Brief Communication

Economic prosperity and environmental sustainability through seaweed culture

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Introduction

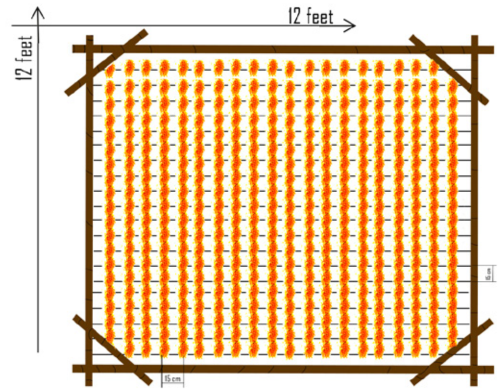
Seaweed farming is a climate-resilient aquaculture practice that provides a sustainable, diversified livelihood option for coastal communities. This cultivation does not require land, freshwater or fertilizers. It reduces the effects of oceanic eutrophication and acidification and oxygenates seawater to create a healthy ecosystem. Seaweeds are valued commercially for their cell wall polysaccharides, such as agar, algin, and carrageenan, and for their bioactive metabolites, manure and fodder. They have a variety of commercial applications in food, pharmaceutical, cosmetics and mining industries. Some seaweeds are also gaining importance as healthy food for human consumption. There are almost 10,000 species of seaweeds available globally that are divided into three main types; red, brown and green seaweeds. India is bestowed with a rich seaweed diversity of nearly 700 species and of these, nearly 60 species are commercially important owing to their high content of polysaccharides. Worldwide, 35.1 million tonnes wet weight of seaweed were produced during 2020, with the first sale value estimated at 16.5 billion USD (FAO, 2022). In India, nearly 47,000 tonnes wet weight of seaweeds are harvested annually from natural seaweed beds (species of *Sargassum, Turbinaria, Gracilaria* and *Gelidiella*) (FRAD, CMFRI, 2023). Estimated Potential Yield of seaweeds from the Indian seas is approximately 0.26 million MT/ year (wet weight) (Kaladharan *et al.,* 2019). India contributes less than one percent of global seaweed production having an annual turnover of around ₹200 Crores. Among the global seaweed production through farming, *Kappaphycus alvarezii* and *Eucheuma denticulatum* contributes to 27.8% of the total seaweed production. Harvesting from natural seaweed beds along the Indian coast is carried out primarily in Tamil Nadu, where the system supports the livelihood of almost 5000 families. In India, seaweed farming is being carried out with *Kappaphycus alvarezii*. It is an economically important red algal species that yields carrageenan, a commercially important polysaccharide. Farming of *K. alvarezii* by the fisherfolk of Tamil Nadu coast had the highest yield; 1,500 tonnes of dry weight, in 2012-13. However, production sharply declined after 2013 due to mass mortality. Approximately 400-500 tonnes of dry weight per year are currently being produced, involving approximately 1,500–2,000 families along the Tamil Nadu coast.

Farming techniques

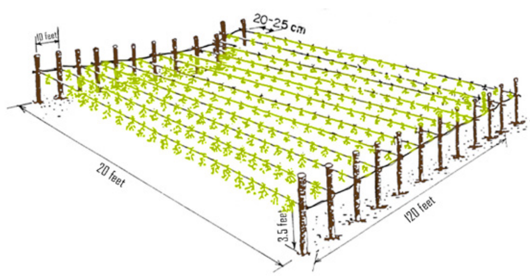
The floating bamboo raft method (12 × 12 feet bamboo poles) is ideal in calm and shallow places. The monoline method of seaweed farming is ideal in places characterized by moderate wave action, shallow depth and less herbivorous fishes. The tube net method is being adopted in places with higher wave actions.

Economics of *Kappaphycus* farming

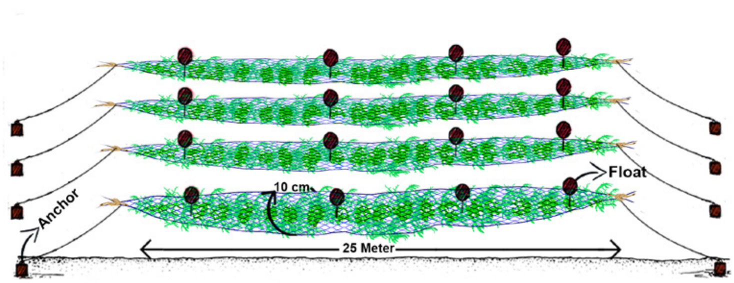
The crop duration for *Kappaphycus* farming is 45-60 days. In a year, four to six crops or cycles (6 to 9 months) can be harvested depending upon the climatic conditions.



Bamboo raft method



Monoline method



Tube net method

Harvested seaweed *Kappaphycus alvarezii*

After seeding, 150 g of plants were grown to 500 to 1000 g in 45 days. The average seed requirement for one 12 × 12 ft raft is 60 kg, whereas for a 25 m long tube net, the average seed requirement is 15 kg. The average dry weight percentage of the harvested seaweed was 10%. Farmers currently receive ₹16/- to ₹18/- and ₹80/- to ₹110/- per kg for fresh and dried seaweed, respectively.

