolloids and its derivatives are unique to the seaweeds, which have essential applications in food preparation and preservation (Tanna and Mishra, 2018; Yan et al.,

2020). Therefore, seaweeds are the promising bioresource for the future to provide high value-added compounds for food and other relevant applications. This helps to protect coral reefs by growing abundance where algae and seaweed have been added together, and it also offers a habitat for different marine organisms (Hasselström et al., 2018).

There are a number of direct and indirect benefits of seaweed farming, providing occupation to the coastal community. It is an eco-friendly activity that provides a continuous supply of seaweed biomass for various industrial applications. It reduces the pressure on the depletion of natural terrestrial-based resources and contributes to the reduction of coastal pollution.

23.4 Principle of seaweed farming

Seaweed is plant-like species attached with a holdfast to shallow coastal waters, requires sunlight and substratum for its growth, but does not have root to supply nutrients, as whole body is involved in nutrient absorption and photosynthesis. Few brown seaweeds are free-floating because of their air-filled bladders (Milledge and Harvey, 2016). Hence the ability of seaweed to grow in the form of attachment to floating objects is the basis of seaweed farming. Any seaweed can be attached to substratum and grow as long as the availability of sunlight, nutrients, oxygen, and carbon dioxide (CO₂), despite the depth. Seaweed farming is defined as the optimized culturing of seaweed crops in seawater for growth and ensuring continuous photosynthesis. The steps in seaweed farming include:

1. Site selection,
2. Species selection and preparation,
3. Cultivation method selection,
4. Maintenance at field, and
5. Harvest followed by drying.

Site selection is the most significant parameter in seaweed farming (Yulianto et al., 2017). Long-spine sea urchins and turtles are causing physical damage to the farm or injuries to the farmers. The diseases, including “ice-ice,” are also a challenge for seaweed farming because it causes damage to the seaweed (Egan et al., 2014). Thus, it is critical to create new strains of marine algae that are light, thermally tolerant, and resistant to disease. The development of more robust and cost-efficient farming systems is needed, especially in the offshore environment. The species is selected based on the ultimate application (food, feed, hydrocolloid, biofuel, and bioactive compounds) and suitability of the environment. Methods for cultivation include the bottom monoline method, fixed bottom long-line method, floating bamboo method, bamboo raft method, mangrove stakes, net cultivation, and integrated multitrophic aquaculture method (Radulovich et al., 2015). The goal of the development of sustainable seaweed farming is to ensure that

the commercial farming of seaweed has a minimal adverse effect on the marine environment. This goal can be achieved by the development of advanced methods of waste management for coastal and open water seaweed farming.

23.5 Advanced technique of seaweed farming

Environmental sustainability of seaweed farming is a complex and multiscale issue involving both direct and indirect interactions with the environment. Offshore cultivation method is a possible step toward large-scale expansion of seaweed farming and reduction of the impact of waste generated in aquaculture (Buck et al., 2018). The offshore cultivation techniques include integrated multitrophic aquaculture and macroalgal cultivation rig, which could reduce the pressure on coastal waters and provide void biomass.

23.5.1 Integrated multitrophic aquaculture

High nutritional content from agriculture or factories in coastal waters may cause unsustainable development of harmful algal blooms and unscrupulous microalgae, which have harmful impacts on marine environments and coastal communities (Xiao et al., 2017). Hence, the offshore cultivation is vital for profitable seaweed industry because of limited area access to coastal beds. Integrated multitrophic aquaculture (IMTA) is an offshore aquaculture technique for sustainable and significant scale expansion of marine food production, but it is an extremely challenging endeavor (Biswas et al., 2020). IMTA holds the opportunity for multiuse of offshore areas to reduce waste and transforming them into valuable coproducts (Buck et al., 2018). As an extractive component, IMTA marine algae can be used to eliminate inorganic compounds and mitigate harmful environmental effects (Califano et al., 2020). The minerals are still being extracted from the water as seaweeds are collected from IMTA (Granada et al., 2018). The *Ulva lactuca* produced in IMTA considerably reduced the nitrogen loads from the water by assimilating about 74% of dissolved nitrogen and help in the growth of sea urchin (Shpiguel et al., 2018).

IMTA provides the coculturing of organisms from the different trophic levels at the same farm to minimize aquaculture waste. It provides cocultivation of fed species (finfish and shrimp) together with organic extractive species (mussels and oysters) work as suspension-feeding and sea urchin and sea cucumber as deposit-feeding and inorganic extractive species seaweed (kelp) to create a more balanced ecosystem. This also provides opportunities for coastal areas with alternate income choices by serving hubs for agricultural activities and maintenance needs (Troell et al., 2009).

