Review

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Seaweed resources in India – current status of diversity and cultivation: prospects and challenges

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Abstract: Seaweeds are an integral part of coastal ecosystems and offer invaluable ecosystem services supporting the life of many marine forms. The economic value of seaweeds significantly contributes to the sustainable development of rural coastal regions. Seaweeds are consumed as food in some Asian countries, but their utilization for production of phycocolloids is widespread across the globe, with an estimated value of more than one billion US\$. In India, seaweeds have been utilized exclusively for the production of phycocolloids but recently they are used for the production of plant growth stimulants for agricultural applications. The domestic agar and alginate industry totally depends on the supplies from natural seaweed beds with some occasional imports. The recent success achieved in both upstream and downstream technologies in production and processing of seaweeds has boosted the prospects for commercialization of seaweed resources in the country. The present article briefly appraises the current status of Indian seaweed resources and their utilization, as well as developments in seaweed farming technologies, the status of seaweed industry and recent efforts to transform seaweed farming into a social enterprise. It also highlights the

challenges encountered for mainstreaming these resources so as to evolve into a marine industry.

Keywords: agar; alginate; cultivation; diversity; seaweed.

Introduction

In 2016–17, India produced over 270 million tonnes of food grains to feed more than 1.2 billion people (Anon 2017). This population is increasing year-on-year and, as it grows, demand for food grain production increases. Traditional Indian agriculture is currently at maximum production levels but lacks the capacity to fill the gap between production and demand. Furthermore, farmlands are put to more lucrative uses of land for building townships, industrial corridors, commercial establishments, infrastructural facilities, etc. Therefore, it is imperative that society must identify alternative resources that will support and supplement the long-term human food demands sustainably with minimal environmental impacts and associated biological phenomena. There is ample evidence of the importance of seaweeds in the context of human food needs and ecological benefits of farming (Craigie 2011, Cornish et al. 2017). Economic uses of seaweeds particularly for food, feed, phycocolloids and agro-based products, are well known for centuries and are now being extensively investigated for their application in bio-fuel, nutraceutical, medicinal, personal-care and food additive industries (Hafting et al. 2015, Kim et al. 2017).

Direct consumption of seaweeds as food in the form of salads, soups and a number of other food preparations is very common in Southeast Asian countries. Japan, China and Korea stand at the forefront of seaweed utilization in human food preparations, whereas in India, seaweeds are used only for the extraction of industrially important phycocolloids such as agar, alginate and carrageenan.

Global production of seaweeds has been estimated at 30.1 million wet tons in 2016 (FAO 2018), with 95% of the

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total produced from culture and the remaining 5% from natural beds. The top seven countries that account for global production of seaweeds are: China, Japan, Korea, Indonesia, Philippines, Malaysia and Vietnam. However, in India, agar and alginate are produced from seaweeds harvested from wild stocks whereas carrageenan is obtained from cultivated *Kappaphycus alvarezii* (Doty) Doty ex P.C. Silva.

The present review provides an overview of Indian seaweed resources, their utilization and the associated seaweed industry. Recent initiatives to develop and transform seaweed farming into social enterprises are described. Opportunities and challenges for building a successful seaweed industry in India are also discussed.

Seaweed diversity

India is among the 12 mega-biodiversity nations in the world. India's coastline is 8100 km long and has an

Exclusive Economic Zone (EEZ) of 2.17 million km² (equal to 66% of total mainland area) (Figure 1). Nearly 30% of its human population is, one way or another, dependent on the rich exploitable coastal and marine resources. The Indian coastline, with its different coastal ecosystems, supports luxuriant growth of diverse seaweed populations, having considerable economic importance. The first report on seaweed diversity was published by Iyengar (1927) on the flora of Krusadai Island, Southeast coast of India. Subsequently, Boergesen (1928) investigated the seaweeds of the west coast and published a new record of *Rosenvingea stellata* Boergesen. Later Thivy (1948), Krishnamurthy (1957) and Umamaheswara Rao (1969) made substantial contributions to increase our knowledge of India's seaweed diversity. During 1980–1990, the Central Salt and Marine Chemicals Research Institute (CSMCRI) made a comprehensive survey and estimated the total seaweed standing stocks as 97,400 tonnes wet wt. from the coast of Tamil Nadu, 7500 tonnes wet wt. from

Figure 1: Map of Indian subcontinent.

the coast of Andhra Pradesh and 19,345 tonnes wet wt. from the Lakshadweep islands (Kaliaperumal and Kalimuthu 1997). Oza and Zaidi (2001) updated the checklist of seaweed diversity based on secondary data and reported 844 species of seaweeds with 434, 194, and 216 species of red, brown, and green seaweeds, respectively. The CSMCRI team explored the seaweed diversity of the Gujarat and Tamil Nadu coasts (Jha et al. 2009) known for their relative abundance of seaweeds. These two maritime states, collectively, are home to 366 seaweed species that account for nearly half of India's total seaweed diversity.

Seaweed diversity of Gujarat coast

The Gujarat coast, more than 1600 km long, is located in northwest India. The coastline has varied topography, geomorphology, coastal processes and river discharges into the Arabian Sea and has been broadly segmented

into five regions viz. the Rann of Kachchh, the Saurashtra coast, Gulf of Kachchh, Gulf of Khambhat and the South Gujarat coast (Figure 2). Among these regions, the Gulf of Kachchh, extending over 1000 km, is a wealthy coastline with the Marine National Park and Marine Sanctuary that includes 42 islands, rocky intertidal regions and mangrove forests supporting rich seaweed diversity. The Gulf of Khambhat is a delta region with several major rivers flowing into the sea, including the Narmada, Tapi and Mahi Sabarmati rivers. The intertidal region comprises mud and sand flats with minimal seaweed diversity.

The survey documenting the intertidal seaweed diversity of the Gujarat coast revealed 198 species representing all three major groups of seaweed; Rhodophyta 109 species from 62 genera; Chlorophyta 54 species from 23 genera; Phaeophyceae 35 species from 16 genera. Seaweed diversity is rich in the Gulf of Kachchh islands totaling 130 species from Dani, Dhabdhaba, Kalubhar, Manmarodi, and Narara Islands. Species collected ranged from 93 species from Kalubhar Island to a minimum

Figure 2: Map of Gujarat coast.

number of 14 species collected from Narara Island (Jha et al. 2009).

