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Review

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Challenges for marine macroalgal biomass production in Indian coastal waters

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Abstract: Due to its large, exclusive economic zone, India has considerable potential for implementing large-scale cultivation of macroalgae. However, such cultivation requires the availability of, and access to, sites where technical, legal, governmental, and environmental factors are favorable. This review discusses the challenges that have held back the development of seaweed cultivation in India. The review is based on a literature survey and informal discussions with industry-related personnel. It cites the strong need for clear and definitive policies related to access to and use of coastal waters to enable the Indian seaweed industry to reach its full potential. The main challenges that the expansion of macroalgal cultivation in India face are related to legal and regulatory aspects that can be resolved by focusing the policy issues on providing planning tools toward success. In addition, there is a strong need for an adequate bioeconomy that clearly defines the need for marine macroalgal biomass for food, chemicals, and biofuels. Furthermore, the Indian government needs to allocate sufficient funds for accelerating seaweed R&D in areas of seaweed cultivation, harvesting, processing technologies, and their implementation in the local industry.

Keywords: Biodiversity Act; bioeconomy; macroalgal cultivation; marine biorefinery; marine policy.

Introduction

Indian economic development is associated not only with improvement in quality of life and longevity, but also addresses various environmental and social problems, including rapid urbanization coupled with an ever-increasing demand for food, materials, and energy (Ingle et al. 2011). To meet India's increasing resource needs while reducing the use of fossil fuels, efforts are focused on finding renewable, domestic resources of feedstock for conversion to food, biodegradable materials, biostimulants, and biofuels. For example, the Indian biofuel policy, as set forth in the Indian Government National Policy on Biofuels published in 2018, encourages the production, application, and blending of biofuels to substitute petroleum fuel for transport, and also urges foreign and joint venture investments (NMRE 2018) in bio-based products/fuels technologies and projects.

Biorefinery, the sequential production of fuel, food, and chemicals from biomass (Star-coliBRi 2011), is an emerging platform for the co-production of renewable materials and biofuels (Hannon et al. 2010). As the need for biodegradable materials and biofuels will increase in upcoming years, the choice of raw biomass feedstock for biorefinery will become critical to meet demand and to ensure efficient production without threatening the environment.

One potential candidate for biorefinery feedstock is marine macroalgae (seaweed), produced in marine farms. A combination of several unique features renders seaweed as an appealing feedstock for biorefinery. Firstly, macroalgae have high polysaccharide content (Hughes et al. 2012), high growth rates, and high biological productivity (Kraan 2013); and do not compete with terrestrial agriculture over arable land and potable water (Potts et al. 2011). Therefore, in recent years, macroalgae have attracted attention for the production of materials and biofuels, such as ethanol, butanol, and methane (Nikolaisen et al. 2008). Moreover, seaweed can be used to produce additional products such as liquid biofertilizer, biostimulants, proteins, animal feed, starch, and lipids, thus maximizing the co-benefits of the biomass (Ingle et al. 2018). The wide variety of seaweed-based products, especially biostimulants, presents an enormous opportunity to India, as the majority of its population depends, directly or indirectly, on agriculture. Figure 1 (Lehahn et al. 2016) demonstrates

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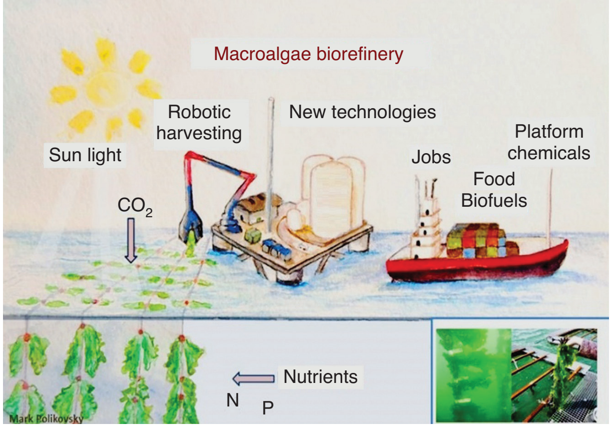

Figure 1: Illustration of an offshore biorefinery for the production of food, platform chemicals, and biofuels.
The inset on the right shows an example off-shore cultivation of macroalgae from the *Ulva* genus (image adapted with permission of-Lehahn et al. 2016, painting by M. Polikovsky).

the concept of offshore biorefineries for the production of food, platform chemicals, and biofuels.

However, macroalgal biorefineries require more research and technology development before large-scale cultivation, harvesting, and processing can be realized. Multiple challenges, from species choice and controlled methods for cultivation and harvesting (Golberg and Liberzon 2015), to the need for technically viable and efficient means to maximize biomass yields, to the establishment of cost-effective production streams suitable to current global markets, have yet to be tackled (Chanakya et al. 2012, Balina et al. 2017). Some fundamental aspects of seaweed cultivation in India, such as cultivating *Kappaphycus alvarezii* (Doty), have emerged, such as that seaweed biomass conversion processes vary with the nature, type, and sources of algal biomass and end-use (Chanakya et al. 2012).

Anaerobic digestion, fermentation, transesterification, and pyrolysis can convert algal biomass into proteins and sugars that can result in food, chemicals, and biofuels. However, at each stage of the production process, a choice emerges between various options that ultimately affects costs, output, and the total profitability (Golberg et al. 2019).

For example, Jiang et al. (2016) discussed the technical aspects and potential of ethanol production from various marine macroalgae. However, the full potential of ethanol production cannot be realized due to the inability of industrial microbes to metabolize other components in macroalgae (Wargacki et al. 2012). Nevertheless, it has been found that all major sugars present in brown macroalgae can be converted to value-added renewable chemicals and biofuels using alginate monomer (4-deoxy-L-erythro-5-hexoseulose uronate, or DEHU) (Enquist-Newman et al. 2014) in the process. Although the bacterium *Escherichia coli* naturally ferments glucose, and mannitol to some extent, Campus et al. (2016) reported that the utilization pathways of heterologous alginate and native mannitol in *E. coli*- BAL161117 are undesirable due to redox balance-related mechanisms (a combination of mannitol operon self-repression, and catabolite repression/activation). Therefore, one of the challenges for bioethanol and biogas production is to find or develop microorganisms that can efficiently convert all types of sugars into biofuels, while maintaining tolerance to inhibitory compounds formed during the process (Suutari et al. 2015). An additional approach could be the development of multi-step fermentation wherein several microorganisms with complementary monosaccharide metabolism are used to convert the seaweed biomass into ethanol (Golberg et al. 2014, Vitkin et al. 2015).