23.5.2 Macroalgal cultivation rig

The macroalgal cultivation rig (MACR) is a large-scale offshore cultivation method. It provides suitable opportunities toward vertical lines that help in switching over from one species to other in between the harvesting process. It is easy to monitor and harvest the macroalgae even if it is exposed to waves. It has a very dynamic approach in terms of growth lines that can alter to horizontal direction under climatic extremes. Multiple partial harvesting (four harvests for *Saccharina latissima* and three harvests for *Alaria esculenta*) are possible without reseeded to reduce the production cost. The MACR is a new technology that shows significant promise in terms of production and yield of *Alaria esculenta* and *Saccharina latissima* under specific ecological conditions (Bak et al., 2018). It is therefore highly fruitful for the ocean deep as well as in the offshore regions. Further, rig comprises fixed lines in horizontal direction along with seed lines toward vertical direction arranged in the form of backbone (Buck et al., 2018). Therefore, MACR tend to be highly suitable, flexible technology to maximize their utilization.

23.6 Ecological significance

Seaweed farming improves primary production by photosynthesis and thus contributes significantly to the global cycles of carbon, oxygen, and nutrients (Chung et al., 2013, 2017). This also decreases eutrophication, as well as greenhouse gases. Seaweed production has the ability to offset fossil energy thus extracting 53 billion tons of CO₂ from the environment each year (Krause-Jensen and Duarte, 2016). Algae conduct nearly half of global carbon fixation (Chung et al., 2011). These may also compensate for half of the global accumulation of biological energy, thereby being a potential way to minimize greenhouse gas emissions (Duarte et al., 2017; Meena et al., 2020). Nutrient processing as well as waste purification and recycling facilities are given by both natural beds and managed seaweed farms. Seaweed farming plays an essential role in carbon sequestration, reducing ocean acidification, and providing habitats for fish and crayfish (Chung et al., 2011). Seaweed farming tends to be advantageous over wild populations. It is a good approach that causes least damage to the coastal ecosystem as observed in case of newly designed nursery plantation having similar setup in the form of habitat to sustain the juvenile forms. Seaweed farming contributes to climate change through the fixation of atmospheric CO₂ to reduce ocean acidification and deoxygenation (Duarte et al., 2017).

23.6.1 Carbon sequestration

The global environment is suffering from elevated temperatures in which CO₂ is the major contributor. Presently, the

TABLE 23.3 Top cultivated seaweed species in the world and their carbon sequestration potential.

Genera	Carbon sequestration rate (ton C ha ⁻¹ year ⁻¹)
<i>Eucheuma</i> spp.	68.43
<i>Kappaphycus striatum</i>	125.51
<i>Laminaria</i> spp.	1156
<i>Ecklonia</i> spp.	562
<i>Sargassum</i> spp.	346
<i>Gelidium</i> spp.	17

rapid economic growth in developing nations has predicted a rise in CO₂ level in the future (Shakun et al., 2012). Therefore, it is important to take all possible steps to reduce atmospheric CO₂ load to prevent the damage to ecological functioning (Jhariya, 2017; Jhariya et al., 2021a,b; Banerjee et al., 2021a,b,c,d). As seaweed can fix higher carbon than terrestrial plant and microalgae, seaweed farming is one of the tools to mitigate global climate change through fixing and removing atmospheric CO₂ (Duarte et al., 2017). Muraoka (2004) and Fakhraoui et al. (2020) reviewed the top cultivated seaweed species in the world and their carbon sequestration potential (Table 23.3).

Carbon sequestration by seaweed farming forms a crucial mechanism to decrease the elevation of atmospheric CO₂ and thereby alleviate the trend toward global warming. Seaweed uses CO₂ in the photosynthesis process and converts into beneficial carbohydrates.

The total annual sequestration of carbon by seaweed farming in Indonesia was 2,656,625 tons C year⁻¹ and 621,377 tons C year⁻¹ from marine and pond culture, respectively (Mashoreng et al., 2019). For carbon sequestration, the species *Kappaphycus* was stated to be 12,551 tons C ha⁻¹ cycle⁻¹ (Fakhraoui et al., 2020).

23.6.2 Reduction of ocean acidification

CO₂ is a potential gas toward heating the Earth's atmospheric temperature released due to anthropogenic activities. Further, nature also causes significant contribution in CO₂ emission. Thus, the problem of warming of the Earth surface becomes aggravated (Raj et al., 2021). Dissolving CO₂ in seawater increases hydrogen ion concentrations and decreases the pH of water (Wood et al., 2008). The global impacts of ocean acidification on the marine ecosystem are of significant concern. Ocean acidification, combined with high-temperature water, resulted in massive bleaching of coral reefs in the Indian Ocean

(vanGinneken, 2019). It can be mitigated through increasing the number of seaweeds to utilize the high level of CO₂ for its growth. So, the CO₂ will not be available for the production of carbonate ion and hydroxyl ions, responsible for ocean acidification. Seaweed has a great intake and recycling of CO₂; kelp uses up five times more carbon than other land-based vegetation (Sinha et al., 2001). The 500 million tons of seaweed output will absorb 135 million tons of carbon, which would be 3.2% of the greenhouse gas pollution applied to seawater. The natural seaweed communities can remove the excess of organic carbon of 3000 g C m⁻² through net primary production. The seaweed aquaculture with the continuous harvest of algal biomass could be used for buffering ocean acidification (Mongin et al., 2016).