Seaweed diversity of Tamil Nadu coast

The Southeast Indian State of Tamil Nadu's coastline (Figure 3) is 1076 km long with 13 coastal districts and 15 major ports and harbours. The convergence of the Bay of Bengal, Arabian Sea, and the Indian Ocean at India's

southern tip is the unique feature of this coast. Distinct variations are seen in the nature of substratum in the intertidal and subtidal regions. The northern coastal area has long and wide sandy beaches intermittently populated with flat rocks, boulders and stones in the lower and upper intertidal regions, experiencing severe surf energy. Species belonging to the genera *Ulva*, *Chaetomorpha*, *Bryopsis* and *Grateloupia* inhabit the rocks and boulders. The central Tamil Nadu coast includes Palk Bay, which falls within the Cauvery deltaic region. The region's muddy intertidal and subtidal coast is due to the confluence of many rivers flowing to the sea. Several species of

Figure 3: Map of Tamil Nadu coast.

Gracilaria, including *G. edulis*, *G. foliifera*, *G. verrucosa* and *G. salicornia* are dominant and commercially harvested in this region. The Gulf of Mannar, located in the southern part of Tamil Nadu, has a rich diversity from all three seaweed groups. Intertidal and subtidal rocks extend up to 1 m deep and they support abundant growth of *Sargassum*, *Acanthophora* and *Hypnea* species. The subtidal coral reefs are populated with *Gelidiella*, *Turbinaria* and *Sargassum* species. The southern Gulf of Mannar's rocky intertidal and lower intertidal regions maintain rich populations of several *Ulva* species. *Ulva* has been collected from all 20 Gulf of Mannar islands supporting high seaweed diversity with potential economic importance.

Studies carried out to determine seaweed diversity from 42 Indian coastal stations and 14 Gulf of Mannar islands (Figure 3) showed a total of 282 seaweed species (Anon 2012). Among these, 80 species were Chlorophyta, 56 species were Phaeophyceae and 146 species were Rhodophyta. The genus *Caulerpa* was represented by the highest number of species (24) among the green algae, followed by *Codium* with seven species and *Halimeda* and *Ulva* with six species each. The genera *Acrosiphonia*, *Anastomonas*, *Boergesenia*, *Dictyosphaeria*, *Neomreis*, *Microdictyon*, *Struvea*, *Valonia* and *Valoniopsis* have a single species each. In brown algae, the genus *Sargassum* had the greatest number of species (15) followed by *Dictyota* with 10 species and *Padina* with seven species. The genera *Turbinaria*, *Dictyopteris* and *Chnoospora* had three species each and the genera *Ectocarpus*, *Hormophysa*, *Hydroclathrus*, *Iyengaria*, *Rosenvingeia* and *Zonaria* were each represented by a single species. Among the red algae, the genus *Gracilaria* represented the highest number of species (20) while the genus *Laurencia* had 12 species. Other red algal genera found include seven species of *Hypnea*, six species of *Grateloupia* and several genera that were represented by a single species including: *Asparagopsis*, *Bostrychia*, *Botryocladia*, *Chondrococcus*, *Chondrocantus*, *Dasya*, *Dictyurus*, *Digenea*, *Enantiocladia*, *Griffithesia*, *Halichrysis*, *Helminthocladia*, *Neurymenia*, *Nitophyllum*, *Peyssonnelia*, *Tenaciphyllum* and *Wrangelia* (Anon 2012).

Commercial harvests of seaweeds along the Southeast Indian coast

According to FAO (2014), global seaweed harvests from wild stocks ranged between 1.0 and 1.3 million tonnes from 2000 to 2009. Unlike Southeast Asian countries, Indian seaweed industries rely heavily on wild harvests for phycocolloid production. *Gelidiella acerosa* (Forsskal) and Feldmann & Hamel and *Gracilaria edulis* (S.G. Gmelin) P.C.

Silva are harvested for agar production, while *Sargassum* spp. and *Turbinaria* spp. are the source material for alginate production. The Gulf of Mannar and Palk Bay coasts are highly productive regions for commercial collection of agarophytes and alginophytes. A long and wide coral reef (140 km length), running along the southern side of the 20 islands of the Gulf of Mannar, supports luxuriant growth of seaweeds; especially *Sargassum* spp., *Turbinaria* spp. and *G. acerosa*. Similarly, the shallow and silty Palk Bay coast harbours rich growth of *Gracilaria salicornia* (C. Agardh) and *G. edulis*. Harvesting techniques include: cutting erect fronds from mono-specific patches of the targeted seaweed. Harvesting takes approximately 12 days per month during spring tides. In the Gulf of Mannar, 1555 fisherfolk from 14 coastal villages are known to harvest seaweeds, including 1270 women and 285 men. Along the Palk Bay coast, 670 fisherfolk from 24 villages harvest seaweeds. Among them, 460 are women and 210 are men. In India, seaweed gathering is traditionally considered as a job for women and teenagers. They earn an average annual income of US \$1000. Seaweed harvesting is seasonal work and helps people earn additional income for their families. Once the seaweed collection season ends, fisherfolk shift their efforts towards fishing and allied jobs.

Harvested seaweeds are dried on the shore and sold to industry buyers. *Gelidiella acerosa* value is USD \$1800 per dry tonne; *Gracilaria* spp, *Sargassum* and *Turbinaria* value is approximately US \$800 per dry tonne. The harvested seaweeds are used for production of phycocolloids, including agar and alginates by 33 industrial firms.

Harvesting of *Gelidiella acerosa* and *Gracilaria edulis* from 2005 to 2016 resulted in a gradual depletion of natural resources due to over exploitation (Figure 4), whereas

Figure 4: Annual landings of agarophytes from wild harvest. Courtesy of © Madurai Agar Manufacturer Welfare Association, Madurai. *Gelidiella acerosa* and *Gracilaria edulis* are collected from Gulf of Mannar islands and mainland coast from Kilakkarai to Valinokkam of Southeast Indian coast.