Table 1. Economics of *Kappaphycus alvarezii* farming in bamboo raft system

Components	Details/Cost
Seaweed production: 1,000 kg/raft/year minus 240 kg, which is used as seed material for 4 crops/year	760 kg (wet weight)
Price of seaweed	₹96/ kg/dry weight (Dry weight = 10% i.e., 76 kg)
Total revenue generated	₹7,296/year/ raft @ ₹96/kg/dry weight
Total cost of production (including capital cost)	₹2,000/raft/year
Net revenue	₹5,296/raft/year (₹7,296 minus ₹. 2000)
Total Net revenue (45 rafts*) in dry weight	45 x Rs 5,296 = ₹2,38,320/year
Net revenue from one hectare (400 rafts) in dry weight	₹21,18,400/year

*A person can handle an average of 45 rafts (12 ft x 12 ft)

Economics of *Gracilaria* farming

Seaweed farming trials by ICAR-CMFRI on various islands of the Lakshadweep since August 2020 under the ICAR-sponsored National Innovations in Climate Resilient Agriculture (NICRA) revealed a promising daily growth rate for the indigenous red algae *Gracilaria edulis* and *Acanthophora spicifera*. The experiments focused on farming using PVC net cages, PVC rafts and bamboo rafts. To scale up the trial farming to a large-scale demonstration with people's participation, the Lakshadweep Administration has initiated a commercial-scale demonstration programme involving women Self Help Groups (SHGs) and the seaweed industry with the technical support of the ICAR-CMFRI.

Bamboo, a natural material, was preferred for the scaled-up demonstration of *G. edulis* by the Lakshadweep Administration. However, grazing by green turtles and fouling by filamentous

Harvested seaweed *Gracilaria edulis*

algae are deterrents in bamboo raft-based farming. The crop duration of *G. edulis* farming is 45 days, and five to six crops or cycles (9 months) can be harvested in a year depending on the weather conditions. After being seeded, 50 g of plants reached 500 to 1500 g in 45 days. For one 12 × 12 ft raft, the average seed weight requirement is 20 kg. The average dry weight percentage of the harvested seaweed was 15% and the farmers receive ₹60/- per kg of dried seaweed.

Table 2. Economics of *Gracilaria edulis* farming

Components	Details/ Cost
Seaweed production (average 20 folds growth)	2400 kg/raft/year minus 120 kg as seed material for 6 crops/year = approximately 2,280 kg (wet weight)
Dry seaweed (Dry weight = 15%)	342 kg
Price of seaweed	₹60/ kg/dry weight
Total revenue generated	₹20,520/year/ raft @ ₹60/kg/dry weight
Total cost of production (including capital cost)	₹3,600/raft/year
Net revenue	₹16,920/raft/year (₹20,520 minus ₹3,600)
Total Net revenue (25 rafts*) in dry weight	25 x ₹16,920 = ₹4,23,000/year
Net revenue from one hectare (400 rafts) in dry weight	₹67,68,000/year

*A person can handle an average of 25 rafts (12 ft x 12 ft)

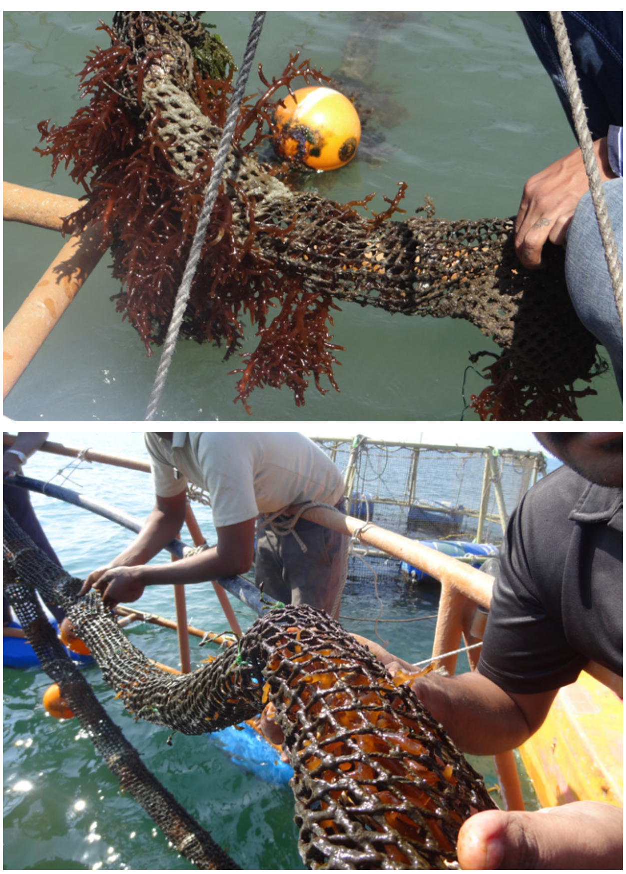
Net-tube integrated seaweed farming at sea cage sites