23.6.3 Mitigation of coastal eutrophication

The intensive agriculture and industrialization cause high input of nutrients into the sea. The consequences are widespread deposition of nutrients in the ocean, causing eutrophication and deoxygenation in coastal waters (Ngatia et al., 2019). It promotes the growth of harmful algal bloom, which causes several environmental problems. Seaweed farming has the potential to absorb this dissolved nutrient, which is removed from coastal waters to land after harvesting of seaweed to overcome of the eutrophication (Roleda and Hurd, 2019). China is a leading country in seaweed farming, and it contributed 32% of seaweed production. Seaweed farming in China characterized by 1604 tons of dry weight/km area corresponding to remove 60.31 tons of nitrogen and 7.60 tons phosphorous per year. Seaweed aquaculture in China has reached a scale that can deliver considerable benefits such as nutrient removal from coastal waters. The seaweed farming annually removes approximately 75,000 tons of nitrogen and 9500 tons of phosphorous from coastal waters (Xiao et al., 2017).

With the growth of seaweed farming, the accumulation of nutrients in coastal waters is projected to decrease, to the point that it may become nutrient-limited in specific areas where intensive seaweed farming and low nutrient intakes occur. Seaweed production will address potential nitrogen deficiencies by introducing aquatic animals into polyculture, including snails, shrimp, crayfish, and mussels (Soto, 2009). The levels of nutrient pollution from the metabolism and excess feed of these humans and animals thus maximize the cultural, ecological, and environmental benefits. The World Bank estimates that producing a global harvest of 500 MT of seaweed by 2050 will consume 10 MT of nitrogen from the water, which is 30% of the nitrogen expected for reaching the sea, and 15 MT of phosphorus, which is around 33% of the phosphorus produced from manure and fertilizers.

23.7 Economic importance

Seaweed farming provides the biomass to meet the demand for the production of hydrocolloid and novel products in food, pharmaceutical, cosmetics, and agro-industry. Seaweed is used as a staple food in Japan and China from ancient times. The green seaweed *Ulva*, *Enteromorpha*, *Codium*, *Caulerpa*, *Porphyra*, *Laminaria*, and *Undaria* are utilized in daily food consumption as a salad or cooked as vegetables (Radulovich et al., 2015; Bouga and Combet, 2015). The dry seaweed biomass is composed of 10%–30% of proteins and 1%–5% of lipid, according to the harvest season. In the farming of 500 million tons of seaweed dry biomass, 150 million tons of algal protein oil can represent about 20% of soy-protein production (Mæhre et al., 2014). The current price per ton for soy meal is about \$550 meaning the protein fraction could be worth of about \$28 billion. Therefore, it is possible that the global expansion of seaweed farming could supplement our existing food supply and provide solutions for the food security challenges. So, producing seaweed biomass through aquaculture could be a great way to produce food economically.

Seaweed hydrocolloids are a versatile ingredient with a wide range of applications in various industries. The hydrocolloids including agar, alginate, and carrageenan have major applications in food and beverages. Alginate is used in the textile printing industry and dentistry for molds of teeth. Agra is used as gelatin and also as the substrate for bacterial and fungal cultures. Carrageenan is used as thickening a stabilizing agent in numerous food products.

Seaweed farming widely attracted attention as a sustainable feedstock for bioenergy. It has high productivity ($1600\text{ g Cm}^{-2}\text{ year}^{-1}$) than terrestrial plants ($470\text{ g Cm}^{-2}\text{ year}^{-1}$) (Balina et al., 2017). Seaweed does not compete with crops from arable land and reducing freshwater algal consumption. Seaweed bio-refinery is an economic approach to the sequential production of diverse bioproducts of commercial importance. The farming of alginophytic seaweed provides 3,890,420 or revenue per ton of dried biomass (Baghel et al., 2014).

23.7.1 Social importance

Seaweed cultivation is commonly seen as a significant economic output for the communities beside the coastal area seems to be a profitable lifestyle. Fishing activity is not able to sustain the livelihood of the people of the coastal area and therefore seaweed cultivation becomes essential as a secondary income source. It is a process which is cost-effective with minimum technological requirements. Seaweed farming shows strong economic potential (62.84%) in comparison to the traditional aquaculture practices (16.97%) and other functions (28.61%) as reported from Indonesia. In the coastal ecosystem, seaweeds form the essential component toward various ecological services that sustains life

in the ocean. It also helps to sustain the rural livelihood of the coastal area. Seaweeds are used as food material across the Asian subcontinents, but its use is more prevalent in terms of hydrocolloid production that has an economic potential of 1 billion dollar. Seaweed farming has become the economic bioresource for the coastal population. Sustainable farming creates a job at the cultivation site through the development of hatcheries, grow-out operations, and processing (Aslan et al., 2018). Generate jobs in the industries providing goods and services to seaweed farming, such as feed, equipment, and advice, required throughout the cultivation (Rameshkumar and Rajaram, 2019).