The current commercial farming of seaweed in India emerged from a strain of *Kappaphycus alvarezii* (Doty) from the Philippines that was obtained by Central Salt and Marine Chemical Research Institute (CSMCRI) in 1984 (Mantri et al. 2017). After initial outdoor culture with outplanting experiments at Port Okha, Gujarat state during 1989–1996, subsequent experimental field trials were carried out at Mandapam, Tamil Nadu state from 1995 to 1997 (Eswaran et al. 2002). In 2000, PepsiCo India Holdings, Ltd. sponsored a CSMCRI project to farm *Hypnea musciformis* (Wulfen) in the Gulf of Mannar as its subsidiary, M/s. Pepsi Foods, Ltd. showed interest in carrageenophytes. The success in this venture in the initial stage supported the exploration of farming *K. alvarezii* (Doty) at the hectare scale. PepsiCo India Holdings, Ltd. initiated seaweed farming on a large scale along Mandapam coast, Tamil Nadu state, once the cultivation technology was transferred to the company in 2001. Thereafter, PepsiCo Holdings India, Ltd. transferred the agribusiness rights to M/s. Aquagri Processing Pvt., Ltd in 2008, and successful commercial cultivation of seaweeds began in India.

Mantri et al. (2017) recently analyzed the overall development of the Indian seaweed sector. While currently focused on *Kappaphycus*, many other seaweed species are now also being cultivated for the production of carrageenans, bacteriological grade agar, food-grade agar, and agarose (Veeragurunathan et al. 2016, Mantri et al. 2019). However, India still imports seaweed products to fulfill local demand, even though there is 600,000 tonnes fresh weight of seaweed on standby (Mantri et al. 2017).

In this review, the term “large-scale” macroalgal cultivation refers to cultivation (of one or more macroalgal species) on a wide marine area to fulfill the demands of a local biorefinery. Golberg et al. (2014) presented a model of macroalgae-based biorefinery for rural development in India, which allows calculating the cultivation area required to fulfill local transportation fuel demand. According to the model, a total area of 45 ha of ponds are needed to supply 100% of the transportation fuel required for an average town in rural India via farming of *Ulva* (15,000–25,000 inhabitants, 20 l of gasoline per capita per year, ~627,000 l year^{-1} bioethanol production capacity). Biorefineries of this capacity are already available today on the market. However, models that combine agriculture, downstream processing (technologies, process engineering), policy, and field implementation models (training personnel, initial pilot facilities) are required to provide planning tools and reduce barriers to local communities interested in using sustainable energy sources. The combined models require a deep understanding of the local political, social, and technological environment.

Mantri et al. (2017) and Seth and Shanmugam (2016) discussed the status of *Kappaphycus* farming and sustainable seaweed farming with economic profits for rural coastal inhabitants in India. The expansion of seaweed farming can be a suitable option for creating employment for the increasing population of India, thereby reducing migration from rural areas to cities. Large-scale cultivation in open Indian coastal waters can open the door to further socio-economic development of rural and coastal Indians and boost rural development (Jiang et al. 2016). Considering the growth potential and expansion of Indian seaweed farming, it has a significant potential to fulfill the demand for transportation biofuels (Ingle et al. 2018).

The implementation of a macroalgal biorefinery model for coastal towns for the conversion of polysaccharides into ethanol, with the extraction of phycocolloids such as agars, alginates, and carrageenans, can increase its profitability (Bruton et al. 2009). The co-production of multiple products from the same biomass can lead to near-total use of the raw material with minimal waste and maximum valorization (Golberg et al. 2019). Together with increasing the customer awareness of bio-based products and subsequent demand, local algal biorefineries (i.e. those that are distributed and significantly smaller than existing refineries) would benefit not only the stakeholders but also the community, including the local agriculture sector (Ingle et al. 2018). However, the expansion of seaweed cultivation in Indian coastal waters is a complex task due to various technological and legal challenges.

As the primary focus of Indian seaweed research is on the production of phycocolloids and other value-added products, only a few articles have addressed the feasibility of expansion of the current cultivation of *Kappaphycus* and other seaweed species for other purposes such as biofuel production. Furthermore, although few studies have been conducted on the technical and environmental facets of seaweed cultivation, such as ecosystem services, there are limited knowledge resources for large-scale cultivation possibilities for biofuel. Few studies have described the social and economic benefits of seaweed farming (Baghel et al. 2015), mass production of germlings at the nursery level (Gupta et al. 2018), or technical and economic feasibility (Ganesan et al. 2017) of large-scale macroalgal cultivation for India. Suganya et al. (2016) discussed the biorefinery approach and mentioned that economic feasibility is the major hindrance to the development of algal biorefineries.

One of the main problems of the agar industry in India, which depends entirely upon seaweed biomass, is the poor quality of the raw material (Kaladharan and Kaliaperumal 1999). Krishnana and Narayana Kumar (2010) also highlight the socio-economic dimensions of seaweed farming in India. They found that several factors, including location disadvantages and lack of supporting policies, are the significant challenges faced by seaweed farming. Mantri et al. (2019) discussed India's agarophyte trade and the need for policy interventions to ensure India's self-reliance on agarophyte production, availability, management, extraction methods, and agar characterization. They highlighted current issues and also made recommendations such as mapping the agarophytes, international collaborations, adopting new technologies, crop insurance, pilot-scale farming, fixing minimum assured price, ensuring regular income, integrating farming and processing, and export licensing. There is a need to study the successful expansion of large-scale cultivation of seaweed in Indian seawaters for biorefinery and to look to other countries where it has been successful (as the Western Indian Ocean and in the Philippines). In Indonesia, for example, the current focus is on the national processing of seaweeds instead of on exporting raw material by making technical partnerships with many Japanese corporate companies and trading houses (FAO 2018).