The cultivation of seaweed has increased in popularity in recent years, which has led to the development of innovative and cutting-edge farming methods. Among several traditional methods of seaweed farming, the net-tube method is the most advanced technique and can be successfully carried out even under extreme weather conditions involving high wind speeds and water currents. It functions effectively in harsh environmental conditions because of its tube-like structure and superior exchange to conventional seaweed techniques, giving it an edge. When the net tube technique is combined with open sea cage farming, such as in Integrated Multi-trophic Aquaculture (IMTA), seaweed grows faster than in a net tube monoculture. Bamboo rafts and the monoline method for seaweed farming are being adopted predominantly along the Tamil Nadu coast. The tube-net method is ideal for coastal states such as Andhra Pradesh and Gujarat.

Net-tube seaweed farming has overwhelmingly favourable socioeconomic advantages, as it involves resource integration and maximum utilization, benefitting fisher folks. Many community-based coastal resource management programmes and fisheries management initiatives have also included this farming technique as an alternate subsistence for fishermen in tropical developing countries. In light of this, it is rational to advocate for seaweed net-tube farming inside sea cages. Net tubes can be further promoted under the Pradhan Mantri Matsya Sampada Yojana (PMMSY)–a scheme to bring about the Blue Revolution via sustainable and responsible development of India's fisheries industry, which can improve resource utilization and help generate more revenue.

Seaweed, *Kappaphycus alvarezii* cultivation using High Density Poly Ethylene (HDPE) raft-based tube net culture method for unprotected sea

Seaweed culture in exposed unprotected sea with dynamic coastal system is not popular like calm and nearshore waters in India due to unavailability of suitable and sturdy faming technology. The floating bamboo raft and monoline methods commonly practiced in India are well adopted and suitable for calm and shallow areas with minimum tidal influences, and these bamboo rafts generally cannot withstand high wave action. Also, seaweeds seeded in monolines are directly exposed to the rough waters, and can get easily damaged. Thus, keeping in hindsight the physical forces existing in tropical marine waters, an innovative High Density Poly Ethylene (HDPE) raft-based tube-net method supported by grid mooring is designed for culturing of *Kappaphycus alvarezii* in adverse climatic conditions prevailing in mainly North East and North West coast of India. This method was tested in the North East coast, off Visakhapatnam and was found suitable to withstand rough weather conditions. High Density Poly Ethylene (HDPE) pipes of 90 mm outer diameter is used to prepare the square shaped (3 x 3 m) floating raft. Short length tube-net (3.0 m in length) is prepared by using HDPE net material for holding growing seaweed. Seeds of 5.0 kg/tube net is seeded separately in each tube net, and 10 different tube nets were attached in one raft structure. Cluster of rafts (25 nos.) were anchored by multi point mooring system with the help of dead-weight permanent anchors made of concrete cement blocks. The five concrete blocks in each corner of the grid are inter-connected with the help of long-link alloy steel mooring chain (13 mm diameter, 80 grade quality). The mooring chain is connected at the top, to the floating HDPE raft with the help of D-shackles. Prior to connection with the raft, fibre reinforced plastic (FRP) cans are attached to the mooring chain at every corner to facilitate chain floatation. It has been observed that the seaweed seeded with approximately 5 kg/tube net helps to yield a production of approximately 30 kg. A total of 300 kg /raft consisting of 10 tube nets could be obtained. Therefore, *K. alvarezii* can be cultured for six cycles in a year with 45 days of culture period/crop. This culture method yields approximately 45,000 kg of seaweed/year/cluster of 25 raft with a net profit of 1.53 lakhs/year/cluster of 25 rafts.



Net tube seaweed farming

Carbon sequestration potential of farmed seaweed

An experiment involving the culture of seaweed (*K. alvarezii*) from three bamboo rafts was conducted to estimate its carbon sequestration potential in Munaikadu, Ramanathapuram district, Tamil Nadu. For each of the rafts (12 ft × 12 ft), three pre-weighed bunches of seaweed were tagged, and their weights were periodically (once in 15 days) measured. Furthermore, subsamples from each bunch were collected, dried and preserved. The samples were analysed for their

HDPE raft-based tube net culture method for *Kappaphycus alvarezii*

carbon content using a CHN- elemental analyser. The average carbon and nitrogen content was 19.92% and 0.99%. The specific growth rate of the seaweed was multiplied by the percent composition of carbon (C) and 3.667 (mass of CO_2= 44/mass of C= 12), which provided an estimate of the specific rate of sequestration (per unit mass of seaweed per unit time) of carbon dioxide by the seaweed. The specific rate of sequestration of CO_2 per gram dry weight of seaweed was 0.018673 g day^{-1} (0.02557 x 0.19915 x 3.667). The specific rate of sequestration (per unit mass of seaweed per unit time) of CO_2 by the seaweed was estimated as 19 kg CO_2/day/tonne dry weight of *K. alvarezii* (= 760 kg CO_2/day/tonne dry weight/ha). The total amount of carbon sequestered in one tonne of dry seaweed can be estimated by multiplying the quantity of dried seaweed by the percent composition of carbon (C). Hence, the total amount of carbon sequestered in one tonne of dry seaweed is 199.2 kg (1000 x 0.1992).