23.8 Policy and legal framework for effective implementation of seaweed farming

The policies and legal framework for the effective implementation of seaweed farming across the world vary with the individual countries. In this chapter, we focus on the regulatory policies and vision of the government of India for seaweed farming. India's recently reformed National Bio-fuel Strategy (2018) has agreed to raise the target for biofuels to 20% by 2030. It is projected that a 10-million-hectare area could produce 460 million tons of fresh seaweed biomass a year. The National Biofuel Policy has decided to provide top priority to the industrial production of seaweeds biofuels and is expected to produce 6.66 billion liters of bioethanol to meet the target fuel mixture in India by 2030. In India, in compliance with the Biological Diversity Act, 2002, it is mandatory to obtain prior approval from national and state biodiversity boards for the purpose of seaweed research and its commercialization operation. Whereas, seaweed cultivation in India permissible to the citizens of India except to the nonresident Indians, nonregistered company, and the registered company in India whose participants are non-Indian. The noneligible participants or users need to take prior approval from the concerned central or state biodiversity boards. Biodiversity Act, 2002, ensures the biological survey, commercial utilization, and scientific research on seaweed in India. Further, Biological Diversity Act, 2002, also guarantees that the advantages gained from the use of biological resources are shared with bioresource custodians.

23.9 Challenges and opportunities in seaweed farming

The cultivation techniques for various valuable seaweeds are developed, but there are many challenges to overcome. Seaweed farming is seen to be negatively affected by climate change including storm, typhoon, ocean warming, earthquakes, prolonged rainy seasons, and strong water currents that are causing significant damage. The epiphytes and

competing organisms like herbivores fish can maximize sedimentation and damage the farms (Largo et al., 2017). The problem associated with the development of local cultivar in the diverse environmental conditions is also a significant challenge in seaweed farming. Cultivation of cold temperate species is difficult in climate change. The quality of seedling diminishes due to a decrease in the environment and an increase in diseases. The technologies must be accessible for the correct strain growth, planting, harvesting, storage, transportation, distribution, ecosystems, and long-term financial viability of product opportunities (Ganesan et al., 2019).

An increase in global temperature of the ocean, the requirement of high thermotolerant, high growth, light-resistant, disease, and fouling resistant strain is essential. To kill epiphytes and competing organisms, pH control method and organic acid are commonly used, but this is a costly approach. To overcome this problem, less costly desiccation method can be used (Hayashi et al., 2019). Development of a robust and cost-efficient farm systems are required in the offshore environment. Therefore, continuous efforts must be taken to increase productivity by improving methods of cultivation and new cultivar to increase the biomass to bioproduct conversion efficiency.

23.10 Conclusion

Seaweed farming is a simple and eco-friendly approach for sustainable development. Because of relatively small expenditure required to set up seaweed farming, marine algae farming is a viable option for coastal developed countries to help mitigate climate change concerns. Seaweed farming has been demonstrated to assist in ocean recovery, lowering ocean acidification, and removing nutrients from eutrophic waters. It provides massive biomass for the production of food and related products, reducing the pressure on land and generates occupation to the coastal community. Therefore, the expansion of seaweed farming and its use as a solution for growing food demands can be considered.

Acknowledgment

SNM wants to acknowledge the Savitribai Phule University for providing research and working infrastructure. SNM sincerely wants to acknowledge the University Grant commission New Delhi for financial support by Dr. DS Kothari postdoctoral fellowship (No. F.4-2/2006 (BSR)/BL/18-19/0416).

References

Aslan, L.O.M., Supendy, R., Aida AdhaTaridala, S., Hafid, H., Ode Sifatu, W., Sailan, Z., Niampe, L., 2018. Income of seaweed farming households: a case study from Lemo of Indonesia. IOP Conf. Ser. Earth Environ. Sci. 175 (1), 012221.

Baghel, R.S., Reddy, C.R.K., Jha, B., 2014. Characterization of agarophytic seaweeds from the biorefinery context. *Bioresour. Technol.* 159, 280–285.

Bak, U.G., Mols-Mortensen, A., Gregersen, O., 2018. Production method and cost of commercial-scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. *Algal Res.* 33, 36–47.

Balina, K., Romagnoli, F., Pastare, L., Blumberga, D., 2017. Use of macroalgae for bioenergy production in Latvia: review on potential availability of marine coastline species. *Energy Procedia* 113, 403–410.