Figure 5: Annual landings of alginophytes from wild harvest. Courtesy of © SNAP Natural Products and Alginates (P) Ltd., Ranipet. *Sargassum wightii*, *Turbinaria conoides*, *T. ornata* and *T. decurrens* are collected from Gulf of Mannar islands and mainland coast from Rameswaram to Kanyakumari of Southeast Indian coast.

Sargassum spp. and *Turbinaria* spp. landings exhibited an irregular value trend (Figure 5). Over-harvesting of seaweeds has a direct effect on marine biodiversity, particularly on the abundance of motile invertebrates, fish and other animals occupying higher trophic levels (Migné et al. 2014, Phillippi et al. 2014). Over-harvesting can negatively impact recruitment and reduce contributions to the marine carbon cycle (Levitt et al. 2002). Intertidal and subtidal seaweeds dominate the habitat and exert a strong influence on the community recruitment (Thompson et al. 2010).

Phycocolloid production

Agar

Indian agar production started in 1940 on a cottage-industry scale, with *Gracilaria edulis* utilized as the raw material. Later, a process for industrial manufacture of agar was developed using *Gelidium micropterum* Kutzing as the raw material. With the development of these industrial methods, a few processors started agar production using either *Gelidiella acerosa* or *G. edulis* as raw material. Since plentiful wild stock resources of *G. acerosa* and *G. edulis* were available, several processors flourished during the 1960s and 1970s. Presently, 25 agar processors are operating with average agar production of 300 and 400 tonnes per annum (Figure 6). Food-grade agar represents 67% of the total annual Indian agar production. Agar production increased steadily, reaching maximum production in 2014–2015. Landings of *G. edulis* decreased substantially during the same time frame corresponding to increased raw

Figure 6: Agar production in India.

Courtesy of © Madurai Agar Manufacturer welfare association, Madurai.

material demands by the processing industry. As a result of supply shortages, several agar processors imported *G. edulis* from Sri Lanka and Indonesia. Additionally, an average of 400 dry tonnes per annum of *Gracilaria salicornia* were harvested from Palk Bay wild stocks from 2012 to 2015 (Mr. Bose, President, Madurai Agar Association, personal communication). *Gracilaria salicornia* is a source of food-grade agar with a gel strength of approximately $510 \text{ g} \cdot \text{cm}^{-2}$ (Meena et al. 2008). This food-grade agar meets most domestic Indian requirements. Food grade agar powder fetches higher prices than agar strips.

Bacteriological grade agar production in India decreased sharply after 2011–2012, with the lowest production of 80 tonnes during 2012–2013 (Figure 6). M/s Marine Chemicals, Cochin a major agar producer, produces more than 70% of the bacteriological-grade agar produced in India. The company imports all its agar raw material from outside India and buys crude agar from small-scale processors in India and refines it for export to other countries.

Alginate

Alginate is extracted from *Sargassum* spp. and *Turbinaria* spp. harvested from wild stocks along the Gulf of Mannar coast. Alginate production has steadily increased from 98 metric tonnes in 2003–200 metric tonnes in 2016 (Figure 7). SNAP Natural Products and Alginate (P) Ltd. is the major producer. SNAP produces a variety of alginate products, including food, pharmacological, industrial, textile and welding grades. Alginates have been used in a wide range of applications as thickening and gelling agents in the food and feed processing industries. Pharmaceutical industrial concerns utilize alginate coloring agent as stabilizers and in the textile industry as water proofing, paper coating and in wastewater treatment.

Figure 7: Alginates production in India.

Courtesy of © SNAP Natural Products and Alginates (P) Ltd., Ranipet.

Seaweed culture

The Southeast Indian coast is considered to be most suitable for commercial seaweed cultivation because it has shallow, wide and flat coastal shorelines with moderate wave action, and rich in nutrients including phosphorus and nitrogen. Seawater salinities and temperatures are optimal for seaweed production making the region suitable for commercial seaweed cultivation year round, except during the monsoon season. Essential cultivation supplies including bamboo, rope and anchors are readily available at reasonable prices close to the cultivation sites. Above all, willing contingents of 14–35 year-old age group fisher women are available for seaweed cultivation (Ganesan et al. 2017).

Culture of carrageenophytes

Kappaphycus alvarezii

Kappaphycus alvarezii is one of the most widely traded tropical red seaweeds, utilized as a source for the extraction of the commercially important phycocolloid kappa-carrageenan (κ -carrageenan). Due to its unique gelling properties, kappa-carrageenan is used as an emulsifier, binder, thickener and gelling agent in a diverse range of products including toothpaste, cosmetics, ice cream, pet foods, beverages, pharmaceuticals, personal care and dairy products.

Farming of *Kappaphycus alvarezii* in India originated with a few grams of biomass imported from Japan by CSIR-CSMCRI in the early 1990s; the importation followed the quarantine procedures appropriate for cultivation and utilization. Initial out-planting trials were done

along the Northwest's Okha coast following laboratory acclimatization studies. Subsequently, southeast Tamil Nadu's Mandapam coast was explored for its suitability as a potential cultivation region from 1995 to 1997. Initial field trials evaluated a variety of cultivation methods, including (a) polythene bags, (b) fish net bags and (c) net enclosed open culture (Eswaran et al. 2002). Eventually, the bamboo raft method was adopted. In this method, 3×3 m rafts made with 7–8 cm diameter bamboo were reinforced utilizing diagonally orientated bamboo braces approximately 1.3 m long to maintain integrity in open sea conditions. Lower portions of the rafts were covered with fishing net minimizing grazing and biomass drifting. Twenty plantings (fresh cuttings) of approximately 100 g. each were attached to raft ropes (3 mm thick polypropylene) at regular intervals using a braider. The seeded ropes were tied at both ends of the bamboo rafts at 15-cm intervals. Initial seeding weight of each raft averaged 40 kg fresh wt. and rafts were moored in clusters of 5–10 and anchored to 30-kg mooring stones. Deployed seaweed cuttings began growing immediately and were harvested after a growth period of approximately 45 days (Figure 8A,B; Mantri et al. 2017).