The objective of this review is to address and survey possible challenges for site selection during the expansion of large-scale seaweed cultivation, including legal, political, social, and environmental aspects. However, it is essential to note that, while the study focuses on large-scale cultivation, the information is based on macroalgal cultivation in a small part of the Indian coast. A caveat is that we assume that these aspects also apply to scaled-up models.

Spatial and regulatory challenges for large-scale cultivation in Indian waters

India has a very long coastline measuring 8118 km (MSSRF 2014), with an Exclusive Economic Zone (EEZ) of 2.37 million km^2, including its three sides, which can be an ideal locale for macroalgal cultivation. Geographically, the Indian coast can be divided into mainland and island areas; and western and eastern regions, as shown in Figure 2. The islands increase India's EEZ, which comprises roughly 60% of India's total land area. Although India has a large EEZ, and most of the coastline has an open sea, it is a challenge to find favorable sites for large-scale macroalgal cultivation. Furthermore, current methods for seaweed cultivation, such as raft and monoline used, for example, in Tamil Nadu state, are not viable. Alongside this, various aspects and hurdles need to be addressed to allow site selection for the expansion of seaweed cultivation in India, including the development of technology (viable farming techniques, efficient seeding and harvesting, and new ways of processing), economic feasibility, socio-economic inclination, environmental sustainability, and supporting policies and regulations by the state. For example, new methods for cultivation, such as tube net technique (Reis et al. 2015), could be useful for the next-step in large-scale cultivation of *Kappaphycus*.

Large-scale macroalgal cultivation requires a long, uniform coastline, not only geographically but also in the regulatory sense. However, these regulations should also protect the ecosystem and ensure that cultivation, harvesting, and processing can occur alongside environmental sustainability. These goals can limit the suitable areas for seaweed cultivation and the variety of seaweed species that can be available for use. For example, after the 1992 Rio de Janeiro environmental summit, India became a signatory to the Convention on Biological Diversity (CBD). Protection of biodiversity became obligatory for the Indian government via law and regulation (Venkataraman 2009). In 2002, the Indian government enacted a law called the Biodiversity Act to save Indian biodiversity. The National Biodiversity Authority (NBA), established in 2003, was assigned responsibility for its implementation. According to the NBA, India's marine areas, including its coastline, which was recognized as ecologically sensitive, were declared marine protected areas, such as national parks and sanctuaries. Currently, there are one marine

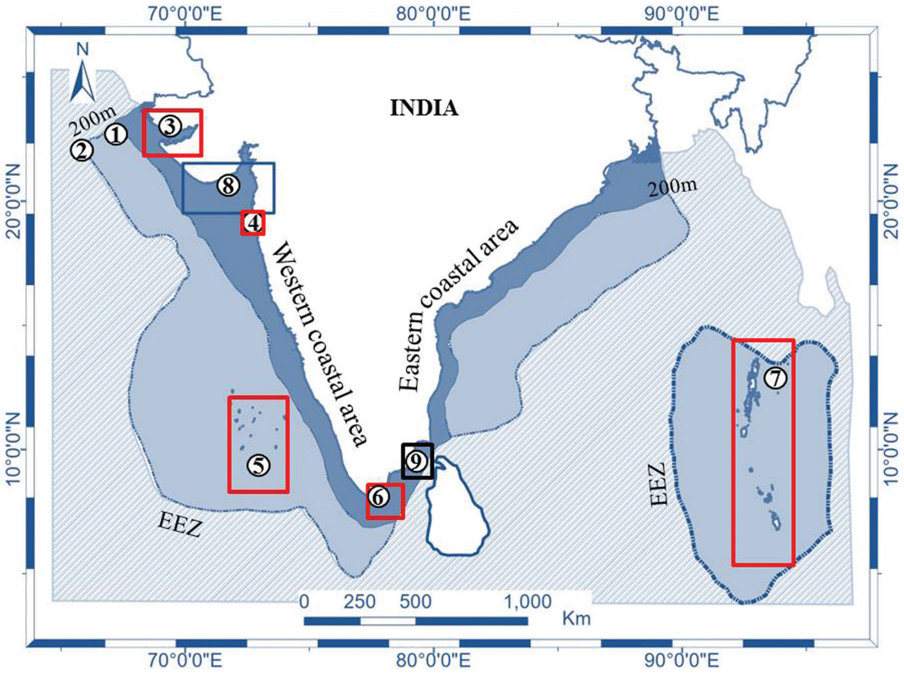

Figure 2: Indian territorial waters (red boxes tentatively denote the presence of coral reef areas; black boxes denote preferable areas for commercial cultivation. Image adapted and modified with permission of MSSRF (2014).
1. Continental shelf line along the mainland India coast. 2. Exclusive Economic Zone (EEZ) line along the mainland and Islands India. 3. Gujarat state coral reef areas. 4. Malvan Konkan areas of coral reefs. 5. Western Island coastal areas (Lakshadweep). 6. Palk Bay and Gulf of Mannar coral reef areas. 7. Eastern Island coastal areas (Andaman and Nicobar). 8. Proposed offshore windfarm nearby Gujarat state-preferable for seaweed cultivation. 9. Proposed offshore windfarm nearby Tamil Nadu state-preferable for seaweed cultivation.

sanctuary and four marine national parks in India. These areas are recognized as Coastal Regulation Zone (CRZ) Category 1, according to the 1991 CRZ notification classification system (Singh 2003). The NBA takes initiatives to protect the biodiversity and oppose applications for intellectual property rights from other countries on any biological resource or knowledge associated with funds obtained from India (Venkataraman 2009).