Banerjee, A., Jhariya, M.K., Yadav, D.K., Raj, A., 2020. Environmental and Sustainable Development Through Forestry and Other Resources. Apple Academic Press Inc., CRC Press: A Taylor and Francis Group, US & Canada, ISBN: 9781771888110, <https://doi.org/10.1201/9780429276026>. 400 pp.

Banerjee, A., Meena, R.S., Jhariya, M.K., Yadav, D.K., 2021a. Agroecological Footprints Management for Sustainable Food System. Springer Nature, Singapore, <https://doi.org/10.1007/978-981-15-9496-0>. 514 pp. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.

Banerjee, A., Jhariya, M.K., Meena, R.S., Yadav, D.K., 2021b. Ecological footprints in agroecosystem—an overview. In: Banerjee, A., Meena, R. S., Jhariya, M.K., Yadav, D.K. (Eds.), *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, pp. 1–23, https://doi.org/10.1007/978-981-15-9496-0_1. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.

Banerjee, A., Jhariya, M.K., Raj, A., Yadav, D.K., Khan, N., Meena, R.S., 2021c. Land footprint management and policies. In: Banerjee, A., Meena, R.S., Jhariya, M.K., Yadav, D.K. (Eds.), *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, pp. 221–246, https://doi.org/10.1007/978-981-15-9496-0_7. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.

Banerjee, A., Jhariya, M.K., Raj, A., Yadav, D.K., Khan, N., Meena, R.S., 2021d. Energy and climate footprint towards the environmental sustainability. In: Banerjee, A., Meena, R.S., Jhariya, M.K., Yadav, D. K. (Eds.), *Agroecological Footprints Management for Sustainable Food System*. Springer Nature, Singapore, pp. 415–443, https://doi.org/10.1007/978-981-15-9496-0_14. eBook ISBN: 978-981-15-9496-0, Hardcover: 978-981-15-9495-3.

Biswas, G., Kumar, P., Ghoshal, T.K., Kailasam, M., De, D., Bera, A., Mandal, B., Sukumaran, K., Vijayan, K.K., 2020. Integrated multi-trophic aquaculture (IMTA) outperforms conventional polyculture with respect to environmental remediation, productivity and economic return in brackishwater ponds. *Aquaculture* 516, 734626.

Bouga, M., Combet, E., 2015. Emergence of seaweed and seaweed-containing foods in the UK: focus on labeling, iodine content, toxicity and nutrition. *Foods* 4 (2), 240–253.

Brownlee, I., Fairclough, A., Hall, A., Paxman, J., 2012. The potential health benefits of seaweed and seaweed extract. In: *Seaweed: Ecology, Nutrient Composition and Medicinal Uses*. Nova Science, pp. 119–136 (Chapter 6).

Buck, B.H., Troell, M.F., Krause, G., Angel, D.L., Grote, B., Chopin, T., 2018. State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Front. Mar. Sci.* 5, 165.

Buschmann, A.H., Camus, C., Infante, J., Neori, A., Israel, Á., Hernández-González, M.C., Pereda, S.V., Gomez-Pinchetti, J.L., Golberg, A., Tadmor-Shalev, N., Critchley, A.T., 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *Eur. J. Phycol.* 52 (4), 391–406.

Califano, G., Kwantes, M., Abreu, M.H., Da Silva Costa, R., Wichard, T., 2020. Cultivating the macroalgal holobiont: effects of integrated multi-trophic aquaculture on the microbiome of *Ulvarigida* (chlorophyta). *Front. Mar. Sci.* 7.