Kappaphycus alvarezii commercial cultivation was initiated in 2001 along the southeast coast of Tamil Nadu by Pepsico India Holdings (P) Ltd., Gurgaon, India after licensing cultivation technology from CSIR-CSMCRI, Bhavnagar. The company successfully adopted a contract-farming model with buy-back arrangements for seaweed produced by the women's Self-help Groups (SHGs). Infrastructure was provided to the SHGs through the national bank subsidies. The contract farming model allocated 45 rafts to each SHG individual member. The amount of distributed rafts was tied to the planting and harvesting 45-day scheduled farming period. Each farmer could conveniently plant and harvest one raft per day. Harvests averaged 240 kg of live seaweed per raft with approximately 40 kg used as raft seeding material for the subsequent farming cycle, leaving 200 kg of fresh biomass or 20 kg of dry seaweed available for sale. More than 1500 households along the Tamil Nadu coast engaged in seaweed farming as an alternative livelihood, each earning approximately US \$300 per month (Table 1).

Seaweed cultivation has emerged as viable option for the economic improvement of low income coastal communities in India (Krishnan and Narayanakumar 2010, Periyasami et al. 2014, 2015, Mantri et al. 2017). Production increased significantly from 21 dry metric tonnes in 2001–1490 dry tonnes in 2013, totaling 7187 dry tonnes biomass, worth US \$2.5 million during the 13-year cultivation period (Mantri et al. 2017). *Kappaphycus alvarezii* commercial farming from Tamil Nadu experienced a

Figure 8: *Kappaphycus alvarezii* cultivation. (A) Raft seeded with *K. alvarezii*; (B) *K. alvarezii* grown on raft.

significant decline in 2013 correlated with a sudden rise in seawater temperature to 36°C and a subsequent onset of bacterial disease. Crop production yields slowly recovered starting in 2016 and increased production is anticipated in the next couple of years. *Kappaphycus alvarezii* commercial production has expanded to six coastal districts in

Tamil Nadu and expansion is underway in Gujarat, where commercial activities commenced in 2017.

Hypnea musciformis

Hypnea musciformis (Wulfen) J.V. Lamouroux is an indigenous carrageenophyte yielding kappa-carrageenan. *Hypnea musciformis* is found in natural beds along the shorelines of several Gulf of Mannar islands. Lagoon waters of Krusadai Island were selected for pilot-scale cultivation of *H. musciformis* utilizing the monoline method (Figure 9; Ganesan et al. 2006). Young actively growing apical portions of *H. musciformis* ranging from 2 to 2.5 g fresh wt. and 5 cm long, were inserted between the braids of 20-m long coir ropes made from coconut husks. The ropes were anchored to wooden stakes and kept afloat with plastic floats. A total of 2000 m of coir ropes were seeded and placed in 10 plots, each consisting of 10 ropes, each 20 m long. *Hypnea* was harvested at 25-day intervals reaching 30–35 cm lengths. Thalli were clipped leaving fragments to grow further. Harvests ranged from 250 to 300 g fresh wt m⁻¹ rope (Ganesan et al. 2006). Fifteen harvests per year yielded a total biomass of 38–40 tonnes fresh wt ha⁻¹ year⁻¹ (Ganesan et al. 2006).

Sarconema filiforme

Sarconema filiforme (Sonder) Kylin is a carrageenophyte containing hybrids of α-carrageenan, iota-carrageenan and pyruvated α-carrageenan (Ganesan et al. 2015a). Currently, industrial utilization of hybrid carrageenans, especially in the food and cosmetic industries, is significantly increasing. Indian waters have two species of *Sarconema* viz. *S. scinaoides* and *S. filiforme*; of these two species, *S. scinaoides* inhabits the intertidal region of India's north west coast (Jha et al. 2009), while *S. filiforme* is sparsely distributed along the southeast and northwest

Table 1: Economics analysis of seaweed cultivation.

S. no.	Expenditure details	<i>Kappaphycus alvarezii</i>	<i>Gracilaria edulis</i>	<i>Gelidiella acerosa</i>	<i>Gracilaria dura</i>
1	Infrastructure cost, farmers contribution with 50% subsidy (in Rs.)	250,000	300,000	300,000	300,000
3	No. of beneficiaries ha ⁻¹	5	5	5	
3	Biomass produced raft ⁻¹ (kg dry · wt)	10	2.5	3.0	2.0
4	Cost of dry weed kg ⁻¹ (Rs.)	40	45.00	120.00	100
5	No. of cycle year ⁻¹	07	07	03	05
4	Value of biomass produced (Rs.)	1,400,000	787,500	1,080,000	1,000,000
5	Net profit person ⁻¹ month ⁻¹ (Rs.)	19,166	8125	13,000	11,660

Figure 9: Monoline method of cultivating *Hypnea musciformis*. (A) Well grown *H. musciformis* on coir rope; (B) a pilot scale farm of *H. musciformis* with 2000-m long coir rope.

coasts (Oza and Zaidi 2001). Pilot-scale cultivation of *S. filiforme* was completed along the Mandapam coast, utilizing the bamboo raft method. Young and actively growing *S. filiforme* (average 0.8 ± 0.25 g fresh wt) were attached to the ropes at 5-cm intervals. Attached to each rope were 25 algal cuttings totaling 20 g, fresh wt rope⁻¹. Each raft, with 20 ropes, totaled 400 g fresh wt equivalent to 160 g fresh wt m⁻² (Ganesan et al. 2015a).

Sarconema reached harvestable size in 25 days and all plants were completely harvested and ropes were freshly stocked with new cuttings after every harvest (Figure 10). 100 rafts were planted with *S. filiforme* and seven harvests were completed each year for 3 consecutive years from

Figure 10: *Sarconema filiforme* cultivation. (A) Seeded lines with fish net; (B) *S. filiforme* ready for harvest.

2011 to 2013. An average of 2.3 kg fresh wt m⁻² was harvested from the initial inocula of 160 g fresh wt m⁻². An average of 150 fresh tonnes ha⁻¹ year⁻¹ of *S. filiforme* could be obtained utilizing this method (Ganesan et al. 2015a).