An example of successful aquaculture with many social and economic benefits is Indian seaweed cultivation for carrageenan, based on *Kappaphycus alvarezii* (Doty), whose cultivation began by acquiring a strain of Philippine origin *Kappaphycus* from Japan. The experimental work of outdoor cultivation, out-planting, and field trials was carried out for more than a decade until the year 2000. Farming began in 2001 by PepsiCo India Holdings, Ltd. under its corporate social responsibility program, on the Mandapam coast of the southern part of Tamil Nadu state. From 2008, M/s. Aquagri Processing Pvt., Ltd. took over the farming rights and began the processing of the biomass (Mantri et al. 2017). Although the growth of the Indian seaweed industry from *K. alvarezii* is admirable (25 t dry weight ha^{-1} $year^{-1}$ by net bag method, 40 t ha^{-1} $year^{-1}$ by raft method, and 45 t ha^{-1} $year^{-1}$ by open culture method in eight harvests; Subba Rao and Mantri 2006), for biorefinery purposes there is a need for expansion to large-scale cultivation in all possible areas (Ingle et al. 2018).

However, it has also been claimed that *Kappaphycus* is not a species native to India (Loureiro et al. 2015) and has invaded coral reefs in the marine protected area in the southern part of the Gulf Mannar marine national park (Chandrasekaran et al. 2008). The use of non-native seaweed species in large-scale cultivation can harm the Indian ecosystem. For example, approximately 227 species and 12 families of coral reef are reported to inhabit the Indian Ocean (Venkataraman 2011). Seaweed could generate competition with coral reefs, as seaweed is known to reduce coral growth rate, reproduction, and survival (Hughes et al. 2007). Moreover, some seaweeds can produce allelochemicals against corals (Paul et al. 2011).

Even if cultivated macroalgal species do not show allelopathic effects on corals (since they are cultivated away from the corals), macroalgae more generally can show adverse effects on them (Longo and Hay 2015) due to overgrowth, shading, and by vectoring coral pathogens, predators, etc. (Rasher and Hay 2014). Therefore, large-scale macroalgal cultivation could theoretically damage India's coral ecosystem so that currently, commercial cultivation is engaged far away from sensitive regions reserved for corals. These restrictions should be retained for both native and non-native algal species until the effects of seaweed aquaculture can be examined as a part of a proof of concept in different locales. In addition, a decision to use non-native seaweed species should be made only after careful examination of their environmental impact, even though it might limit the areas and variety of seaweed species suitable for commercial cultivation.

Techno-economic considerations for Indian biorefinery locations

To determine the adequate location, size, and capacity of large-scale cultivation on the Indian coastline, a range of economic, regulatory, political, sustainability, and technical factors must be considered. From the techno-economic point of view, our previous studies derived the equations for the optimum size, capacity, and efficiency of a single biorefinery (Golberg et al. 2014). The calculations have shown that under fixed photosynthetic efficiency, and current biomass-to-product conversion efficiency when no energy is invested in cultivation, the economic efficiency of a single biorefinery is limited by the size of the cultivation site and the distance the products travel from the cultivation site to the processing facilities (Lehahn et al. 2016). Furthermore, previous analysis on the potential of marine biorefineries to provide biomass, protein, and biofuels using an integration of climatological oceanographic data with metabolism and growth rate model (Lehahn et al. 2016), demonstrated that the maximum economic distance depends on the energy density of all products produced by the marine biorefinery and the energy invested in transportation of the feedstock, first to shore and then to a storage and/or a processing plant (Lehahn et al. 2016).

Reducing the fuel demand for transport will improve the footprint of macroalgal production. The analysis results showed a connection between the transportation distance and dried weight (DW) content of the algae, wherein a decrease in the moisture content of the algae will increase the distance of the offshore cultivation site from the processing facility. It is possible to establish a few facilities for dehydration or sun drying in that environment. If biomass dehydration is performed on-site, the energy consumption thereof will have to be added to the energy efficiency calculations. Also, major processing plants and biorefineries can be in the nearby area of the coastal region, to further increase the distance of the cultivation site from the shore. On the contrary, in the case of export, process industries will likely need to pay a fee to the government. For the overall process to be economically efficient, design of the adequate location, size of the biorefinery, and the specific technology used for transportation will have to consider the algal species farmed, including their moisture content, the value of products and the available techniques for dehydration and processing.

Environmental considerations for Indian cultivation locations

Other factors that influence the location of large-scale seaweed cultivation are the climate and the weather. Algae are sensitive to their growth conditions, including light intensity, turbidity, water temperature, nutrient concentrations, pH, and salinity. The unique seasonal pattern, variations, and natural disasters (high tides, hailstorms, cyclones, and tsunami) of the Indian subcontinent can quickly impact seaweed cultivation, through various changes in the quantity and quality of the water near the cultivation area. Furthermore, floods during the rainy season may cause pollution and contamination of the seaweed. Frequent storms and sedimentation, for example, are hurdles for commercial cultivation of seaweeds, particularly for agarophyte production (Ganesan et al. 2017). Several seaweeds in Indian waters are cultivated for phycocolloid production, such as agar-agar, alginate, and carrageenan. For instance, *Gelidium* can be used for bacteriological-grade agar production, while *Gracilaria* is utilized for food-grade agar production (Meena et al. 2008).

After the agar extraction, the residual pulps from certain agarophytes were found to contain cellulose that can be utilized for further bioethanol production (Kumar et al. 2013). However, environmental changes challenge the possibility of obtaining large quantities of this byproduct. Comparison between India's coastal regions shows that the southeast part of the country is ideal for large-scale seaweed farms, both technically and economically. Its geography comprising a flat, wide, shallow intertidal region with moderate wave action and nutrient-rich seawater with optimum temperature and salinity renders it feasible for large-scale cultivation (Ganesan et al. 2017). Avoiding the areas where coral reefs are protected as per law, the remainder will be available for cultivation if no other obstacles emerge, as shown in Figure 2.

While seaweed can be cultivated in offshore and nearshore environments (Subba Rao and Mantri 2006, Sudhakar et al. 2018, Chemodanov et al. 2019), the term "offshore" is not clear; it generally suggests a substantial distance away from the coast (Buck et al. 2018). If aquaculture is engaged within territorial waters, it can be described as *"coastal" aquaculture*, and beyond that, it is *"offshore" aquaculture*. If it occurs in the EEZ, then it is described as *"EEZ" aquaculture*. Buck et al. (2018) defined offshore aquaculture as the transfer of farm installations or the establishment of new aquaculture enterprises from a sheltered environment to a more exposed location, as well as in exposed sites. Large parts of the shallow intertidal water around the Indian coastline are therefore potential areas for cultivation.