- Camus, C., Infante, J., Buschmann, A.H., 2019. Revisiting the economic profitability of giant kelp *Macrocystispyrifer* (Ochrophyta) cultivation in Chile. *Aquaculture* 502, 80–86.
- Chung, I.K., Beardall, J., Mehta, S., Sahoo, D., Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: a critical appraisal. *J. Appl. Phycol.* 23 (5), 877–886.
- Chung, I.K., Oak, J.H., Lee, J.A., Shin, J.A., Kim, J.G., Park, K.S., 2013. Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean project overview. *ICES J. Mar. Sci.* 70 (5), 1038–1044.
- Chung, I.K., Sondak, C.F., Beardall, J., 2017. The future of seaweed aquaculture in a rapidly changing world. *Eur. J. Phycol.* 52 (4), 495–505.
- Duarte, C.M., Wu, J., Xiao, X., Bruhn, A., Krause-Jensen, D., 2017. Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* 4, 100.
- Egan, S., Fernandes, N.D., Kumar, V., Gardiner, M., Thomas, T., 2014. Bacterial pathogens, virulence mechanism and host defence in marine macroalgae. *Environ. Microbiol.* 16 (4), 925–938.
- Fakhraini, M.S., Wisnu, W., Khathir, R., Patria, M.P., 2020. Carbon sequestration in macroalgae *Kappaphycus striatum* in seaweed aquaculture site, Alaang village, Alor Island, East Nusa Tenggara. *IOP Conf. Ser. Earth Environ. Sci.* 404 (1), 012044.
- FAO (Food and Agriculture Organization of the United Nations), 2018. The Global Status of Seaweed Production, Trade and Utilization. *Globefish Research Programme* vol. 124, 1–114.
- Ferdouse, F., Holdt, S.L., Smith, R., Murua, P., Yang, Z., 2018. The Global Status of Seaweed Production, Trade and Utilization. *Food and Agriculture Organization of the United Nations*.
- Ganesan, M., Trivedi, N., Gupta, V., Madhav, S.V., Reddy, C.R., Levine, I. A., 2019. Seaweed resources in India—current status of diversity and cultivation: prospects and challenges. *Bot. Mar.* 62 (5), 463–482.
- Gao, K., McKinley, K.R., 1994. Use of macroalgae for marine biomass production and CO₂ remediation: a review. *J. Appl. Phycol.* 6 (1), 45–60.
- Granada, L., Lopes, S., Novais, S.C., Lemos, M.F., 2018. Modelling integrated multi-trophic aquaculture: optimizing a three trophic level system. *Aquaculture* 495, 90–97.
- Hasselström, L., Visch, W., Gröndahl, F., Nylund, G.M., Pavia, H., 2018. The impact of seaweed cultivation on ecosystem services—a case study from the west coast of Sweden. *Mar. Pollut. Bull.* 133, 53–64.
- Hayashi, L., de Jesus Cantarino, S., Critchley, A., 2019. Challenges to the future domestication of seaweeds as cultivated species: understanding their physiological processes for large-scale production. *Adv. Bot. Res.* 95.
- Jhariya, M.K., 2017. Vegetation ecology and carbon sequestration potential of shrubs in tropics of Chhattisgarh, India. *Environ. Monit. Assess.* 189 (10), 518. <https://doi.org/10.1007/s10661-017-6246-2>.
- Jhariya, M.K., Banerjee, A., Meena, R.S., Yadav, D.K., 2019a. Sustainable Agriculture, Forest and Environmental Management. Springer Nature, Singapore, <https://doi.org/10.1007/978-981-13-6830-1>. 606 pp. eISBN: 978-981-13-6830-1, Hardcover ISBN: 978-981-13-6829-5.
- Jhariya, M.K., Yadav, D.K., Banerjee, A., 2019b. Agroforestry and Climate Change: Issues and Challenges. Apple Academic Press Inc., CRC Press: A Taylor and Francis Group, US & Canada, <https://doi.org/10.1201/9780429057274>. 335 pp. ISBN: 978-1-77188-790-8 (Hardcover), 978-0-42957-274-8 (E-book).
- Jhariya, M.K., Meena, R.S., Banerjee, A., 2021a. Ecological Intensification of Natural Resources for Sustainable Agriculture. Springer Nature, Singapore, <https://doi.org/10.1007/978-981-33-4203-3>. eISBN: 978-981-334-203-3, Hardcover ISBN: 978-981-334-206-6.