Integrated Multi-Trophic Aquaculture (IMTA)

Intense fishing pressure along coastal waters, coupled with the negative impacts of climate change, has recently started impacting the livelihoods of fishers. While harvests are dwindling, the demand for marine fish is increasing steadily owing to the crucial role of marine fish in ensuring food and nutritional security. This necessitates augmenting marine fish production through the farming of promising commercial species of fish in the sea. Realizing this important priority, ICAR-CMFRI has developed and standardized technologies for the seed production and farming of marine finfishes and shellfishes in open sea cages. One of the anticipated issues while expanding sea cage farming is the possible increase in organic and inorganic loads in water and consequent disease problems. In this context, the idea of bio-mitigation along with increased biomass production can be achieved by integrating different groups of commercially important aquatic species that have varied feeding habits. This concept is known as Integrated Multi-Trophic Aquaculture (IMTA), which has recently gained global importance. ICAR-CMFRI has successfully conducted trials and demonstrated IMTA under the NICRA project by integrating seaweed with sea cage farming of marine finfishes/shellfishes in Tamil Nadu, Gujarat and Andhra Pradesh. This has resulted in an increased production of seaweed, which has improved the livelihood of farmers and contributed to the increase in carbon availability in the country.

Table 3. Economics of IMTA (comparison of integrated and non-integrated seaweed farming)

Particulars	With IMTA	Without IMTA	Gain
Average yield per raft on fresh weight basis (45 days/cycle)	390 kg	250 kg	+ 140 kg
Fresh seaweed production excluding the seed material–60 kg per raft (for 4 cycles, 16 rafts)	21,120 kg (330 X 16 X 4)	12,160 kg (190 X 16 X 4)	+ 8,960 kg
Dried seaweed production (for 4 cycles, 16 rafts) (Dry weight = 10%)	2,112 kg (33 X 16 X 4)	1,216 kg (19 X 16 X 4)	+ 896 kg
Price of dried seaweed (₹ per kg)	96.00	96.00	-
Revenue (₹)	2,02,752	1,16,736	+ 86,016
Costs (₹2,000 /raft)	32,000	32,000	-
Net Profit (₹)	1,70,752	84,736	+ 86,016

Aerial view of IMTA farm at Mandapam

ICAR-CMFRI has promoted cage farming of cobia, a high-value marine fish, since 2010. To achieve environmental sustainability and economic stability, the innovative idea of integrating seaweed with sea cage farming of cobia was demonstrated during 2014-17 at Munaikadu, Palk Bay, Tamil Nadu. A total of 16 bamboo rafts (12×12 feet) with 60 kg of seaweed per raft were integrated for a span of 4 cycles (45 days/cycle) i.e., 180 days along with one of the cobia farming cages (culture period 7 months i.e., 210 days). The rafts were placed 15 feet away from the cage in a semicircular manner to enable the seaweed to absorb the dissolved inorganic and organic nutrient waste that moves along the water current from the cage.

Currently, through IMTA, seaweed rafts integrated with cobia farming cages have a better average yield of 390 kg per raft, while in non-integrated rafts, the yield is 250 kg per raft. An additional yield of 140 kg of seaweed per raft (56% additional yield) was achieved through integration with the cage farming of cobia. Under traditional methods, 1 kg of seaweed grows to 4.1 kg in 45 days. However, the application of IMTA substantially enhanced this growth rate, with seaweed reaching an impressive ~6.4 kg in the same timeframe. An additional net income of ₹86,016/- was generated through the integration of seaweed rafts with cobia cages (Table 3). Carbon dioxide sequestration (per unit mass of seaweed/day/16 rafts/4 crops) into the cultivated seaweed in the integrated and non-integrated rafts was calculated as 47.4 kg CO_2/day/tonne dry weight of *K. alvarezii* vs 30.4 kg CO_2/day/tonne dry weight. Hence, an additional 17.0 kg of CO_2/day/tonne dry weight credit was obtained through the integration of 16 seaweed rafts (4 cycles) with one cobia farming cage (per crop) (Table 4). Thus, in one hectare area, a total of 20 cages of 6 m in diameter can be integrated with 320 bamboo rafts (12× 12 feet) @ 16 bamboo rafts per cage. IMTA is an eco-friendly option ensuring sustainable income for coastal fishers. It is also one of the significant mitigating measures for reducing the adverse impacts of climate change and earning carbon credit in our country.

