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Algae Farming: Alternative in Aquaculture Sector

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Abstract: Algae farming has emerged as a promising alternative within the aquaculture sector, offering multifaceted benefits ranging from sustainable feed production to environmental remediation. This practice involves the cultivation of various species of algae in controlled settings, providing a renewable source of biomass rich in proteins, lipids, and carbohydrates. Algal cultivation presents opportunities for reducing dependence on traditional fish feed sources, mitigating environmental pollution through nutrient absorption, and serving as a viable solution for carbon sequestration. Moreover, algae farming showcases potential applications in pharmaceuticals, biofuels, and wastewater treatment, emphasizing its significance in fostering a more sustainable future for the aquaculture industry. This review discusses seaweed farming practices, different species of seaweed under cultivation practices, and their economic importance, especially in the Indian aquaculture system. In addition, this review focuses on commercial uses of seaweed and its byproducts. Finally, challenges and opportunities in seaweed farming are also discussed.

Keywords: Algae farming, Aquaculture, Biofuels, Pharmaceutical applications, Sustainable feed

Algae are diverse plant-like organisms that are autotrophic, primarily found in aquatic regions, and few are present on land. Algae vary in size from unicellular structures known as microalgae to multicellular systems called macroalgae, with marine macroalgae (commonly referred to as seaweed) explored for their commercial applications. For centuries, seaweed has been used in Asian cuisines and medicines, but in recent years, other industrial applications have been discovered and continue to be explored. Seaweeds can be broadly classified based on their pigmentation: Chlorophyta or green algae, Rhodophyta or Red algae, and Ochrophyta or brown algae (Leandro et al., 2019). Seaweeds have become increasingly popular to meet the growing need for sustainable bioresources. All three classes of seaweeds have multifunctional properties, making them economically important. Brown algae such as *Laminaria sp, Saccharina sp.,* and *Undaria sp.* and red algae species such as *Grateloupia* sp. and *Porphyra sp.* are low-caloric edible seaweeds with high content of proteins, vitamins, minerals, dietary fiber, and trace minerals (Leandro et al., 2019).

In addition, alginates, agar, and carrageenan extracted brown and red seaweed species, respectively, have various applications, especially in food industries – utilized in sorbets, breads and pastries. In addition, these hydrocolloids are used in livestock feed, plant biofertilizers, and healthcare textiles such as wound dressing, vascular grafts, sanitary towels, and sutures (Janarthanan and Senthil Kumar 2018). In 2019, algae production contributed nearly 30% of the global aquaculture production, with red and brown seaweeds accounting for the second and third-largest groups in world aquaculture, respectively (Cai et al., 2021). Global Market Insight predicts the commercial seaweed market will be USD 95.8 billion by 2027. East and Southeast Asian countries contributed to most of the global seaweed production, estimated at 97.4%, while America and Europe contributed 2.2% (Cai et al., 2021). According to an FAO survey, China, Indonesia, Korea, Philippines, Japan, and Malaysia were the largest seaweed producers in 2019. Interestingly, more than 99% of the seaweeds produced in these countries were from seaweed farms, except for Japan, where ~83% were produced from seaweed farms (Cai et al., 2021).

Seaweed farming does not compete with arable land and does not require fertilizers, feed, or antibiotics. Typically, seaweed is cultivated in open marine water, either near-shore or off-shore, by attaching propagules (or baby seaweeds) to nets while optimizing culture parameters (Radulovich et al., 2015). India has an extensive coastline stretching up to 8100 km, including the coastlines of the Arabian Sea, Bay of Bengal, Lakshadweep, and Andaman and Nicobar Islands, with an exclusive economic zone of 2.17 million km^2 (Ganesan et al., 2019). The Indian coastline is home to around 865 seaweed species inhabiting deep waters, shallow waters, and low and high tidal regions (Shetye, 2024). Seaweed industries in India mainly depend on wild harvests, leading to the overexploitation and depletion of native species such as *Gelidiella sp, Sargassum sp, and Gracilaria sp*. (Mantri et al., 2019).

Central Salt and Marine Chemicals Research Institute (CSMCRI) and Central Marine Fisheries Research Institute

(CMFRI) attempted the first experimental seaweed cultivation in India in 1967. The two organizations jointly developed sustainable cultivation technology and trained local fish farmers to experiment with *Gelidiella and Gracilaria* sp. evaluated the economic performance of seaweed farming in Ramanathapuram district, Tamil Nadu (Rameshkumar et al., 2019). The authors reported that the average annual income from a three-year farming project was Rs. 6,76,300, with the net cash flow increasing to Rs. 9,83,000 in the second and third years. Seaweed farming is a promising alternative to fish farming communities in India and a more sustainable practice in the aquaculture sector.