- Jhariya, M.K., Meena, R.S., Banerjee, A., 2021b. Ecological intensification of natural resources towards sustainable productive system. In: *Ecological Intensification of Natural Resources for Sustainable Agriculture*. Springer, Singapore, https://doi.org/10.1007/978-981-33-4203-3_1. eBook ISBN 978-981-334-203-3, Hardcover ISBN: 978-981-334-202-6.
- Kaladharan, P., 2018. Seaweed farming. *Aquaculture Spectrum* 1 (3), 24–32.
- Keating, B.A., Herrero, M., Carberry, P.S., Gardner, J., Cole, M.B., 2014. Food wedges: framing the global food demand and supply challenge towards 2050. *Glob. Food Sec.* 3 (3–4), 125–132.
- Khan, N., Jhariya, M.K., Yadav, D.K., Banerjee, A., 2020a. Herbaceous dynamics and CO₂ mitigation in an urban setup—a case study from Chhattisgarh, India. *Environ. Sci. Poll. Res.* 27 (3), 2881–2897. <https://doi.org/10.1007/s11356-019-07182-8>.
- Khan, N., Jhariya, M.K., Yadav, D.K., Banerjee, A., 2020b. Structure, diversity and ecological function of shrub species in an urban setup of Sarguja, Chhattisgarh, India. *Environ. Sci. Pollut. Res.* 27 (5), 5418–5432. <https://doi.org/10.1007/s11356-019-07172-w>.
- Khan, N., Jhariya, M.K., Raj, A., Banerjee, A., Meena, R.S., 2021a. Soil carbon stock and sequestration: implications for climate change adaptation and mitigation. In: Jhariya, M.K., Meena, R.S., Banerjee, A. (Eds.), *Ecological Intensification of Natural Resources for Sustainable Agriculture*. Springer, Singapore, https://doi.org/10.1007/978-981-33-4203-3_13. eBook ISBN 978-981-334-203-3, Hardcover ISBN: 978-981-334-202-6.
- Khan, N., Jhariya, M.K., Raj, A., Banerjee, A., Meena, R.S., 2021b. Eco-designing for sustainability. In: Jhariya, M.K., Meena, R.S., Banerjee, A. (Eds.), *Ecological Intensification of Natural Resources for Sustainable Agriculture*. Springer, Singapore, https://doi.org/10.1007/978-981-33-4203-3_16. eBook ISBN 978-981-334-203-3, Hardcover ISBN: 978-981-334-202-6.
- Krause-Jensen, D., Duarte, C.M., 2016. Substantial role of macroalgae in marine carbon sequestration. *Nat. Geosci.* 9 (10), 737–742.
- Langton, R.W., Augyte, S., Price, N., Forster, J., Noji, T., Grebe, G., Gelais, A.S., Byron, C.J., 2019. An Ecosystem Approach to the Culture of Seaweed. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
- Largo, D.B., Chung, I.K., Phang, S.M., Gerung, G.S., Sondak, C.F., 2017. Impacts of climate change on Eucheuma-Kappaphycus farming. In: *Tropical Seaweed Farming Trends, Problems and Opportunities*. Springer, Cham, pp. 121–129.
- Le Mouél, C., Forslund, A., 2017. How can we feed the world in 2050? A review of the responses from global scenario studies. *Eur. Rev. Agric. Econ.* 44 (4), 541–591.
- Liu, L., Heinrich, M., Myers, S., Dworjanyan, S.A., 2012. Towards a better understanding of medicinal uses of the brown seaweed *Sargassum* in traditional Chinese medicine: a phytochemical and pharmacological review. *J. Ethnopharmacol.* 142 (3), 591–619.
- Mæhre, H.K., Malde, M.K., Eilertsen, K.E., Elvevoll, E.O., 2014. Characterization of protein, lipid and mineral contents in common Norwegian seaweeds and evaluation of their potential as food and feed. *J. Sci. Food Agric.* 94 (15), 3281–3290.
- Mantri, V.A., Kavale, M.G., Kazi, M.A., 2020. Seaweed biodiversity of India: reviewing current knowledge to identify gaps, challenges, and opportunities. *Diversity* 12 (1), 13.
- Mashoreng, S., La Nafie, Y.A., Isyirini, R., 2019. Cultivated seaweed carbon sequestration capacity. *IOP Conf. Ser. Earth Environ. Sci.* 370 (1), 012017. IOP Publishing.