Table 4. CO_2 sequestration into the cultivated seaweed in the integrated and non-integrated rafts

Particulars	With IMTA	Without IMTA
Fresh seaweed production in tonnes (for 4 cycles of 45 days each, 16 rafts)	24.96 (390 X 16 X 4)	16.00 (250 X 16 X 4)
Dried seaweed production in tonnes (10% of fresh weight)	2.496	1.6
Specific rate of sequestration of CO_2 by the seaweed in kg CO_2/day/tonne dry weight	19.00	19.00
Total amount of CO_2/day/tonne dry weight of *K. alvarezii* sequestered (per unit mass of seaweed /day/16 rafts/4 crops) (2) × (3)	47.4 kg	30.4 kg

Nitrogenous waste removal by seaweeds

The nitrogenous waste removal amounts from the integrated and non-integrated seaweed were 2.49 kg and 1.59 kg, respectively. Hence, an additional 0.9 kg of nitrogen removal was achieved by integrating one cobia farming cage (per crop) with 16 seaweed rafts (4 cycles) (Table 5).

Table 5. Nitrogenous waste removal by seaweeds

Particulars (180 days)	With IMTA	Without IMTA
Fresh seaweed production in tonnes (for 4 cycles, 16 rafts)	24.96 (390 X 16 X 4)	16.00 (250 X 16 X 4)
Dried seaweed production in tonnes (10% of fresh weight)	2.496	1.6
Percentage nitrogen content in dry seaweed	0.996	0.996
Total amount of nitrogen removed during the culture period (2) × (3)	2.49	1.59

Fish carbon

The carbon biomass in the integrated and non-integrated cobia cages were 729.56 kgs= 2675.7 kg CO_2 and 583.11 kgs= 2138.1 kg CO_2 respectively. Hence, an additional 147 kg of carbon credit was generated by integrating one cobia farming cage (per crop) with 16 seaweed rafts (4 cycles). Comparatively, the fish biomass increased 14 per cent in cobia cultured with IMTA compared with those cultured without IMTA (Table 6).

Table 6. Fish carbon in the IMTA system

Particulars (210 days)	With IMTA	Without IMTA
Cobia production in kgs	3,316	2,651
Cobia production in kgs dry weight (Average moisture content of fish is 60%)	1,326.48	1,060.2
Carbon content	729.56	583.11
(Average carbon content of fish is 55% of dry weight)	(55% of 1,326.48)	(55% of 1,060.2)
Carbon content (in kg CO_2 equivalent)	2,675.7	2,138.1

Nitrogenous waste removal by fish

The nitrogenous waste removal amounts from the integrated and non-integrated seaweed were 26.53 kgs and 21.20 kgs, respectively. Hence, an additional 5.30 kg of nitrogen was removed by integrating seaweed with cobia (Table 7).

Table 7. Nitrogenous waste removal by fish

Particulars (210 days)	With IMTA	Without IMTA
Cobia production in kg	3,316	2,651
Cobia production in kgs dry weight (Average moisture content of fish is 60%)	1,326.48 (2% of 1,326.48)	1,060.2 (2% of 1,060.2)
Total amount of nitrogen released during the culture period	26.53	21.20

Water quality parameters of the non-integrated and integrated systems

The water quality parameters of the integrated systems are better than those of the non-integrated farming system.

Table 8. Average water quality parameters of the IMTA system

	Non-integrated		Integrated
Parameters (210 days)	Cobia-Control	Seaweed-Control	Cobia+ Seaweed
Water temperature (^oC)	30.6 ± 2.7	29.8 ± 2.5	29.0 ± 2.1
pH	8.2 ± 0.1	8.1 ± 0.1	8.1 ± 0.1
Salinity (ppt)	34.4 ± 0.5	34.6 ± 0.5	34.6 ± 0.5
Dissolved oxygen (ml/l)	5.2 ± 0.2	5.7 ± 0.3	5.8 ± 0.5
Nitrite (mg-at- NO_2-N/l)	0.00313 ± 0.001	0.00272 ± 0.001	0.00161 ± 0.0007
Nitrate (mg-at-NO_3-N/l)	0.724 ± 0.115	0.580 ± 0.223	0.265 ± 0.100
Phosphate (mg-at-PO_4-P/l)	0.024 ± 0.014	0.012 ± 0.012	0.018 ± 0.013
Silicate (mg-at- Si/l)	0.0160 ± 0.009	0.002 ± 0.001	0.005 ± 0.001
Ammonia (mg-at- NH_3-N/l)	0.046 ± 0.012	0.044 ± 0.008	0.018 ± 0.006

Doubling farmers income

Integrating seaweeds into cage farming systems has proven to enhance fish farmers income as detailed here. In a regular cage culture system with cages of 6 m in dia. x 5 m depth and with either Indian pompano, silver pompano, grouper, cobia, snapper, or rabbit fish as farmed species for a duration of 7-8 months, the annual gross revenue for 2 cages was estimated as ₹17.5 lakhs and the net revenue was estimated as ₹7.0 lakhs. Integrating this cage culture system with seaweeds *i.e.,* 32 seaweed rafts along with 2 cages of fish results in an additional gross revenue of ₹4.79 lakhs from the seaweeds alone. The net revenue after reducing the cost of production (0.64 lakhs) was ₹4.15 lakhs. Thus, integrating seaweeds resulted in enhancement of farmer's income by 60 per cent.