Farming System and Methods of Seaweed Cultivation

Seaweed cultivation depends on several factors, including the type of species (and strains), the location of the farms, the cultivation methods, and the resources available for the maintenance of the farms (Radulovich et al., 2015, Jagtap et al., 2022). Seaweed can be cultivated extensively in natural water utilizing natural resources such as sunlight, natural water currents, and organic and inorganic nutrients from marine water. Naturally occurring seaweed species in extensive systems are cultivated with specific farming techniques to improve productivity. In addition, based on the suitability of culture parameters, non-native species may be introduced; however, risks of decimation of native species must be considered.

For large-scale commercial production, farming areas in the sea beds are supported with natural or artificial substrates such as ropes or nets for seaweeds to absorb the nutrients to the maximum and prevent them from washing offshore or being carried away by waves (Sijl 2015). Furthermore, these open-water farming systems are practiced as (a) offshore and (b) near-shore cultivation. In the case of offshore cultivation, seaweed farms are located at a certain distance from the coastline (>2 km), either submerged by attachment to a rigid substrate or floating on anchored lines or nets. The significant issue with offshore cultivation includes the exposure of seaweeds to the harsh effects of oceans and unfavorable environmental conditions. However, installing robust substrates that can withstand the adverse effects of the sea will minimize the loss of biomass (Fernand et al., 2017, García-Poza et al., 2020). The near-shore cultivation is a traditional yet widely practiced technique, where seaweed farms are easily accessible as they are located close to the coast and have shallow waters with a depth of not more than 40 m. (Soto and Wurmann 2019). The largest seaweed-producing countries, such as China, Korea, and Japan, adopted near-shore cultivation methods in the late 1940s and significantly contributed to global seaweed production (Hwang et al., 2019). In general, these systems require minimal capital investments and are labor-intensive.

In comparison, an intensive system is practiced in enclosed systems, such as in ponds or tanks with constant water agitation and supplied with natural or artificial lights, organic or inorganic fertilizers, and phytohormones. This land-based system, known as on-shore cultivation, can cultivate many seaweed genera except the largest seaweeds, such as kelps. In addition, land-based cultivation systems allow farmers to control, monitor, and optimize environmental conditions for enhanced production and efficient use of resources. In general, seawater is pumped onshore; however, secondary sources such as effluent water from aquaculture ponds are also utilized to avoid the addition of external nutrients, thereby having the advantage of sustainability (Ahmad et al., 2022). Although land-based systems, especially tank systems, produce the highest yield compared to other cultivation systems, high capital investments, and high power inputs are limiting factors for the large-scale production of seaweeds (Tullberg et al., 2022). Radulovich et al., (2015) summarize all the possible cultivation methods that apply to extensive and intensive systems. Most of the methods described in the review, such as line cultivation, net cultivation, floating raft system, and tank or pond culture system, use a substrate to support the seaweed propagules (seedlings) during cultivation. While the cultivation method varies based on the species, the most popular and suitable methods for Indian seaweed farming include fixed-off bottom, floating raft, and integrated multitrophic aquaculture (IMTA) methods.

Fixed, bottom-line method: In this method, wooden stakes are hammered into the substrate and arranged in rows at 1 m intervals. Next, monofilament nylon lines or propylene ropes are tied to the wooden stakes, each row 10 m apart. Farmers have easy access to the lines during low tide, allowing them to monitor until harvest. Farmers in Tanzania and Mexico employ an off-bottom-line method for cultivating *Kappaphycus spp*. (Valderrama et al., 2015). *Eucheuma cottonii, Eucheuma denticulatum, and Eucheuma spp* are other species cultivated using this technique (Gavino 2022).

Bamboo raft method: Bamboo rafts of an area of 3×3 m^2 with a diameter of 7 to 8 cm and knots measuring 15 cm are built by tying the bamboo diagonally with each other with the length of the raft reaching up to 1.3 m; size may vary based on the species selected. Lower portions of rafts are covered with fishing nets to protect the rafts from open sea conditions and prevent seaweed grazing and biomass washing away. Approximately 100 g of fresh cuttings (plantings) or 400 seedlings per raft (150 g $knot^{-1}$) are added, bringing the initial weight of the rafts between 40 to 60 kg. The rafts are then anchored to stones (~30 kg) to allow the rafts to float in the seawater. Farmers can regularly monitor the rafts to ensure they are safe from biofouling and may alter the position of rafts during unfavorable weather conditions (Ganesan et al., 2019). Both off-bottom line and floating raft methods are susceptible to biofouling, where fouling species, such as bryozoans, tunicates, and epiphytes, compete with growing seaweeds for dissolved nutrients, sunlight, or cause physical damage to the infrastructure by weighing down the seaweeds, especially kelps (Bannister et al., 2019).