Culture of agarophytes

Gelidiella acerosa

Gelidiella acerosa is the preferred source of raw material for the production of Indian pharmaceutical and bacteriological grade agar with a gel strength ranging from 850 to 2200 g cm² (Ganesan et al. 2015b). Indian agar processors

produce an average of 100 tonnes of pharmacological grade agar from *G. acerosa*. Unscrupulous harvesting of natural seaweed beds continuously led to gradual reduction of wild standing stocks. The over exploitation of natural *Gelidiella* populations necessitated the development of cultivation methods for farming seaweeds. Initial methods included long-line ropes (Subbaramaiah et al. 1975), single rope floating technique (SRFT; Subbaramaiah and Banumathi 1992), coral stone culture method (Patel et al. 1986), and concrete stone method (Ganesan et al. 2009). These methods resulted in low biomass yields and were difficult to manage in terms of planting, monitoring and harvest practices. Therefore, it became necessary to develop improved methods resulting in higher biomass and easier cultivation operations. The bamboo raft method successfully used for the commercial

cultivation of *Kappaphycus alvarezii* was adopted for *G. acerosa* (Figure 11A; Ganesan et al. 2009) yielding significantly higher harvested biomass than previous methods. The suspended stone method was developed to enhance the bamboo raft method by tying approximately 2 g of seedlings to nylon thread, which was wound around the stones (15–70 cm² area and 100–200 g weight) and hung 5 cm below the polypropylene ropes (3 mm diam). The polypropylene ropes were tied across the bamboo frames of 1.5×1.5 m size. The suspended ropes orientated the algal thalli upwards. Eight inoculated stones were tied to each rope with 10 polypropylene ropes per square raft (2.0×2.0 m). Each raft was seeded with 160 g fresh biomass equivalent to 71 g fresh wt m⁻². Harvesting entailed cutting erect thalli and leaving the basal portions on the stones for further growth (Figure 11B). The stone-modified raft method resulted in three harvests per year yielding 8–15 kg fresh wt raft⁻¹ per harvest (Ganesan et al. 2011).

Figure 11: *Gelidiella acerosa* cultivation. (A) Raft method; (B) suspended stone method.

Gracilaria edulis

Gracilaria edulis, the major raw material source for Indian food-grade agar, exhibits a gel strength of approximately 490 g cm⁻² with 8% alkali treatment (Meena et al. 2008). Although the Indian coastline has 32 species of *Gracilaria* (Krishnamurthy 1971), *G. edulis* is the dominant alga with significant standing stocks. Indian agar industries annually harvest 100–200 dry tonnes of *G. edulis* from wild stocks along the southeast coast of India. Over-harvesting of this resource has led to depletion of wild stocks. Several technologies have been developed for *G. edulis* cultivation. The long-line rope method yielded approximately 20 tonnes dry wt ha⁻¹ y⁻¹ (Raju and Thomas 1971) and increased to 30 tonnes dry wt ha⁻¹ y⁻¹ with the adoption of the Single Raft Floating Technique (Subbaramaiah and Thomas 1995). Both methods experienced significant grazing pressure hindering their commercial scale adoption. Finally, the bamboo raft method was adopted for *G. edulis* cultivation as this method minimized seaweed drifting and herbivore grazing by covering the lower portion of bamboo raft below the planted ropes with fishing net.

In the bamboo raft method, young fragments of *Gracilaria edulis* (average 2.0 ± 0.25 g fresh wt) were tied to polypropylene ropes at 5-cm intervals. Each rope contained 25 seedlings with a total fresh weight of 50 g rope⁻¹. A bamboo raft (2×2 m size) with 20 ropes had an initial seedling biomass of 1.0 kg fresh wt raft⁻¹ (Figure 12A). Seven harvests were completed in a year (Figure 12B) and 35 tonnes dry wt ha⁻¹ y⁻¹ were harvested (Ganesan et al. 2011).

Figure 12: *Gracilaria edulis* cultivation.
(A) Young seedlings on raft; (B) dense growth of *G. edulis* after 45 days.

Gracilaria dura

Gracilaria dura (C. Agardh) J. Agardh attracts significant interest as a source of agarose with a gel strength of 2200 g cm^{-2} , gelling temperature of 30°C and sulfate content of 0.15% (Prasad et al. 2007). The distribution of *G. dura* is restricted to the west coast of India. Several experimental scale cultivation methods were initiated along India's southeast coast including the bottom net, net bag, net pouch and bamboo raft methods (Veeragurunathan et al. 2015). Ultimately, the bamboo raft method resulted in the largest yield. Bamboo rafts ($2 \times 2 \text{ m}$ size), with initial plant density of $1.2 \text{ kg fresh wt raft}^{-1}$, yielded $8 \text{ kg fresh wt raft}^{-1}$ in 45- to 60-day cultivation cycles. Six harvests were achieved in a year (Figure 13A).

Figure 13: *Gracilaria dura* cultivation.
(A) Raft method; (B) tube net method.

Recently, an initial cultivation effort for *G. dura* along the Simar, Gujarat coast, in northwest of India has utilized the tube-net method. The tube-net method's seed material (10 kg fresh) was uniformly loaded in 25-m tube nets made from fishing nets and sealed at both ends with polypropylene rope (Figure 13B), then transplanted in rows to the shallow coastal waters with anchor supports and floats. The daily average growth of *G. dura* ranged from 2 to $3\% \text{ day}^{-1}$ and the yield was $30\text{--}35 \text{ kg fresh biomass}$ in 40–45 days (Mantri, personal communication).

Gracilaria salicornia

Recently, *Gracilaria salicornia* has been commercially harvested from wild stocks as a result of the decline of

Figure 14: Tube net method of cultivating *Gracilaria salicornia*. (A) At seeded stage; (B) at harvest stage.

Gracilaria edulis standing stock. The agar from this alga has a gel strength of approximately $510 \text{ g} \cdot \text{cm}^2$ (Meena et al. 2008). Over-harvesting of *Gr salicornia* depleted the standing stock resulting in its cultivation by adopting the tube-net method. Each single tube net is filled with 400 g of *G. salicornia* seed material. The raft ($2 \times 2 \text{ m}$ size) consists of 15 tube nets totaling an initial biomass of 6.0 kg fresh weight with harvesting every 30–40 days as thalli attain harvestable size. Harvest yields range from 14.1 to 60.62 kg fresh wt raft⁻¹ (Figure 14) with seven harvests each year (Ganesan et al., unpublished).