Similarly integrating marine ornamental fish rearing with seaweed culture has also proven to be more beneficial to farmers in terms of economic returns as detailed here. For *Kappaphycus alvarezii* farming in 45 rafts of 12 x12 feet dimension for a culture period of 45 days (4 cycles of culture of 45 days each) the annual gross revenue was estimated as ₹3.28 lakhs and the net revenue was 2.38 lakhs. Integrating ornamental fish rearing along with this seaweed farming system resulted in an additional gross revenue of ₹4.6 lakhs. The ornamental fish rearing system details are as follows: 8 glass tanks of 150 litre each stocked with clown fish at 50 numbers (fish of half inch size) per tank for a rearing period of 60 days for a total of 6 rearing cycles in a year. The annual gross revenue from the ornamental fish was ₹4.6 lakhs and after reducing cost of production (₹2.0 lakhs) the annual net revenue was ₹2.6 lakhs.

Thus, in this integrated system of seaweed and ornamental fish, the economic returns to farmers were enhanced by 109%. Hence, both these types of integrated seaweed farming systems can be promoted as approaches for doubling farmers' income in the coastal regions of the country.

Awareness and outreach programme on the PMMSY

Owing to the importance of seaweed farming, the Government of India is promoting seaweed farming through Pradhan Mantri Matsya Sampada Yojana (PMMSY) by providing financial, marketing and logistical support to ensure income and welfare gains for small fisher populations, especially women- and fisherwomen-headed households. To reach the fishing community at the village level, ICAR-CMFRI has been conducting a series of awareness-cum training programmes on Pradhan Mantri Matsya Sampada Yojana (PMMSY) and seaweed farming. This has created interest among many farmers/entrepreneurs in adopting seaweed farming. Since 2021, a total of 94 training programs involving 8,896 participants have been organized on seaweed farming for the promotion of seaweed cultivation.

Fishermen being sensitised on seaweed and IMTA farming

Promoting seaweed farming

ICAR-CMFRI, which has implemented the Scheduled Caste Sub-Plan (SCSP), NICRA-SCSP, AINP-SCSP and other programmes, provides inputs and technical assistance for seaweed farming activities. A total of 207 families (414 fishers) have directly benefited from this programme and were undertaking seaweed farming on 2,520 rafts along the Tamil Nadu coast.

Promoting seaweed farming activity through Scheduled Caste Sub-Plan (SCSP) Programme

The way forward

Need for large-scale seaweed farming

The domestic requirements for agar and alginate are approximately 400 tonnes per annum and 1,000 tonnes per annum, respectively, whereas only 30% and less than 40%, respectively, of these materials are produced indigenously. The domestic requirement for carrageenan is 1,500-2,000 tonnes/year. Considering the demand for agar, alginate and carrageenan, the total annual seaweed requirement on a dry weight basis is 4,000 tonnes of agar yielding algae, 5,000 tonnes of alginate yielding algae and 4,500–6,000 tonnes of carrageenan yielding algae (Johnson *et al.,* 2023). Hence, to attain self-sufficiency in seaweed-based products, large-scale farming needs to be promoted.

Marine spatial plans

In view of the emerging importance of seaweed mariculture, an all-India preliminary survey for the selection of sites suitable for seaweed farming was conducted by ICAR-CMFRI using approximately 15 parameters across all the maritime states of India. ICAR-CMFRI identified 24,251.9 hectares of potential seaweed farming area (a spatial map of 333 locations with geo-coordinates along the Indian coast within a 1000 m distance from the lowest low tide line) through coastal surveys and remote sensing data analysis (Johnson *et al.*, 2020: Johnson *et al.*, 2023). Out of the 333 sites, trial farming activities were carried out at 78 sites. These sites can yield a maximum of 9.7 million metric tons of seaweed (wet weight) annually, facilitating the country's imminent expansion and effective adoption of seaweed farming. ICAR-CMFRI has also provided a "decision support spatial suitability map for Seaweed Farming in India" (Divu *et al.,* 2021). In line with such studies, a detailed spatial suitability map of seaweed farming sites along the Indian subcontinent along with island systems is essential, and the first step is to cater to the targets anticipated by the nation through commercial farming activities. Hence, prioritization of marine space usage through marine spatial planning is highly essential for creating an investor-friendly atmosphere for seaweed farming augmentation through joint collaboration with maritime state governments since fisheries are a state subject according to the Indian constitution. Apart from these, the most critical factor that must be considered before concluding must be the stakeholder perspective, which in turn must be obtained through various consultation meetings along the country's coastal villages.