The floating raft method is a popular method for the cultivation of carrageenophytes such as *Kappaphycus spp, Sarconema spp, Hypnea spp, Euchema spp*; agarophytes such as *Gelidium spp and Gracilaria spp* (Ganesan et al., 2019). In addition, the Central Salt and Marine Chemical Research Institute (CSMCRI) Marine Algal Research Station (MARS), developed the single rope floating raft system (SRFR) for culturing agarophytes in a broader and deeper area in the open water where wooden stakes are attached to synthetic anchor cables to keep them afloat. The CSMCRI suggests that the floating raft technology is suitable for seaweed cultivation on the Kerala coast and a few areas in the Gulf of Kutch. (Mohamed 2015)

Integrated mariculture: In East Asian (China) and Southeast Asian (Vietnam, Philippines, and Taiwan) countries, co-culturing methods of fish and seaweeds are widely explored for their cost-effectiveness and high yield potential, and for the reduction of pollutants from the aquaculture wastewater. Seaweeds behave as biofilters – absorb excessive inorganic nutrients such as nitrogen and phosphorus from shrimp culture and finfish effluents (Arumugam et al., 2018). Several studies found similar results with the integration of seaweed with shrimp or finfish cultures (Kang et al., 2021) and the culture techniques can be distinguished as seaweeds are cultivated in tanks or cages along with the fish and in tanks receive effluents from the adjacent fish ponds or tanks.

Furthermore, to increase the efficiency of the culture system, selecting seaweed species and optimizing environmental conditions such as dissolved oxygen, water temperature, and light intensity is crucial. Compared to the traditional polyculture system, Integrated Multitrophic system (IMTA) is a novel approach that offers a better monitoring system where the culture parameters can be easily manipulated to increase the biomass of multispecies (fish, seaweeds, invertebrates, and microbes). The shrimp aquaculture industry in India is rising; however, 95% of the shrimp farms in India discharge effluents into nearby water bodies without treating them (FIAPO 2020). IMTA is an effective tool for establishing nutrient recirculation in land-based intensive farms and reducing the environmental pollution arising from effluents. Several countries, such as Canada and Portugal, are promoting the adoption of the IMTA system for kelps and fish polyculture and red algae, fish, and mollusks (Buck et al., 2018).

Seaweed Species of Economic Importance

Selection of species is of utmost importance for selecting the optimal farm site with suitable environmental conditions and the best farming technique. Generally, seaweed species are chosen based on their application and profitability, such as human food supplement, feed supplement, phycolloid production, bioactive compound extraction, biofuel production (Jagtap et al., 2022) or to mitigate environmental stress such as sequester carbon and to improve water quality in marine waters. Introducing non-native species may invade native species, alter the biodiversity of the coastal ecosystem, and affect the productivity of native species. (Eggertsen and Halling 2021). Since there is limited data on the consequences of cultivating alien species in the Indian coastal system to increase biomass production, initial seaweed farming initiatives in the country can focus on utilizing wild species for selective breeding, certifying seaweed varieties, hybridizing species, and increasing genetic variations among them. Similar methods have been successful in the world's largest seaweed-producing countries, such as China, Korea, and Japan (Hwang, Yotsukura et al*.,* 2019). Survey conducted by the Botanical Survey of India records 865 seaweed species from the intertidal and deep-water region of Indian waters. Red algae are the most diverse group, followed by green and brown algae (Mantri et al., 2019). However, only 60 species are found to be commercially significant, and fewer species are dominant on the international market (Mohamed 2015).

***Porphyra* spp.:** *Pyropia* (or *Porphyra*) spp. are among the most popular red seaweed species cultivated in Korea, Japan, and China, with the highest commercial value of USD 0.89/kg. (Cai et al., 2021). Korea exported USD 525 million of *Pyropia* products to 110 countries, making it the world's top exporter in 2018 (Hwang and Park 2020). In 2019, the global annual production of farmed *Porphyra* was about 3 million tonnes, which generated a first-sale value of USD 2.7 billion (Cai et al., 2021). The most common species cultivated in top-producing countries are *P. yezonensis, P. tenera,* and *P. haitanenisi*. At the same time, *Porphyra vietnamensis* and *P. indica* are the two most abundant species found in India, especially on the west coast, including Maharashtra, Goa, and Karnataka (Kavale et al., 2021). However, *Porphyra* spp is currently not commercially cultivated in India. *Pyropia* is primarily used as human food for distinct flavor and nutrient profile, including high levels of protein and vitamins. Kaur

(2025) reported that *P. vietnamensis* and *P. indica* have excellent antioxidant properties and are suitable for application as nutraceuticals. The growth of wild *Porphyra* spp commences at the beginning of the monsoon in June and lasts till September. Due to heavy rainfall during the monsoon season, the temperature and salinity of the water gradually decrease, favoring Porphyra sp's growth. Further, the thickness of the seaweed blade is affected by the motion of the water, and a calmer environment is preferable.