Gracilaria crassa

Gracilaria crassa Harvey ex J. Agardh is an important agrophyte yielding agar with a gel strength of approximately 800 g cm^{-2} with 8% alkali treatment (Meena et al. 2008). Standing stocks of *G. crassa* are limited to a few locations along the southeast and northwest coasts of India. Recent cultivation efforts included 10 tube-nets inoculated with

Figure 15: *Gracilaria crassa* cultivation. (A) *G. crassa* grown on net; (B) close-up view.

10 kg fresh wt raft⁻¹. A maximum of 30 kg biomass was harvested at the end of a 45-day growing cycle (Figure 15).

Economics of seaweed cultivation

The bamboo raft system is the preferred method for all industrially valuable Indian seaweeds. Advantages include: raft located in sub-surface seawater column providing adequate sunlight exposure; rafts are easily handled and relocated to suitable locations free from epiphytes and grazing; and bottom nets minimize herbivore grazing of algae. Materials for making rafts (e.g. bamboo, anchor stones, polypropylene rope, etc.) are commonly available close to the farm areas. *Kappaphycus alvarezii* raft size is $3 \times 3 \text{ m}$; 500 rafts would occupy 1 hectare. The

raft size typically used for *Gelidiella acerosa*, *Gracilaria edulis* and *Gracilaria dura* cultivation is 2×2 whereby 1000 rafts can fill 1 ha. Table 1 highlights the materials required, biomass harvested and income from cultivation of each seaweed.

Future directions in seaweed culture in India

Indian seaweed cultivation dates back nearly four decades. Cultivation technologies have been developed for several industrially valuable seaweeds over the last 20 years but there are still many challenges to overcome. Challenges include the need for high-temperature-tolerant and fouling- and disease-resistant strains. Most Indian seaweed cultivation is located in near-shore waters, and to overcome inshore challenges an alternative farming strategy including expanding to offshore culture systems is recommended.

Offshore cultivation

Indian near-shore commercial cultivation of *Kappaphycus alvarezii* began in 2005 and the annual production reached a peak of 1490 tonnes in 2013 (Mantri et al. 2017). Nevertheless, the quantity of production is relatively low when compared with Indonesia, who produced 15 million tonnes of seaweeds in 2015 (Buschmann et al. 2017). Indian seaweed cultivation in near-shore areas faces several challenges. Expansion of cultivation grounds is a major constraint due to water use conflicts with fish landing centers and commercial fishing activities. Eutrophication due to human sewage rich in phosphate and nitrate from major municipalities and small towns has negative impacts on seaweed growth. Run-off from land-based agriculture, thermal power plants and chemical factories inundates near-shore waters and contributes to commercial cultivation challenges. Shallow, near-shore seawater temperatures often reach levels that inhibit seaweed growth. These challenges represent contributing reasons to relocate seaweed cultivation operations to offshore sites.

Offshore seaweed cultivation has several potential advantages including: elimination of space limitation as vast ocean areas are available; water use conflicts are minimized due to minimal fishing activities; and offshore waters are clean and transparent as agricultural runoff, sewage and industrialized discharges are minimized due to open ocean dispersion. Offshore algal farming

has potential disadvantages including: maximum wave height of 5–10 m; current velocity of 2–3 knots; and wind speeds of 35 m s⁻¹ all of which can damage and dislodge the farm infrastructure. Offshore farming units must be able to withstand these dynamic conditions. The development of novel, offshore seaweed farms could play a major role in generating sustainable energy from biomass. Use of special textile mats can simplify seaweed farming and substantially increase yields (Sulaiman et al. 2015). A pioneering seaweed farm was developed by a consortium of 11 companies working together in the European At-Sea project. It was successfully tested at three locations (Kassila et al. 2019). A similar initiative for large-scale offshore seaweed cultivation needs to be attempted in India.

Commercial cultivation using spore based methods

Traditional seaweed farming techniques involving vegetative propagation require a large amount of seed stock biomass. An average of 20–30% of harvested material needs to be recycled during seeding procedures. Thallus aging can be a critical challenge in vegetative propagation. Strains can lose vigor after successive generations and productivity can decrease after 2–3 years of continuous cultivation. Epiphyte colonization is another important impediment of vegetative propagation. Epiphyte associations can build after 2–3 harvests because the old plants lose their chemical defenses (He and Yarish 2007).

Alternatively, mass culture utilizing spores requires only a few grams of reproductive material. Geminating spores can generate thousands of plantlets which can be used for mass propagation. Spore-originated thalli have high polymorphism due to their origins from several different genotypes. Such diversity can enable adaptation to changes in environmental conditions. Large scale cultivation from isolated spores has been successfully developed to provide raw material for the phycocolloid industry using the carageenophytes *Kappaphycus alvarezii* (De Paula et al. 1999), *Sarcothalia crispata* (Avila et al. 1999), *Gigartina skottsbergii* (Buschmann et al. 2001), and agarophytes such as *Gracilaria verrucosa* (Oza et al. 1994), *Gracilaria rex* (Ramiro Rojas et al. 1996), *Gracilaria chilensis* (Alveal et al. 1997), *Gracilaria Parvispora* (Glenn et al. 1998) and *Gracilariopsis bailinae* (Rabanal and Azanza 1999).

Indian *Gracilaria* resources are dwindling due to over exploitation of *Gracilaria edulis* and *Gracilaria salicornia* by agar based industries. *Gracilaria* spp. typically have two diploid stages in addition to the gametophyte stage. Tetrasporophytes are similar to male and female gametophytes

while the alternate diploid phase, cystocarps occur on the surface of the female thallus. Cystocarps produce profuse numbers of carpospores that can rapidly recruit, germinate, and grow making them ideal for commercial scale cultivation. Future cultivation of *Gracilaria* spp. could be successful utilizing spore based culture only.