Improvement in the quality and quantity of seaweed seed material

The scarcity of quality seed material for *Kappaphycus* cultivation in coastal areas and quality seed materials of native species such as *Gracilaria edulis, Gracilaria dura* and *Gracilaria debilis,* especially after monsoon rains, are the major bottlenecks for the development of seaweed farming in our country. To address this issue, importing high-yielding species/varieties and establishing seedbanks to improve the availability of quality seed material to support farming activities are needed. As a national interest, ICAR-CMFRI has planned to convert four RCC tanks, each with a 1000 tonnes water holding capacity, at the Mandapam Regional Centre for quality seaweed seed production. The dimensions of the three tanks are 30 m×14 m×2.3 m, and one tank is 35 m×15 m×2.3 m. A total of 200 tonnes of *Kappaphycus* seeds per year can be produced and supplied from this facility.

Quality seaweed seed materials

Vegetative cuttings obtained from earlier harvests or from seedlings in natural beds have been extensively utilized in modern seaweed farming. However, there are significant drawbacks to this farming technique, including diminished genetic variability and physiological variance in the seed stock, which lowers the seaweed growth rate, carrageenan yield, and gel strength. Seaweed aquaculture requires more innovative methods than ever before to meet growing worldwide market needs. Large-scale seaweed production continues to face substantial challenges, primarily related to the availability of seedlings for year-round marine farming. As a result, high-quality seedling materials are required for continuous biomass production throughout the year.

Seedlings from natural beds and vegetative propagation

In this method, fragments from plants are used as seeding material and are collected by leaving the basal portion for regeneration.

- The seedlings that need to be harvested should not have any grazing or a whitened thallus (which might indicate disease), and they should be brittle, shiny, and have young branches with sharp pointed tips.
- After sowing, similar to *K. alvarezii* plants, which are farmed through vegetative propagation, healthy seedlings should be collected, preferably from the young portion of the plant, which has more apical portions. If seedlings are taken from other districts/states, they should be placed in a clean net bag and kept at the bottom (1-2 m depth) of the sea for a few days before planting.
- A scalpel was used to collect small, wiry plants, such as *Gelidiella acerosa,* that were firmly connected to the substrate.
- Lengthy plants such as those of the *Sargassum* and *Turbinaria* can be easily collected by hand alone. Handpicking is an effective method for gathering the intertidal and shallow water plants such as *Caulerpa racemosa*, *Ulva lactuca* and *Enteromorpha compressa*, *Acanthophora spicifera* and *Hypnea valentiae* are also handpicked.
- *Gracilaria edulis* grows up to 1-2 m below the surface. It grows as epiphytes on seagrasses, pebbles, and small stones. It is thin and simple to remove from the substrate.
- The seed materials are gathered in seawater-filled plastic buckets, polythene bags, or gunny sacks. For long-distance transit by road, the water conditions would constantly change.
- In the case of seaweed farming unit, if the field conditions are favourable for further cultivation, the remnants of the first harvest are allowed to grow further, or a portion of the harvested material is used as seed material for succeeding crops after the material is brought to the shore and transferred to a plastic bin or FRP tank containing clean seawater.
- The seed materials were collected in gunny bags, polythene bags or plastic buckets containing seawater. Frequent change of water is required on the way for long-distance transportation.

Seedlings through spore production

Spores are typically cultured on an artificial substrate and maintained in a land-based seedling-rearing facility until they reach the appropriate plantlet size for transplantation. The plantlets were attached to ropes and released into the open sea for field cultivation. This method can provide a reliable supply of seedlings for seaweed farming. The reproductive ability of seaweed species largely determines their efficacy. Reproductive cells (spores or gametes) have been used to propagate species with high reproductive potentials, such as the *Pyropia, Ulva, Saccharina, Undaria* etc. Using spores to produce seed is one possible way to increase production and improve cultivation techniques.

- Researchers may develop a combination of various abiotic factors to induce reproductive maturity and eventual sporulation independent of the natural life cycle based on their understanding of the reproductive biology of seaweed.

- Carpospores are easier to use as a seed source because the naked eye can observe their spore sacs (cystocarp). The use of spores as a source of seedlings has been successful in several countries. However, rigorous, long-term experimentation is needed to optimize the conditions that can trigger maturity and sporulation in a given species.

- Thus, for industrial seedling production, it is critical to use optimum culture conditions to manage the development and reproduction of species-specific conchocelis cultures.

- However, the environmental cues that induce fertility and spore/gamete release in this species are difficult to detect, necessitating a fundamental understanding of the underlying biological mechanisms that control the rate of embryo formation and reproductive cycles for successful cultivation. Indeed, an alternative seedling production system that does not rely on vegetative fragments or reproductive cells is expected to address these issues.