For large-scale production of *Pyropia spp.* farmers in Korea use artificial seeding to culture seaweed propagules. In this method, free conchocelis filaments (a growth stage in the life cycle of *Pyropia spp*) are allowed to attach to the oyster shells, which serve as a substrate. After a couple of weeks, the conchocelis mature within the shells to release conchospores. Seedlings of *Pyropia* are produced by outdoor seeding and indoor seeding. In both methods, cultivation nets are immersed in seawater or tank water for the conchospores to attach to the substrate. Controlling conchospore density is more feasible in indoor seeding but requires sophisticated infrastructure. Seaweed farmers in Korea periodically expose the nets to the air as a control measure to reduce or kill epiphytes and enhance seaweed growth (Hwang and Park 2020).

Kappaphycus alvarezii: *Kappaphycus alvarezii* is the most widely cultured and traded red seaweed, with a net global production of 11.6 million tonnes (33.6% of all seaweed) in 2019, which generated a first sale value of USD 2.4 billion (Cai et al., 2021). Most of the production was from Asian countries, with Indonesia (9,795,400 tonnes) being the highest producer, followed by the Philippines (1,498,788 tonnes) (Cai et al., 2021). *K. alvarezii* is a source of κ-carrageenan, a phycocolloid with industrial applications as an emulsifier, thickening agent, stabilizer, and gelling agent in food, beverages, cosmetics, and pharmaceutical products. CSIR-CSMCRI imported *K. alvarezii* biomass from Japan in 1996, which was indigenous to the Philippines, and initial cultivation was performed in Okha, on the west coast of India. Further, researchers introduced the seaweed into the coastal waters of Mandapam coast of Tamil Nadu for acclimatization and large-scale cultivation. *K. alvarezii* was also cultured in Kurusadai Island, at the Gulf of Mannar Marine Biosphere Reserve (Arasamuthu et al., 2023). Pepsico India Holdings (P) Ltd., Gurgaon, played a pivotal part in the commercial cultivation of *K. alvarezii* in India. The company provided 45 rafts to each women's Self-help Group member, distributed to farmers. The ropes with seaweed seedlings were tied to these rafts and planted on the coastal water. It is to be noted that most Southeast Asian countries produce seedlings by vegetative or self-propagation, where healthy branches from young, robust seaweed are cut and tied to ropes (Carabantes 2020). Farmers followed either fixed off-bottom or floating raft cultivation methods with a 45-day farming period. Farming cycles were designed to allow each farmer to plant and harvest one raft daily. The average yield per raft ranged between 240 kg and 280 kg of live seaweed, of which 40 kg was used as seed for the successive farming cycle. One hectare of farm could support 900 rafts with a net annual income of Rs. 4,60,000 (Ganesan et al., 2019). *K. alvarezii* farms are susceptible to grazing herbivores such as signanids, puffers, turtles, and sea urchins; therefore, it is essential to select appropriate farm sites.

In addition, ice-ice disease is a common problem observed in these seaweeds that causes a whitish appearance on the thalli, causing the thalli to break. It is unclear whether a bacterial or viral infection causes the disease. Hence, developing new disease-resistant varieties tolerant to high light intensity and temperature is imperative (Kim et al., 2017). In Kerala, cultivating *K. alvarezii* by following a nylon hook method for a farming period of 86 days and 63 days post-monsoon season increased the yield 34.42-fold and 30-fold, respectively. Also, integrated farming of *K. alvarezii* with green mussels resulted in a 20-fold increase in yield (Mohamed 2015).

Gracilaria edulis* and *G. dura: *Gracilaria spp.* is the second most cultivated red seaweed species, with a global production of 3.6 million tonnes in 2019 with USD 2 billion as the first-sale value (Cai et al., 2021). *Gracilaria* is the major source of superior-quality food-grade agar and agarose, which have various applications in the food and pharmaceutical industries. According to a survey conducted by FAO, the global seaweed production in 2019 was contributed by six East and Southeast Asian countries: China, Indonesia, Vietnam, Korea, Taiwan and Philippines (Cai et al., 2021). China comprises 30 *Gracilaria* species, but the two most widely cultivated species are *G. tenuistipitata* and *G. lemaneiformis* with pond-scattering and floating raft technique being the primary cultivation method. India is home to 32 species of *Gracilaria*, of which *G. edulis* is the most abundant and grows along the Gulf of Mannar and the southeast coast (Veeragurunathan et al., 2019).