Conventional breeding method for producing vigorous strains of phycocolloid seaweeds

The reduced value of Indian agarophyte seaweeds like *Gracilaria* and *Gelidiella* is due to the low quality agar obtained from these algae. Repeated harvests from natural stocks resulted in the loss of algal vigor. *Kappaphycus alvarezii* farm yields are constantly declining over time. The major challenge facing the Indian phycocolloid industry is to improve phycocolloid quality in order to penetrate international markets. Therefore, cultivation enhancement programs must be implemented for all phycocolloid yielding seaweeds to produce superior varieties with higher growth rates and increased phycocolloid yields. Indonesia's cross breeding of free moving gametes of *Gracilaria* strains resulted in high growth rates and increased cell wall thickness (Ginneken 2018). Development of focused breeding efforts is imperative for the industrially valuable Indian phycocolloid seaweeds.

Macroalgal functional genomics

Higher seaweed values have increased the demand for raw materials but has also highlighted the necessity for functional trait improvements. Unlike for terrestrial crops, acknowledging the need for functional trait improvements in seaweed cultivars is a recent concept. Seaweed genome sequences are essential in order to design strategies for the functional trait improvements. Terrestrial plant functional genomics contributed significantly to crop improvement by understanding their bio-architecture, physiology, regulation and metabolic activations. However, seaweed functional genomics databases are limited despite their proven economic value. Historical perspectives include: (1) the 1940s witnessed continued expansion in the applications of *in vitro* plant cell and tissue culture techniques but these techniques were not adapted for seaweed research and development studies until the early 1990s (Reddy et al. 2008a,b, 2010); and (2) seaweed genome editing techniques were unavailable until a recent report by Oertel et al. (2015) on developing

suitable vectors and stable transformation in *Ulva mutabilis*. The lagging pace of seaweed genomics development can therefore be viewed as one of the bottlenecks retarding the progress of seaweed improvement programs.

Nevertheless, seaweed expression sequence tag (EST) libraries and a few transcriptome profiles have been generated for seaweeds and these facilitate understanding of regulatory mechanisms relevant to various stresses (Dittami et al. 2009, Gravot et al. 2010, Pearson et al. 2010, Dittami et al. 2011, 2012, Heinrich et al. 2012, Coelho et al. 2013). Whole genome sequences are now available for brown algae including: *Ectocarpus siliculosus* (Cock et al. 2010) and *Saccharina japonica* (Ye et al. 2015), and for the red alga *Chondrus crispus* (Collen et al. 2013). Such information could shed light on the novel physiological processes of seaweeds that impact on their propagation in highly dynamic oceanic conditions. Novel metabolic pathway genes of interest from commercial seaweeds include flavonoid pathway genes homologous to those in vascular plants synthesizing phenolic molecules; halide metabolism and the presence of 21 putative dehalogenases and 2 halo alkane dehalogenases; development of multi-cellularity and evolution (Cock et al. 2010); halogen metabolism; oxylipin synthesis; and micro-RNA and transcription factors for the development of multi-cellularity (Collen et al. 2013). Furthermore, understanding the genomic regulation of hydrocolloid synthesis, assembly and transport of cell wall matrices is a promising research sector. Decoding the 'language' of their biosynthesis will eventually help in improving the crop yields and extract qualities. Recently, seaweed genomic research has attracted increased global attention but India's contribution towards understanding seaweed functional genomics is negligible. Decoding seaweed functional genomics should be a research priority of India's Seaweed 2020 program. Seaweed functional genomics must develop more tools to assay the effects of genes, allowing the discovery of gene regulatory network relationships with seaweed-specific, specialized metabolic pathways. Novel metabolic engineering research endeavors may be initiated for the production of targeted specialized seaweed metabolites.

Downstream process for extraction of seaweed products

Conventional phycocolloid seaweed processors, who do not embrace biorefinery process technologies, use only 15–30% of the total dry seaweed biomass while the remaining 70–85% is degraded during the phycocolloid extraction processes or is discarded as waste streams. However, recent studies have reported that the seaweeds are rich in

valuable metabolites, such as natural pigments, proteins, lipids, minerals and cellulose which can be extracted and utilized through biorefinery processing methodologies (Ingle et al. 2011, Baghel et al. 2015, Bikker et al. 2016, Trivedi et al. 2016, Gajaria et al. 2017).

Seaweeds have relatively low lipid contents, but their composition is rich in C18 (linoleic and alpha-linolenic) fatty acids and low in C20 PUFAs (polyunsaturated fatty acids), a combination that has been associated with the prevention of cardiovascular diseases, osteoarthritis and diabetes. The potential of the phycocolloid ulvan as a dietary fiber is supported by reports that the cell wall polysaccharide is not degraded by human gastrointestinal enzymes. This insolubility contributes to the water retention capacity of the ulvan fibers, supporting its use as a bulking agent reducing pathologies related to intestinal transit dysfunctions. Various studies (O'Sullivan et al. 2010, Tabarsa et al. 2012, Alves et al. 2013, Venkatesan et al. 2015) report that ulvan or derived oligosaccharides significantly lowered serum total cholesterol, LDL-cholesterol and reduced triglyceride levels, while they increased the levels of serum HDL-cholesterol. These preliminary results provide evidence supporting the application of ulvan or derived oligosaccharides in functional foods and feed. The gastrointestinal and lipid metabolism benefits of ulvan are in addition to its immunomodulatory, antitumor, strain-specific anti-influenza activities and anticoagulant activities.

Proteins synthesized by macroalgae are known to contain all the essential amino acids (EAA), although seasonal variations in EAA concentrations are reported. *Ulva lactuca* has been found to possess a high protein content comparable to traditional high protein plant sources, justifying its direct use in human or animal nutrition (Fleurence 1999, Bleakley and Hayes 2017).

Cellulose and other polysaccharide fractions extracted from seaweeds can be converted to ethanol, levulinic acid and its derivatives, including ethyl levulinate, which can be used as a fuel additive for both diesel and biodiesel (Jeong et al. 2015, Francavilla et al. 2016, Trivedi et al. 2016). Seaweed biomass has almost no lignin, therefore conversion costs could be lower than those incurred using cellulosic biomass.