Many other areas along the shore are not acceptable for seaweed cultivation due to productive fishing. However, the fish catch in other areas of India's east coast is meager and no longer economical, and these areas could be repurposed into seaweed cultivation (Chanakya et al. 2012). Offshore cultivation has the potential to expand the area under cultivation significantly. However, the primary issue surrounding seaweed cultivation in the deep-sea environment is the high cost due to the engineering challenges of operating in the deep sea (Milledge and Harvey 2016). The design of cultivation structures that enable seaweed survival in rough ocean conditions is required (Milledge and Harvey 2016).

Further challenges are associated with species selection. A seaweed feedstock for biofuel and food production should have the following characteristics: (a) a simple reproductive cycle that allows seedling production (as there are no species being used for spore-based farming in India yet); (b) a high growth rate; (c) be easily harvested; (d) a low ash, sulfur, and nitrogen content; (e) a low moisture content (after drying); (f) a high caloric value; (g) be resistant to bacteria, fungi, epiphytes, and grazers (Milledge and Harvey 2016); (h) a high biomass yield; and (i) a high market demand. In nature, seaweed can serve as a producer of food and shelter for various animals and microorganisms. Therefore, cultivated algae are exposed to grazers and epiphytism by other algae. These grazers can be several types of invertebrates, such as small crustacea, fish, turtles, and birds. Ingle et al. (2018) discussed many pests possible in seaweed aquaculture. In India, smaller herbivrous fish, such as rabbitfish, are one of the main seaweed grazers, particularly of *Kappaphycus alvarezii* (Doty), and cause massive economic loss. Sensible location and species selection should minimize these threats. Further R&D for strain improvement and pest and predator control are required to achieve good stocks of potential seaweed adapted to Indian situations.

For successful seaweed cultivation, quality and straightforward germplasm for seeding should be available. Diseases and predators can also attack these juvenile macroalgal seeds. Therefore, sterilization of incoming water and control of environmental factors should be achieved. Also, for "pure culture" and minimization of procedures and epiphytes, seaweed needs to be decontaminated before juvenile production (Milledge and Harvey 2016). Redmond et al. (2014) produced an extensive description of how to establish a seaweed culture laboratory together with a culture system "roadmap" for the production of young seed plants (Milledge and Harvey 2016).

Successful cultivation of commercially important seaweeds such as *Laminaria/Saccharina* and *Porphyra/Pyropia* in Asia was only possible once life cycles were understood and incorporated into the production of "seed" in nursery operations (Roesijadi et al. 2010). However, the sporophyte method performed in China was seasonal, time-consuming, and represented a significant cost component of the overall production (Milledge and Harvey 2016). Kraan (2013) concluded that juvenile sporophyte production is a bottleneck in establishing large-scale seaweed cultivation. In sexual propagation, seaweed gametophyte cloning techniques have been developed for particular seaweeds (*Gracilaria* and *Eucheuma*), which may enable crop improvement and possible sporophyte stockpiling for cultivation (Kumar et al. 2007, Zhang et al. 2008, Redmond et al. 2014). Further R&D and field testing of the cloned seaweed under a variety of field conditions is required. For example, the gametophyte stage in kelp, which represents the sexual phase, can be controlled by various environmental variables such as sunlight, photoperiod, water temperature, and availability of nutrients (Redmond et al. 2014). These gametophytes mature under favorable environmental conditions and produce a reproductive phase. In the lab, under controlled conditions, the zygotes can be developed into juvenile diploid sporophyte blades, which have further use.

The development of a new biorefinery, its design, and construction requires significant investment. Furthermore, research and development are needed on technology for algal cultivation, harvesting, and processing before large-scale seaweed cultivation can be realized. However, the socio-economic development of rural areas, the benefits for the environment, and the reduction of the dependency upon imported crude petroleum should be the driving forces. Acceptance of seaweed farming enterprises and policies of state governments as well as the central government are vital for securing long-term investments and further research and development.

Large-scale seaweed cultivation is carried out in the Western Indian Ocean (WIO) (Tanzania, Madagascar, Mozambique, Mauritius, and Kenya) and in the Philippines (Borines et al. 2011). This successful seaweed cultivation, official policies, and ways of coping with problems can set an example and a model for the Indian government and policymakers. Borines et al. (2011) discussed in depth the current seaweed cultivation and production in the Philippines, where about 365 species of marine benthic seaweeds are documented as commercially important, and few among those are farmed, the most common being food-grade red seaweed. Almost 90% of seaweed production in the Philippines is farmed, while the remaining 10% is wild-harvested (Borines et al. 2011). Coastal farming systems commonly occur in shallow habitats (<500 m depth), which enable a sheltered growth environment, while offshore systems are an emerging macroalgal culture technology with water depths of between 500 m and 3000 m. The commercial production of macroalgae from both wild-harvest stocks or through farming is regulated by the Philippines Fisheries Administrative Order (Pellinggon and Tito 2009), which provides for the conservation of the natural macroalgal beds, in addition to promoting sound management of farming areas.

Msuya et al. (2014) discussed the current cultivation and production of seaweed in the WIO, where mostly three main red seaweed species, *Eucheuma denticulatum* (N.L. Burman), *Kappaphycus alvarezii* (Doty), and *Kappaphycus striatum* (Schmitz) are cultivated. Among these countries, Tanzania is the dominant red seaweed producer, producing up to 15,088 t (DW) year^{-1} (Department of Marine Resources and Zanzibar 2012). WIO-produced seaweed is exported mainly to France, Denmark, the USA, Spain, Chile, and China. *Kappaphycus* farming in the WIO is more lucrative than that of *Eucheuma*, due to the value of *kappa*-carrageenan (Msuya et al. 2014).