Indian agar industries primarily sourced agar from wild stocks of *G. edulis* by harvesting 100 to 200 dry tonnes yearly, leading to over-exploitation of these seaweeds. To bridge agar's supply and demand gap in the country, industries began harvesting other species of *Gracilaria* wild stocks, Therefore, developing cost-effective high-yield methodologies with technological interventions is crucial for the self-sustained production of *Gracilaria* spp. The increased biomass production from July to August, with the maximum yield obtained from November to December. In addition, during the 60-day harvest period, the sub-tidal cultivation system showed a significant increase in biomass with the period removal of epiphytes (Islam et al., 2021). Due to the depletion of wild *G. edulis,* sourcing seedlings from wild stocks has been more challenging. Several studies found *G. dura* to be a viable substitute for large-scale production of the *Gracilaria* seaweed. The polypropylene net and floating bamboo raft methods have proven to be the highest-yielding cultivation methods on the southeastern coast of India, with daily growth rates of 3.748 day-1 and 2.61- 3.17, respectively (Veeragurunathan et al., 2015). The studies suggest that the cultivation period between October and March is ideal for increased productivity, while the seaweed is susceptible to grazing herbivores between April and August and epiphyte growth due to increased temperature.

Sargassum spp and Turbinaria spp: Globally, brown seaweed serves as a food source. However, in India, it is a major source for the extraction of alginates, which have industrial applications as thickeners, gelling agents, emulsifiers, and stabilizers. In 2019, brown seaweed production contributed to 47.3% of world seaweed production, among which two genera - *Laminaria* or *Saccharina* and *Undaria* – were the most widely produced, with East Asian countries being the largest producers (Cai et al., 2021). In India, naturally occurring genera include *Sargassum, Turbinaria, Cystoseira, Spatoglossum, Hormophysa, Chnoospora,* and *Rosenvingea*, of which *Sargassum sp.* and *Turbinaria sp.* are of commercial importance (Mantri et al., 2019). In general, industries in India rarely indicate the specific species utilized, but *Sargassum wightii* and *Turbinaria conoides* are believed to be the most predominant species (Mantri et al., 2020). In 1966, artisanal fishermen began harvesting wild stocks of *Sargassum* sp and decade later 1975, *Turbinaria* sp. was also gathered from the coastal belt extending between Kanyakumari and the Gulf of Mannar. The fishermen, predominantly women, collect seaweed from the intertidal and sub-tidal regions of the coastal belt for 10-12 days per month throughout the year (Mantri et al., 2019). *Sargassum* sp. and *Turbinaria* sp. are valued at approximately USD 800 per dry tonne; despite the steady increase of alginate production in India, brown seaweeds are not cultivated in seaweed farms (Ganesan et al., 2019). Continued harvest of wild stocks leads to their depletion and threatens the marine ecosystem. To minimize the overexploitation of brown seaweed, further studies should focus on examining competent strains, developing effective farming methods, and selecting farm sites with favorable environmental conditions.

Traditionally, in Korea, *Sargassum spp.* Seedlings were collected from wild stocks and inserted into a seedling rope. Next, the seedling rope was attached to a main longline and planted near the shore at 2-3 m depth. Alternatively, seaweed farmers preserve the attached holdfasts obtained from the seedlings and reuse them in the next cultivation cycle. However, biomass productivity decreases after every year, resulting in less yield. Recently, farmers have started using a more sustainable technique by obtaining seeding produced through sexual reproduction. This method collects fertilized eggs from vegetative fronds (stem-like), and the germinating rhizoids are attached to seeding ropes. The seedling strings are transferred from nursery tanks to open seawater, where they are attached to the seabed by the fixed-off-bottom method for mass production. Furthermore, the holdfasts may be re-used for the subsequent growing season without the loss of biomass (Kim et al., 2017).