Vegetative fragments or reproductive cells (spores or gametes) are principally employed in seaweed farming as a source of propagation in plants (propagules). For such types of seaweed, vegetative reproduction has been successful, especially when vegetative pieces have a greater propensity to increase, as in the cases of *Kappaphycus*, *Gracilaria*, *Gelidiella*, *Gelidium*, etc. Nevertheless, a sizable crop product (one-fourth of the total) is used as a seed for further farming activities. Additionally, using seedlings with the same genotype repeatedly causes vigour loss, a decrease in production, and susceptibility to diseases and pests. The potential loss of all crops owing to sudden changes in climatic conditions is a significant risk factor for seaweed farming in open waters. To support the seaweed farming industry, a novel scalable seedling production technique that generates a large number of high-quality plantlets in a sustainable manner is needed.

Seed production through micropropagation

The use of tissue culture and micropropagation techniques has recently increased the supply of seeds and produced uniform seedlings in considerable numbers in a shorter time, showing promise for the future of seaweed production. Several seaweed species have been successfully cultivated and transformed into new plantlets in laboratory settings through direct regeneration, callus culture, and protoplast culture. Seedling quality is further improved by the addition of bio-stimulants and plant growth regulators to culture media. Micropropagated plants grew more quickly than conventionally cultured plants and exhibited superior biochemical characteristics. To improve their chances of survival, tissue-cultured plants were advised to go through an acclimatization phase before being moved to a land-based grow-out system or ocean nets for farming. Preventing disease, pest infestations, and grazing by herbivorous fish and turtles during construction requires routine monitoring.

Offshore seaweed farming

- Future societal demands for renewable energy and biobased products, such as sources for biodegradable packaging materials, biofuels, and sustainable fertilizers, can be satisfied by offshore seaweed farming, and seaweeds represent an untapped biomass potential. The following are crucial considerations for offshore farming:

- Suitable species of seaweed is to be chosen for offshore cultivation. The seaweed species that are available naturally in the wild in that particular region would be ideal.

- Optimized growth properties suitable with growing in offshore conditions are demonstrated under simulated onshore circumstances.

- The appropriate cultivar need be used for the environment and for mechanical planting and harvesting on sophisticated, extensive textile cultivation substrates.

- Studies on bioprocessing to maximize the production of desired products, such as animal feed from digester waste, should be launched, and butanol production for renewable biofuels should be concentrated.

- An updated economic analysis need be conducted considering the economics of seaweed-related products and offshore seaweed farms.

- By minimizing ship movement, a largely automated and very reliable seaweed farm can be constructed to reduce expenses, risks to people and property, and global warming. This is accomplished by using an Autonomous Underwater Vehicle (AUV) to monitor the growth of the macroalgae and the state of the substrates and anchoring.

- Since production zones serve as nurseries for smaller fish in places off-limits to ships and fishermen, offshore seaweed cultivation also benefits fish populations.

Biotechnological interventions

Advances in plant biotechnology, such as mass propagation, genetic engineering and the production of bioactive compounds, were mainly due to the development of tissue culture techniques. The methods adopted for higher plant tissue culture were modified and used for seaweed tissue culture. The process commonly involves the preparation of axenic explants and their culture on solid agar media enriched with a range of macro- and micronutrients, vitamins and sugars. Even regeneration and callus formation could be achieved. However, for more complex biotechnological applications in seaweeds, absolute control of growth and development, as is achieved through higher plant tissue culture, is required (Baweja *et al.,* 2009). Micropropagation, or *in vitro* clonal propagation, is an effective tool for providing a greater quantity of plants for commercial cultivation in a shorter duration (Yong *et al.,* 2011). This approach will also pave the way for sustainable utilization and conservation of natural seaweed resources (Nair and Yocie, 2011). With the development of a tissue culture system, *in vitro* mass propagation and the production of genetically modified good-quality seedlings can be achieved. Developing *in vitro* cell culture techniques for selected seaweeds is crucial because it will facilitate a year-round mass supply of seed materials maintained under controlled conditions. Strain development and hybridization of *Kappaphycus* and *Gracilaria* through protoplast fusion techniques are envisaged to produce fast-growing, productive and high-temperature-tolerant seaweed seed materials.

Policies and institutional support

The formation of seaweed-based Fish Farmers Producers Organizations (FFPOs) is needed to economically empower seaweed farmers and enhance their bargaining power. The financial support provided under the PMMSY to each FFPO primarily includes the cost of formation and incubation, management, equity grants, training and skill development. Appropriate financing and insurance coverage for crop losses due to natural calamities are essential for further promoting seaweed farming in Indian waters. Currently, Indian seaweed cultivation occurs in nearshore waters. To experiment with offshore farming techniques, policy interventions and their technoeconomic viability are essential. The integration of seaweed and cage farms can be promoted wherever possible for bio-mitigation. As a healthy food for human consumption, seaweed must be promoted through awareness campaigns and festivals.The large-scale mariculture of seaweeds is a green technology that will improve the livelihood of coastal fishers, mitigate major greenhouse gases and prevent ocean acidification.

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