Both the WIO countries and the Philippines have demonstrated several ways of coping with cultivation and processing challenges over the years that will be relevant to the emerging Indian industry, including (1) renewed efforts and private investment in cultivation areas (Msuya et al. 2014); (2) moving seaweed farms to deeper water by using new cultivation techniques; (3) conversion of fishing regions to seaweed farms (Borines et al. 2011); (4) training of research assistants in Tanzania and Zanzibar and that of scientists and anglers; and (5) conducting cultivation trials of new species (Msuya et al. 2014).

The framework for large-scale macroalgal cultivation for biorefinery

Although India has a long coastline with an exclusive economic zone, which can be ideal for macroalgal aquaculture, legal aspects divide the country and make large-scale cultivation difficult. For regulatory clearance, several questions are raised, particularly on environmental concerns. Here we present our view of the framework in four steps (as shown in Figure 3): (1) Legal support and encouragement; (2) Legislation and licensing; (3) Site selection and environmental aspects; and, (4) Market-orientation view.

Step 1: governmental support and encouragement

Although seaweed farming is encouraged in India, local policies differ for the agricultural and industrial sectors. India is an agricultural country, where farmers, specifically small landholders, are strongly affected by climate and environmental factors and are therefore entitled to subsidies and other governmental benefits. For the macroalgal sector, however, there is no clear policy or employment model stating whether the fields are considered industry or agriculture. The Indian government identifies seaweed cultivation as a priority area. Legal support is generally based on financial assistance and professional training through various agencies such as the National Fisheries Development Board and the State Bank of India in collaboration with the Aquaculture Foundation of India, an NGO based in Chennai, Tamil Nadu (Mantri et al. 2017).

Furthermore, there are no available guidelines at the national level for the encouragement of research, business, or institutional development in the seaweed field as there are in other seaweed farming countries such as the Philippines or Indonesia (Mantri et al. 2017). The National Academy of Agricultural Sciences (NAAS) issued a strategy document pertaining to the commercial farming and processing of seaweed to encourage the sector. Following the Bureau of Aquatic and Fisheries Resources in the Philippines and Indonesia, this strategy recommends establishing a particular unit of the Agriculture Ministry responsible for the implementation of large-scale commercial cultivation programs and establishing the connections between ministries relevant to this sector.

Although the Indian government generally encourages biofuel and bio-based product manufacture and research thereon, it still focuses on products other than seaweed feedstock. In India, bioethanol is mainly produced from molasses as one of the byproducts of the sugar industry. Hence the production of ethanol depends upon

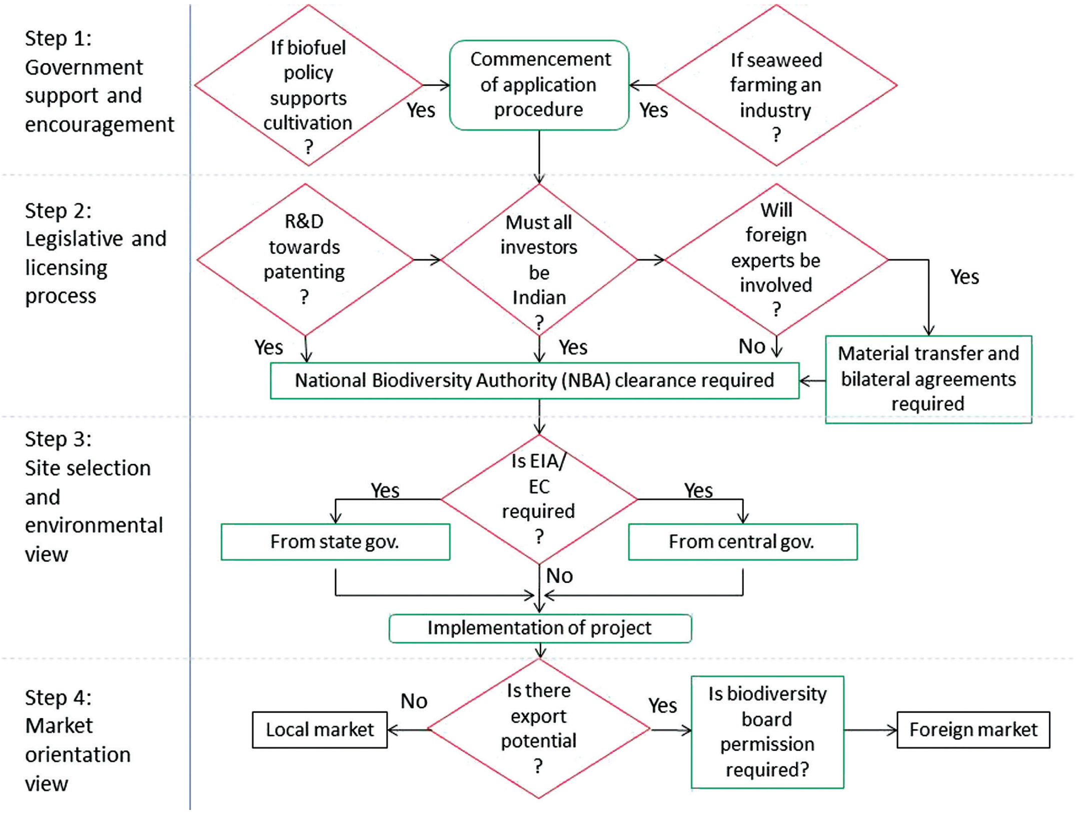

Figure 3: A legal and legislative framework for large-scale cultivation of macroalgae.

the sugar industry's structure, policies, and management paths. Blending bioethanol in petrol for transportation is already mandatory since 2008 (Bandyopadhyay 2015). Also, although the biofuel blending target for both bioethanol and biodiesel was 20% by 2017, the government encountered various difficulties in implementation. Furthermore, although the sugar industry has a permit to produce ethanol directly from sugarcane juice, there is still a shortage in bioethanol for transportation due to high demand from the paint and beverage industries.