Uses of Seaweed and Seaweed Products

For centuries, East Asian and South Asian countries have used seaweed as a staple in their traditional cuisines, making seaweed a popular food commodity (Lu and Chen 2022). In addition, local communities utilize seaweeds to treat several diseases without genuinely understanding their underlying mechanisms (Shannon and Abu-Ghannam 2019). Since seaweed farming requires minimal to no feed or fertilizers, or additional water input and seaweed tends to have high biomass productivity and has proven more sustainable than fish aquaculture or agricultural practices. Consequently, researchers developed a keen interest in examining numerous seaweed species' biochemical composition and bioactive properties and exploring their potential uses in the food and non-food sectors (Cotas et al., 2023). Globally, seaweed-derived products are now in great demand; thus, seaweed farming has tremendous potential to provide socio-economic benefits to fish farming communities in India (Ganesan et al., 2019).

Seaweed as a food source: The nutrient profile of seaweeds varies from species to species, but generally, seaweeds are rich in protein, carbohydrates, dietary fibers, and minerals but are low in lipids and fats. Padam and Chye (2020) reported that the protein content in seaweed is comparable to high-protein foods such as soybeans, lentils, chickpeas, and mung beans. Although seaweeds are considered low-energy food due to the presence of lower lipids and fatty acid content, seaweeds comprise nutritionally essential fatty acids, including polyunsaturated fatty acids (PUFA) that protect heart health due to their potential anti-inflammatory, antithrombotic, antiarrhythmic, hypolipidemic effects and offers other health benefits such as anti-cancer effect (Kapoor et al., 2021). In Japan, *Nori* or *Pyropia* is consumed in sushi by wrapping dried seaweed sheets in boiled rice. In Korea, premenopausal women who consumed dried *Porphyra* had a lower risk of developing breast cancer (Kumar and Sharma 2021). In Hawaii, Indonesia, the Philippines, Malaysia, and Vietnam, *Gracilaria spp.* is considered a salad vegetable. Although most seaweed production is utilized as human food (Mahadevan 2015), Indians rarely incorporate seaweed into their diet. However, food manufacturers can use seaweed as an ingredient to formulate snacks, pasta, and soups to introduce seaweed as a food product in the Indian markets Wendin et al., (2020), found that Swedish consumers preferred to eat seaweed from store-bought products or in restaurants and were willing to try seaweed if added in breads or snacks. Most respondents knew of seaweed's sustainability advantage as a food source. Similar studies on Indian consumers would provide deeper insight into their perception of seaweed and its products.

Phycocolloids and functional ingredients: Besides protein, seaweeds are rich in polysaccharides, which can be found as storage carbohydrates that serve as a photosynthetic reserve or present in the cell wall or extracellular matrix, which acts as a mechanical barrier (Rioux and Turgeon 2015). These polysaccharides produce hydrocolloids, often called phycocolloids, with several food and non-food applications. Alginate, extracted from brown algae, while agar and carrageenan, extracted from red algae, have high commercial importance. On average, the annual global production of phycocolloids is estimated to be around 100,000 tons, with a net market value of 1 billion USD annually. Food industries are the most significant users of phycocolloids as raw materials, accounting for 80% of global agar and carrageenan production and 30% of global alginate production (Pangestuti et al., 2015).

Agar, alginates, and carrageenan are excellent emulsifiers, stabilizers, thickening, gelling, and foaming agents and are used to produce bakery products, confectionery, and beverages. Besides the rheological properties contributing to the elevation of textural and sensory attributes of food products, these natural ingredients provide many health benefits. For instance, the incorporation of agar in daily diet aids in weight management by reducing total cholesterol levels and improves gut health by increasing probiotic-bacterial survival (Rubaab et al., 2020). Reported that micro-dosing sodium alginate to a beverage formula decreased blood glucose and insulin levels in diabetic patients. Furthermore, the techno-functional properties of carrageenan have attracted meat industries to formulate low-fat, low-sodium meat products (Kerry et al., 2023). Besides food applications, agar is used in nutrient medium formulations essential for multiple microbiological and cell culture studies. Both agar and alginates are used in pharmaceutical and medical applications and the cosmetic, paper, and textile industries (Pirsa et al., 2023). Many bioactive compounds can be extracted from seaweed, which has excellent therapeutic properties. For instance, seaweed-derived carotenoids have antioxidant and protective activity against cancer and cardiovascular diseases (Kumar et al., 2021). Macro- and micro-algae-derived pigments such as beta-carotene, phycocyanin, and phycoerythrin can be used as natural food colorants.

Livestock feed supplement: Conventional livestock feed production consists primarily of high protein and high energy feeds like cereal grains, corn meal, soybean meal, and grass pastures, which compete with crop production for human consumption. The addition of seaweed feeds as an alternative feed reduces the stress on conventional crop production, and several studies suggest that the bioactive compounds in seaweed provide health benefits – improve the gut health of animals (Maheswari et al., 2021).