Biofuel production from seaweeds

Seaweeds are appealing potential biofuel feedstock candidates for the production of transportation fuel, as they grow rapidly and exhibit high photosynthetic light harvesting efficiency (Hannon et al. 2010). Globally, several countries

including India have reported efficient conversion of macroalgae to biofuels such as bioethanol, biobutanol, biomethane and biohydrogen. Potential Indian seaweed genera for biofuel production in India include *Ulva*, *Kappaphycus*, *Gracilaria*, *Gelidium*, *Sargassum*, etc. (Khambhaty et al. 2012, Kumar et al. 2013, Trivedi et al. 2013, Baghel et al. 2015, Veeramuthu et al. 2017). Red algal genera including *Kappaphycus*, *Gracilaria* and *Gelidium* have been cultivated in India for phycocolloid production. Due to their potential for large-scale farming, these seaweeds have been examined for their biofuel production potential, utilizing their phycocolloid or cellulose content as substrates. Recently, green seaweeds, mainly *Ulva* sp., have also emerged as potential feedstock for biofuel production due to their high carbohydrate content, higher growth rates and lack of direct commercial utilization (Trivedi et al. 2016).

Several research groups in India are actively working on the growth engineering of seaweeds, bio-refinery techniques for extraction of value-added products and photobioreactor design for high biomass production. Biofuel production from residual biomass after extraction of value-added bio-products from seaweeds makes the process economically viable from an industrial perspective.

Seaweeds contain both homo- and hetero-polysaccharides which require special enzymes and microbes to release and ferment hydrolyzed sugars. Metabolic modelling of biomass conversion using serial fermentation is a novel approach to enhance the overall yield of seaweed-based biofuel production. The development of new seaweed varieties with diverse genotypic and phenotypic characteristics utilizing biotechnological techniques is ongoing. Seaweed feedstock development through somatic hybridization and mutagenesis are attractive and available techniques for producing hybrid and mutant seaweed cultivars with useful proximate composition (Charrier et al. 2015, Gupta et al. 2015). Enhanced cultivars would improve seaweed yields for the production of biofuels and platform chemicals.

Opportunities and challenges for establishing successful seaweed industries in India

Opportunities

Bio-fertilizer and bio-stimulants from seaweeds have immense potential in the Indian agriculture sector. Seaweed bio-stimulants increase crop yields and quality,

reduce use of chemical fertilizers and help improve the soil fertility. India imports seaweed bio-stimulants made from *Ascophyllum*, *Macrocystis* and *Kappaphycus* worth US \$25–30 million annually from Canada, Norway, Indonesia, Philippines and China. There are opportunities to promote indigenous seaweed-based technology for the production of bio-stimulants. *Sargassum* spp. *Kappaphycus alvarezii* and *Gracilaria* spp. are excellent sources of bio-stimulants (Rathore et al. 2008, Zodape et al. 2008, 2009, 2010). Promoting indigenous seaweeds for bio-stimulants will reduce the fertilizer subsidy burden of the Indian exchequer.

Seaweeds have the potential to be used in a broad spectrum of products such as: food, biofuels, chemicals, cosmetics, medicines, etc. The National Bio-fuel Policy of India (2018) targeted 20% blending of biofuels by 2030. It is estimated that, if 460 million tons of fresh seaweed biomass per year could be harvested from a 10 million hectare area (corresponding to about 5% of total EEZ of India), it could generate 6.66 billion liters of bioethanol, which would meet the targeted petrol blending by 2030 in India. Industrial production of biofuel from seaweeds needs to be given top priority.

India's traditional food practices are different from other Asian seaweed consuming nations. Although 30% of the Indian population lives close to the sea, people are not accustomed to eating seaweed. Formulation of a wide variety of recipes by food technology institutes for adaptation to Indian palates and popularization through social media are needed for promoting seaweed-based foods in India. International collaboration for processing and preparation of seaweed-based foods should be established with the Southeast Asian countries where consumption of seaweed food is popular.

Seaweeds have tremendous business potential for generating revenue and jobs in bioactive and cosmetic sectors as they possess anti-ageing, anti-oxidant and moisturizing properties (Bedoux et al. 2014). However, such applications are not yet developed at the industrial level in India and so an initiative to do so needs to be given priority. Seaweeds with high pharmaceutical and cosmetic applications need to be identified and cultivated at large scale through industrial collaborations. Identifying suitable cultivable and scalable seaweed strains for pharmaceutical and cosmetic applications should be undertaken by an industrial public sector collaboration.

Challenges

Several cultivation technologies have been developed through significant Indian research and development

efforts, and commercial seaweed farming is being carried out using floating rafts (Mantri et al. 2017) along the southeast coast of India. Such structures are suitable for near-shore waters where low tidal amplitude and minimal tidal influences persist. However, a major portion of the Indian coastline is exposed to the open sea and has high tidal amplitudes. Recently, CSIR-CSMCRI has successfully developed tube net method for *Kappaphycus alvarezii* and *Gracilaria dura* cultivation on the Gujarat coast. Tube-net systems withstand rough sea conditions while producing good biomass yields. Several other culture systems which can withstand high water dynamics in open water areas needs to be developed through vigorous R & D efforts.

Seasonal dependency on Indian seaweed culture represents a crucial challenge needing to be overcome. Monsoonal (Southwest and Northeast monsoon) periods in India are associated with occasional occurrence of cyclones and typhoons and create high seawater turbulence and high tidal fluctuations. Cultivation during this period is restricted to seed bank preservation.

Land-based cultivation in intensively operated ponds has been done successfully for several species of *Gracilaria* (Friedlander and Levy 1995), *Gelidium* (Friedlander 2008) and *Chondrus crispus* (Bidwell et al. 1985). In India, seaweeds are mainly used for extracting phycocolloids and the high cost of pond-produced seaweeds may not be profitable unless the harvested seaweeds are processed for multiple products e.g. biofuel, bio-stimulants, food, cosmetics and pharmaceuticals. Seaweed growers are receiving minimal prices for their harvested seaweeds due to their sale to cottage-level industries for indigenous phycocolloid extraction. Export of dry seaweeds has been banned for several decades. If the ban is lifted and export of dry seaweeds is permitted, farmers will realize higher prices for their seaweeds. Other challenges in seaweed farming affecting crop productivity and quality are crop health issues such as high temperature impacts, diseases, epibionts and grazing pressures which rely on R&D efforts to reduce or eliminate.

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