Indian biofuel policy states that biofuels are liquid or gaseous fuels produced from biomass and are used in place of, or in addition to, fossil fuels for transport and other applications (NMRE 2018). Indian national policy on biofuel includes many new initiatives for encouraging biofuel production from various biomass resources such as the biodegradable fraction of products, wastes, and agricultural, forestry, and related industries' residues (NMRE 2018). It also includes a biodegradable fraction of industrial and municipal wastes (NMRE 2018) but still does not address seaweed. The lack of a clear definition for the biomass sources could lead to the production of unsustainable feedstocks, as occurred in the early days of the EU biofuel policy (Banja et al. 2019). For the implementation of large-scale seaweed cultivation, it is necessary to acknowledge the possibility of using it as feedstock for biofuel in the biofuel policy. Furthermore, seaweed biomass, either fresh or dried, should be considered an agriculture product for all purposes, including biofuel production.

Step 2: legislation and licensing

The complicated and strict Indian licensing process should be simplified to allow the successful implementation of large-scale cultivation. While its strictness is designed to protect and preserve the coral reef's current status in Indian waters, all commercial farming is presently away from ecologically sensitive areas. At the same time, seaweed farmers do not have to obtain legislative approval/permits, and several states such as Tamil Nadu, Gujarat, Andhra Pradesh, etc. allow individual farmers to start cultivating after obtaining approvals from local governing bodies at the village or town panchayat levels. The eastern coast of mainland India shows almost total absence of corals due to the influence of freshwater flow from rivers. Also, the west coast shows small availability for corals, specifically in few areas, such as Konkan part of Maharashtra state and Gulf of Kutch of Gujarat state. These areas could have been used for macroalgal cultivation, but the rules apply in the same manner for all coastal areas irrespective of the biodiversity or state of the environment. Moreover, according to CRZ notification, construction activities along the coast are prohibited. This may become a barrier since large-scale cultivation requires facilities like a nursery, storage, etc. in nearby areas.

Step 3: site selection and environmental aspects

Site selection is one of the key challenges for large-scale cultivation and demands both time and financial expenditure. Moreover, there is no seaweed technology currently available in the country for adaption by industry. While seaweed can be cultivated in the open sea, its growth depends upon various environmental factors such as current, water quality, temperature, depth, and salinity (Sudhakar et al. 2018). Offshore cultivation involves the use of anchored ropes, which can be combined with an offshore wind farm (Langlois et al. 2012) or other renewable energy enterprises. In East Asian countries, nori seaweed farmers use free-living conchocelis for seeding, but many use oyster shells for conchocelis (He and Yarish 2006). Although seaweed cultivation is common throughout East and Southeast Asia, its main purpose is production of food resources, so that related policies are oriented to the food sector. For example, in the Philippines, seaweed farming is considered agriculture.

Site selection is essential in terms of control of possible epiphytes, as is the selection of cultivation methods such as a fixed pole, semi-floating raft, or floating raft (Kim et al. 2017). In India, most of the technologies used are laboratory scale and have not been even validated at pilot scale. For example, the trials of large-scale cultivation of *Gracilaria edulis* have remained at the experimental level even after considerable effort (Mantri et al. 2019). However, in subsequent years, the perfection of *Gracilaria* was finally achieved in cultivation techniques (Subba Rao and Mantri 2006, Mantri et al. 2019). Therefore, for successful seaweed enterprises, there is a need for parallel development on all fronts, including the technological development from lab to commercial-scale production and persistence with the application. For example, in energy extraction, while various technologies are reported, the production of bioethanol and the full potential of brown seaweed still cannot be realized without fermentation of alginate (Enquist-Newman et al. 2014). While the use of an engineered strain of *Saccharomyces cerevisiae* for ethanol production from brown macroalgae (Enquist-Newman et al. 2014) appears technically feasible at laboratory scale, for industrial application, it has several challenges (Campus et al. 2016). However, these are global challenges for seaweed bioenergy, and the primary need of the Indian seaweed sector is still seaweed farm cluster development.

In terms of the environmental impact of large-scale cultivation of seaweed, currently environmental impact assessment (EIA) is an essential tool for mapping the possible effects. Although large-scale cultivation does not use any harmful chemicals, or create harm to human beings, it is still necessary to obtain environmental clearance due to its potential to harm the environment in case of failure or disaster. The Indian Ocean contains some of the most crucial maritime shipping routes, mainly for the transport of petroleum around the Indian peninsula. Spillage of crude oil is an economic problem for the fishing community and has tremendous potential to harm large-scale macroalgal cultivation and cause economic and ecological losses. For example, in Indonesia, seaweed farmers are seeking more than US$137 million from Thailand's "PTT Exploration and Production" to cover the damage they claim to have suffered after the Montara explosion (Offshore engineering, retrieved July 2019).

Traveling and fishing boats are a central activity in Indian territorial waters. More than 300,000 fishing boats operate in Indian coastal areas, particularly on the west coast and especially after the monsoon season (ReCAAP 2012). Furthermore, most of the Indian waters are under control of the Indian navy and the coast guard. For security purposes, the navy regulates movements and keeps watch on every activity. While it is difficult to estimate how these factors might affect cultivation, it is clear that large or unexpected movement of ships can disrupt farming. Therefore, Indian policies may restrict or prohibit farming in shipping lanes.

Step 4: market orientation aspect

The co-production of multiple products from the same biomass can maximize the seaweed biomass's benefits with close to zero waste and would benefit the local community, including local agriculture (Ingle et al. 2017). Among the products to which the seaweed biomass can be converted are ethanol, butanol, acetone, methane, proteins (for food and animal feed), high-value products, lipids, and biofertilizer (Hafting et al. 2015). Previous studies have shown that the remaining pulp after extraction of high-value polysaccharides (agar, alginate, carrageenan) still contains high quantities of carbohydrates and nutrients including protein, lipids, and minerals, which may be used as a source of raw material for extraction of other products rather than treated as waste (Golberg et al. 2019). For example, after carrageenan extraction, it is observed that 60%–70% of the resultant solids are considered waste (Uju Wijayanta et al. 2015, Ingle et al. 2017), which can be converted into biofuels after hydrolysis. The production of bioethanol from *Gracilaria verrucosa* is also reported after agar extraction (Kumar et al. 2013).