In addition, earlier studies reported that seaweed supplementation, especially red seaweed *Asparagopsis spp.* reduces enteric methane emissions in ruminants by 50-98% (Roque et al., 2019, Abbott et al., 2020, Kinley et al., 2020, Vijn et al., 2020). Using regenerative aquaculture technology, a Hawaiian start-up, Symbrosia, successfully cultivated and produced a low-cost ruminant feed additive called SeaGraze™ from *Asparagopsis taxiformis*. Their pilot-scale studies observed a 75% reduction in enteric methane emissions; further scaling up is in progress (Gillman 2022, Symbrosia 2022).

Besides ruminants, seaweed feed supplementation to poultry, laying hens, and fish provides comparable nutrition to conventional feed (Kulshreshtha et al., 2020). Adding 2% of raw brown seaweed *Sargassum sp.* in a regular broiler chicken diet reduces the total cholesterol levels and increases high-density lipoproteins; however, the final body weight gain was slightly lower than the conventional diet (Morais et al., 2020). Seaweed-based feed production can be achieved using clean technologies to reduce environmental implications further, thereby making them a more sustainable feed source.

Bio-fertilizer and bio-stimulants: Seaweeds have proven to be beneficial in human and livestock diets, and their uses extend to providing excellent sources of nutrients for plants and soil, making seaweeds a better replacement for chemical fertilizers. Due to the similar biochemical composition of plants and seaweed, they are biocompatible (Hassan et al., 2021), reducing the risk of developing adverse effects on plant health upon seaweed extract application. Studies report that seaweed consists of growth-promoting compounds that increase seed germination rate, plant root, and shoot length, enhancing plant productivity and overall crop yield (Nanda et al., 2021). Deepana et al. (2021) observed that in rice soil supplemented with 12.5 kg/ha of seaweed extract and 0.5% foliar spray of seaweed liquid extract increased plant height, leaf area, root length and volume, and yield. In addition, soil fertility improved as the biofertilizer had higher soil nutrients available, including N, P, K, and trace mineral compounds. Seaweeds can serve dual purposes as bio-fertilizers and bio-stimulants in agriculture. Biostimulants enhance plant nutrient and water uptake efficiency, abiotic stress tolerance, and crop quality by increasing antioxidant activity, fruit length, and diameter (Du Jardin 2015, Hassan et al., 2021). Di Stasio et al. (2020) added two combinations of seaweed extract to cultivate tomato plants under salt stress conditions. The authors observed decreased leaf water potential in treated plants due to the high concentration of osmotically active molecules and ions. In addition, the nutrient use efficiency was increased, resulting in higher yield. Overall, seaweed as biofertilizers may qualify as biologically safe and environmentally friendly.

Biofuel and biogas production: In light of the rising demand for fossil fuels and fuel price inflation, the need to develop sustainable alternative fuels is becoming increasingly important. Seaweed yields high biomass with abundant carbohydrate content with relatively minimal inputs, making it an ideal choice for cost-effective biofuel production (Twigg et al., 2024). Biofuels may be broadly classified into liquid biofuels such as bioethanol, biodiesel, biomethane, and Biogas. The biofuel extraction and yield differ from species to species due to the variability of biochemical composition; green seaweed, such as *Chaetomorpha antennina,* and red seaweed *Gracilaria corticata* comprises high lipid content, suitable for biodiesel production, while brown seaweed, such as *Sargassum angustifolium* and red seaweed such as *G. salicornia* comprises of high carbohydrate content making them ideal for bioethanol production (Sudhakar et al., 2024). Liquid biofuel production from seaweed is primarily achieved by fermentation by converting sugar molecules into alcohol. To make complex polysaccharides such as cellulose more accessible to microbes as simple sugars during fermentation, pre-treatments of algal biomass by hydrothermal treatment with acid or alkali, followed by enzymatic degradation, is feasible and cost-effective for industrial-scale production (Jiang et al., 2016). However, studies suggest that acid-hydrolysis of seaweed produces furfural as a by-product, inhibiting biofuel yield. Implementing species-specific thermal treatment coupled with hydrolysis is believed to increase biofuel production efficiency (Maneein et al., 2018). Biogas production is achieved by a process called anaerobic digestion. Pantis (2024) studied the effectiveness of co-digesting bovine slurry, an organic waste product produced from animal farms with five seaweed varieties: brown seaweed spp, including *Laminaria digitata, Saccharina latissima, Saccorhiza polyschid Fucus serratus* and green seaweed *Ulva sp.* The co-digestion of *S. latissima* resulted in the highest biogas yield with a 35% production during the first three days, followed by *S. polyschid* with an increase in production rate from the 13thday.