- Meena, R.S., Lal, R., Yadav, G.S., 2020. Long-term impact of topsoil depth and amendments on carbon and nitrogen budgets in the surface layer of an Alfisol in Central Ohio. *Catena* 194, 104752. <https://doi.org/10.1016/j.catena.2020.104752>.
- Milledge, J.J., Harvey, P.J., 2016. Golden tides: problem or golden opportunity? The valorisation of Sargassum from beach inundations. *J. Mar. Sci. Eng.* 4 (3), 60.
- Mongin, M., Baird, M.E., Hadley, S., Lenton, A., 2016. Optimising reef-scale CO₂ removal by seaweed to buffer ocean acidification. *Environ. Res. Lett.* 11 (3), 034023.
- Muraoka, D., 2004. Seaweed resources as a source of carbon fixation. *Bulletin of Fisheries Research Agency, Japan*, pp. 59–64.
- National Bio-fuel Strategy. <https://economictimes.indiatimes.com/small-biz/productline/power-generation/national-policy-on-biofuels-2018-here-are-key-things-you-should-know/articleshow/71922729.cms?from=mdr>.
- Ngatia, L., Grace III, J.M., Moriasi, D., Taylor, R., 2019. Nitrogen and phosphorus eutrophication in marine ecosystems. In: *Monitoring of Marine Pollution*. Intech Open.
- Ohno, M., Critchley, A.T. (Eds.), 1998. *Seaweed Resources of the World*. Kanagawa International Fisheries Training Center, Japan International Cooperative Agency.
- Pablo, G., Gomes-Dias, J.S., Rocha, C.M., Romaní, A., Garrote, G., Domingues, L., 2020. Recent trends on seaweed fractionation for liquid bio-fuels production. *Bioresour. Technol.* 299, 122613.
- Radulovich, R., Neori, A., Valderrama, D., Reddy, C.R.K., Cronin, H., Forster, J., 2015. Farming of seaweeds. In: *Seaweed Sustainability*. Academic Press, pp. 27–59.
- Raj, A., Jharia, M.K., Yadav, D.K., Banerjee, A., 2020. *Climate Change and Agroforestry Systems: Adaptation and Mitigation Strategies*. Apple Academic Press Inc., CRC Press: A Taylor and Francis Group, US & Canada, ISBN: 9781771888226, <https://doi.org/10.1201/9780429286759>. 383 pp.
- Raj, A., Jharia, M.K., Khan, N., Banerjee, A., Meena, R.S., 2021. Ecological intensification for sustainable development. In: *Ecological Intensification of Natural Resources for Sustainable Agriculture*. Springer, Singapore, https://doi.org/10.1007/978-981-33-4203-3_5. eBook ISBN 978-981-334-203-3, Hardcover ISBN: 978-981-334-202-6.
- Rameshkumar, S., Rajaram, R., 2019. Impact of seaweed farming on socio-economic development of a fishing community in Palk Bay, southeast coast of India. In: *Coastal Zone Management*. Elsevier, pp. 501–513.
- Rhein-Knudsen, N., Ale, M.T., Meyer, A.S., 2015. Seaweed hydrocolloid production: an update on enzyme assisted extraction and modification technologies. *Mar. Drugs* 13 (6), 3340–3359.
- Roleda, M.Y., Hurd, C.L., 2019. Seaweed nutrient physiology: application of concepts to aquaculture and bioremediation. *Phycologia* 58 (5), 552–562.
- Romdoni, T.A., Ristiani, A., Meinita, M.D.N., Marhaeni, B., 2018. Seaweed species composition, abundance and diversity in Drini and Kondang Merak Beach, Java. In: *E3S Web of Conferences*, vol. 47. EDP Sciences, p. 03006.
- Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A., Bard, E., 2012. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation. *Nature* 484 (7392), 49–54.
- Shannon, E., Abu-Ghannam, N., 2019. Seaweeds as nutraceuticals for health and nutrition. *Phycologia* 58 (5), 563–577.
- Shimazu, T., Borjigin, L., Katoh, K., Roh, S.G., Kitazawa, H., Abe, K., Suda, Y., Saito, H., Kunii, H., Nihei, K., Uemoto, Y., 2019. Addition of Wakame seaweed (*Undaria pinnatifida*) stalk to animal feed enhances immune response and improves intestinal microflora in pigs. *Anim. Sci. J.* 90 (9), 1248–1260.
- Shpigel, M., Shauli, L., Odintsov, V., Ben-Ezra, D., Neori, A., Guttman, L., 2018. The sea urchin, *Paracentrotus lividus*, in an integrated multi-trophic aquaculture (IMTA) system with fish (*Sparus aurata*) and seaweed (*Ulva lactuca*): nitrogen partitioning and proportional configurations. *Aquaculture* 490, 260–269.
- Sinha, V.R.P., Fraley, L., Chowdhry, B.S., 2001. Carbon dioxide utilization and seaweed production. In: *Proceedings of NETL: First National Conference on Carbon Sequestration*, vol. 6.
- Soto, D., 2009. Integrated Mariculture: A Global Review (No. 529). Food and Agriculture Organization of the United Nations (FAO).
- Tanna, B., Mishra, A., 2018. Metabolites unravel nutraceutical potential of edible seaweeds: an emerging source of functional food. *Compr. Rev. Food Sci. Food Saf.* 17 (6), 1613–1624.
- Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H., Fang, J.G., 2009. Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* 297 (1–4), 1–9.
- vanGinneken, V., 2019. The application of the seaweeds in neutralizing the “ocean acidification” as a long-term multifaceted challenge. *J. Geosci. Environ. Prot.* 7 (12), 126.
- Wood, H.L., Spicer, J.I., Widdicombe, S., 2008. Ocean acidification may increase calcification rates, but at a cost. *Proc. R. Soc. B Biol. Sci.* 275 (1644), 1767–1773.
- Xiao, X., Agusti, S., Lin, F., Li, K., Pan, Y., Yu, Y., Zheng, Y., Wu, J., Duarte, C.M., 2017. Nutrient removal from Chinese coastal waters by large-scale seaweed aquaculture. *Sci. Rep.* 7, 46613.
- Yan, F., Wang, M., Chen, X., Li, X., Wu, Y., Fu, C., 2020. Effects of alginate oligosaccharides treatment on preservation and fresh-keeping mechanism of shrimp during frozen storage. *Food Sci. Technol.* 40, 380–386.
- Yulianto, H., Damai, A.A., Delis, P.C., Elisdiana, Y., 2017. Spatial analysis to evaluate the suitability of seaweed farming site in Lampung Bay, Indonesia. *Turk. J. Fish Aquat. Sci.* 17 (6), 1253–1261.
- Zava, T.T., Zava, D.T., 2011. Assessment of Japanese iodine intake based on seaweed consumption in Japan: a literature-based analysis. *Thyroid. Res.* 4 (1), 14.
- Zerrifi, S.E.A., El Khalloufi, F., Oudra, B., Vasconcelos, V., 2018. Seaweed bioactive compounds against pathogens and microalgae: potential uses on pharmacology and harmful algae bloom control. *Mar. Drugs* 16 (2), 55.