Utilization of seaweed as fertilizer, for example, has been proposed (CEVA 2011, 2012), and several trials reported on the development of an integrated method for utilization of fresh seaweed biomass, such as *Kappaphycus alvarezii* (Doty), to maximize the number of products. In this time-saving method, the sap is released by crushing seaweed and further utilized as a potent liquid fertilizer. Moreover, after certain treatments, the process's residue is utilized as raw material for *kappa*-carrageenan extraction (Eswaran et al. 2005). Biofertilizer has proven to have many benefits for local crop yields, is disease resistant, and easy to produce and use, which are important for rural applications (Ingle et al. 2017). Moreover, as liquid biofertilizer is usually used locally on agricultural land, the transportation cost of the residue to the processing plant is reduced. The waste is also richer in carrageenan, leading to higher yield per mass of processed biomass (Eswaran et al. 2005).

Golberg et al. (2019) describe in detail the economics of marine biorefineries, their implementation, supply chain design, and assessments. The profitability of marine biorefineries is subject to various sources of uncertainty, such as feedstock supply, processing technology, investment, contracting, and demand. The primary driving factors for market demand are expected to increase due to the availability of raw materials at a reduced cost, rising customer awareness, and government initiatives to promote green products. However, the lack of policies supporting the biorefinery sector limits the long-term investment decision required. There is a need for a distinct policy driver for the utilization of bio-based chemicals.

Currently, large scale cultivation is present in the south-west coast of India, and it focuses on the carrageenan and other value-added products (Figure 4).

Macroalgae can also be utilized as a food and nutrition source and provide local food security. The main challenge is to change Indian public opinion and increase their acceptance of macroalgae as food. Seaweed is not a regular part of Indian cuisine but is a popular food in East Asia.

While traditionally, seaweed is not considered regular food in India, it may have medicinal value in Indian culture. The ancient therapies, particularly Ayurveda, mentioned seaweed and its use as medicine, but

Figure 4: Seaweed cultivation in Mandapam, Tamil Nadu state, India.
(A) Local products such as bamboo, rope, etc. are used for cultivation practices. (B) Vegetative cultivation methods are used. (C) Local fishermen are involved in farming due to economic benefits. (D) Fish capture in the cultivation sites. Cultivation areas are suffering from grazing of fish, particularly Signids or rabbitfish.

not as food. As Indian cuisine is based on classical and traditional ingredients, it will be challenging to gain community acceptance of seaweed as a food. However, nowadays, in India, many foreign dishes, including Chinese and other cuisines, are becoming popular. Therefore, marketing and consumer awareness in this area, combined with adequate policy, can improve local market acceptance.

The design of large-scale seaweed cultivation in India should consequently take into account the diversification into the local market as food as well as fuel, especially in the case of excess growth. Seaweed's value as food is higher than that as fuel. Therefore, early efforts in the food market will likely drive large-scale production. The increased growth of the sector will be required to make fuel far more economically viable. Cultivators and planners should carefully select macroalgal species for growth and consider the possibilities and limitations of selling the products as food in the local market. Generally, seaweed cultivators in India are women, so the policies and schemes related to the development of this sector should have a focus on gender in aquaculture and the advancement of women's status. This should be manifested in their quality of life, health, education of their children, etc. (Mantri et al. 2017).

Recommendation

(1) There is a need for an in-situ study on the impact of seaweed farming on corals. It might be possible that seaweed farming is helpful in coral conservation by providing protection, and thus limiting photo-damage from the sun, acidification, and/or nutrient pollution.

(2) There is a need for an explicit declaration of the abundance and diversity of corals in the coastal sites and their vulnerability, alongside possible ways to expand macroalgal farming without harming them.

(3) The complicated and strict Indian licensing process should be simplified to allow implementation of large-scale cultivation. There is a need for a distinct policy driver for the utilization of bio-based chemicals. The Indian government encourages organic products. Therefore, seaweed-producing companies, such as those that produce plant bio-stimulants, should utilize this advantage.

(4) The Indian government needs to allocate appropriate funds to accelerate R&D in designated areas of algal cultivation, harvesting, and processing technologies.

(5) There is a need to establish a dedicated unit of the Agriculture Ministry responsible for the implementation of large-scale commercial cultivation of seaweed;

and establishing the connection between departments relevant to this sector.

(6) Setup for implementation of local biorefineries in the coastal areas (as dehydration or sun drying facilities), which will ease the transportation of raw material, should be established.

(7) Those engaged in seaweed cultivation should be considered farmers rather than workers or contract servants, as this will protect them financially. Administrative support should be provided to them in case of any damage by natural disasters, such as sudden storms or cyclones, as is generally customary for terrestrial farmers.

Conclusion

A significant part of the challenges for the successful implementation of large-scale macroalgal cultivation on the Indian coastline is related to legal and regulatory aspects. Combined agriculture, process engineering, and policy models are required to provide planning tools for success. A clear, adequate biomass and biorefinery policy, taking into account the apparent economic need for marine biofuel resources; and legal permission for foreign holding investment, along with suitable area availability, will be the critical steps toward the development of this resource in the Indian seas. The policy should answer clearly whether these fields are considered part of industry or agriculture.

Government recognition of those directly employed in seaweed cultivation, production, and aquaculture as farmers instead of workers will allow them to receive subsidies and other governmental benefits generally granted to conventional farmers and will encourage talented employees to join this field. Furthermore, specific policy regarding the development and encouragement of the local market to use macroalgal products as food can help achieve socioeconomic development goals, energy, and food security issues, while causing no harm to the environment.

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Graphical abstract

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Challenges for marine macroalgal biomass production in Indian coastal waters

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Review: To open the door for the development and expansion of large-scale marine macroalgal cultivation in Indian coastal waters, a definitive framework (including: governmental support and encouragement, legislation and licensing, site selection and market orientation), should be established and implemented.

Keywords: Biodiversity Act; bioeconomy; macroalgal cultivation; marine biorefinery; marine policy.