Similarly, further research should be performed to evaluate the co-digestion of aquaculture effluents and seaweed species for biogas production. Applying this hurdle method would allow small-scale and marginal-scale fish farmers to have renewable and affordable energy sources and treat the effluents. In addition, the biochar produced from biogas production can be used for aquaculture pond sediment management as a mitigation strategy for greenhouse gas emissions (Raul et al., 2020). Comparatively, bioethanol is the most promising alternative fuel for transportation; further research efforts on improving production technology will promote the commercialization of biofuels.

Challenges and Prospects of Seaweed Farming

Seaweed farming and producing seaweed-derived products offer many opportunities and socio-economic growth for stakeholders throughout the food supply chain and other industries, including pharmaceutical, textile, and biofuel sectors (Ismail and Zokm 2025). In addition, seaweed farming provides a positive ecological impact, including carbon sequestration, control of coastal eutrophication, and minimization of ocean acidification (Kim and Kim 2024). Despite the many advantages and the ease of seaweed farming with minimal input and a high output rate, future research efforts and policy interventions should focus on addressing issues highlighted in several studies. Some challenges and future opportunities are discussed below:

Challenges

1. Biofouling is a significant concern in seaweed farming. Epiphyte growth in the cultivation nets competes with the nutrients required for seaweed growth (Sahu et al., 2020). In addition, grazing herbivores reduce the net biomass yield. Thus, strategies must be developed for controlling the biofouling effect.
2. The vast Indian coastline includes both low-tidal and high-tidal regions. New cultivation technologies should be designed and tested to tolerate the harsh effects of the ocean and minimize biomass drifting.
3. With the global temperature increase, seaweed species' survival rate in the open marine water is hindered.

Thermo-tolerant variety development is a plausible strategy to improve biomass yield. In addition, minimal efforts are made to enhance the native species for increasing productivity or specific bioactive compounds with commercial importance. Further research on seaweed variety improvement is recommended.

4. Besides the demand and supply gap of algin and agar in India, the profitability of these products in the international market is limited due to low seaweed extract quality. Government organizations such as FSSAI should re-examine and perform amendments to Indian standards of phycocolloids to qualify them as food-grade with superior quality (Behera et al., 2022).

Future Prospects

1. The Indian coastline is enriched with a wide range of native species of seaweed, but their biochemical composition is seldom documented. In addition, no efforts have been made to investigate the techno-functional properties of these seaweed extracts. By identifying commercially profitable species, local farmers can be encouraged to cultivate native species without introducing invasive species into the coastline.
2. Introducing training programs in marginal communities, especially for women, will empower them to contribute to their families' financial stability, provide quality education, and more.
3. The Indian diet is diverse and versatile, yet food options with nutrient-dense seaweed are uncommon. Food manufacturers and product developers should explore innovative ways to incorporate seaweed-derived ingredients and bioactive compounds in packaged food to increase seaweed market demand.
4. Applying seaweed-derived bio-fertilizers and bio-stimulants in the agricultural sector is economically feasible for farmers and a safer environmental choice (Divakar et al., 2024).

Although the current report discusses the cultivation methods and potential uses of seaweed (macroalgae), microalgae are also an excellent nutrient source and contain valuable bioactive compounds. Identifying economically significant varieties and developing cultivation technologies in fishponds and tanks is paramount. In addition, optimization of farming methods and culture parameters will improve net productivity.

CONCLUSION

This review sheds light on the promising prospects of seaweed farming, particularly within the coastal/brackish water aquaculture sector, and its diverse benefits. Cultivating algae in controlled environments offers a sustainable solution for producing biomass rich in essential nutrients, potentially reducing reliance on traditional aquatic animal feed sources. Furthermore, seaweed farming demonstrates its potential in environmental remediation, particularly in nutrient absorption and carbon sequestration, and various other industries such as pharmaceuticals, biofuels, and wastewater treatment. The present snapshot document emphasizes the relevance of seaweed farming practices in India, highlighting the economic importance of different seaweed species and their commercial uses. It underscores the multifaceted applications of seaweed and seaweed-derived byproducts in various industries, emphasizing the pivotal role of this farming in promoting sustainability within the aquaculture sector and beyond. However, challenges and opportunities in seaweed farming signify the need for continued research and innovation to address hurdles and maximize the potential of this burgeoning industry. Overall, this work encapsulates the significance of algae and seaweed farming as transformative practices that hold the key to a more sustainable future for the aquaculture industry and offer promising solutions to global environmental challenges.

AUTHORS' CONTRIBUTION

Conceptualization of research work and designing of experiments (NKT,VM); Preparation of manuscript (DC, AK).

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