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Seaweed Farming and Utilisation

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI
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Preface

India has emerged as a global leader in fish production, being the largest inland capture producer, the sixth largest marine capture producer, and the second largest aquaculture producer. The country's fisheries are inexorably moving towards a future that is farming-oriented. Among the farmed resources, seaweeds are finding a prime place in the country's aquaculture future. Seaweeds, a highly valuable group of marine macroalgae, have numerous ecological, social, and economic benefits. They have diverse applications, including serving as raw materials for biochemicals like agar, alginate, agarose, and carrageenan, as well as for food, enzymes, medicines, animal feed, fertilizer, cosmetics, textiles, and biotechnology. They also contribute to climate change mitigation processes by serving as carbon sinks, effectively sequestering atmospheric carbon dioxide. Recognizing the potential of seaweed cultivation and the by-product industry in India, the Pradhan Mantri Matsya Sampada Yojana (PMMSY) of the Department of Fisheries, Government of India has allocated a budget of Rs. 640 crores for developing seaweed farming.

The seaweed sector of the country has changed appreciably, moving from a "collection" mode to a "farming" mode, aided by the outputs of several R&D institutes of the country. Over the years, research on seaweed mariculture and utilization have flourished and standardized culture methods for several seaweed species have been brought forth. More recently, ICAR-Cental Marine Fisheries Research Institute (CMFRI) has identified 24,252 hectares of potential seaweed farming area from 333 locations with geo-coordinates on the coast of India within 1 km distance from the lowest low tide line through coastal surveys and remote sensing data analysis. The identified sites alone possess the potential to produce about 10.0 million tonnes of seaweed (wet weight) annually.

The importance of seaweeds and seaweed farming was identified by the National Academy of Agricultural Sciences (NAAS) much earlier. A policy paper on 'Seaweed Cultivation and Utilization' was brought out in 2003 by the Academy. In continuation of that, the present brainstorming session on "Seaweed Farming and Utilization" was organized by the Academy, on 16th November, 2022.

This policy paper is an outcome of the discussion during this brainstorming session. It presents an in-depth analysis of the status, prospects, and way forward of seaweed research & development in India. I believe that the recommendations put forth in this policy paper will provide a succinct roadmap for the development of the seaweed farming sector of the country. I sincerely wish that India emerges as a world leader in seaweed production, ensuring the economic and ecological security of the country and its ecosystems while providing for the nutritional security of the global population.

I, on behalf of the Academy, thank Dr. J.K. Jena Deputy Director General (Fisheries Science), ICAR, Convener and Dr. A. Gopalakrishnan, Director, ICAR-CMFRI, Kochi, Co-convener of the Brainstorming Session for synthesising the opinions, comments, and suggestions of the participants in the form of this document. I also thank my colleague scientists from ICAR-CMFRI, Drs Johnson B., M. Muktha, Kajal Chakraborty, Reeta Jayasankar, Ranjith L., Divu D., and Suresh K. Mojjada, who contributed to the preparation of this document. Further, I place on record my appreciation and thanks to the Editors of the Academy Dr. V.K. Baranwal and Dr. R.K. Jain for their sincere efforts in bringing out this Policy paper.

April 2024 **(Himanshu Pathak)**
New Delhi

Seaweed Farming and Utilisation

1. INTRODUCTION

Seaweeds, a type of marine macroalgae, are highly valued for their numerous ecological, social, and economic benefits. They have diverse applications, including serving as raw materials for biochemicals like agar, alginate, agarose, and carrageenan, as well as forfood, enzymes, medicines, animal feed, fertilizer, cosmetics, textiles, and biotechnology. Seaweeds also contribute to climate change mitigation processes by serving as carbon sinks, effectively sequestering atmospheric carbon dioxide. Presently, 97% of the world's production of seaweed, amounting to 34 million tonnes, comes from farming (FAO, 2022). In India, there are more than 700 seaweed species, with a wet harvestable biomass of approximately 0.26 million tonnes/year. About 52,000 tonnes (wet weight) of seaweeds that occur naturally along the Indian coast are collected every year from seaweed beds (species are *Sargassum, Turbinaria, Gracilaria* and *Gelidiella*) by nearly 5000 families in Tamil Nadu (CMFRI, 2023).

Wild seaweed supplies have proven insufficient to meet industrial demands, necessitating the development of mariculture as a supplemental source. Unlike traditional land-based agriculture, seaweed cultivation offers distinct advantages such as independence from freshwater, arable land, and fertilizers. Moreover, seaweed farming has substantially minimal to no adverse effects on marine and coastal ecosystems, distinguishing it from other commercial aquaculture practices in the present era. Seaweed farming holds significant potential for global climate change mitigation beyond carbon capture. This includes producing low-carbon food, biofuel generation, reduction of methane emissions through seaweed in cattle feed, and substitution of inorganic fertilizers. Seaweed farming systems also provide additional benefits like wave energy attenuation, shoreline protection, pH regulation of surrounding waters, and oxygenation, thereby mitigating the adverse impacts of localized ocean acidification and hypoxia. Consequently, seaweed farming has been suggested as an alternative or complementary approach to traditional agriculture. Moreover, in numerous underdeveloped countries, seaweed cultivation is recommended as a management strategy to alleviate fishing pressures and poverty and empower women in economically challenged coastal communities by providing a sustainable income source.

Realising the importance of seaweeds and seaweed farming, the National Academy of Agricultural Sciences (NAAS) brought out a policy paper 20 years ago after conducting brainstorming session (NAAS, 2003). Further, appreciating the changes that have happened in the seaweed sector during the intervening years, this policy paper examines the current seaweed farming and utilization status in India and makes recommendations for the sector's overall development.

2. STATUS OF SEAWEED FARMING

Farming seaweed is among the world's rapidly expanding industries, encompassing approximately 48 million km^2 of farming regions among 132 nations, with 44 countries actively engaged in seaweed production. It is reported that 27 different seaweed species are being cultivated worldwide (FAO, 2022). China and Indonesia hold the top positions in seaweed production in Asia and also globally. In India, seaweed farmers primarily operate on a small scale, cultivating predominantly red algae in small patches of intertidal sand flats. The main cultivation methods involve vegetative propagation using fragments from mother plants or different kinds of spores. The ICAR-Central Marine Fisheries Research Institute (CMFRI) has been actively engaged in seaweed mariculture and utilization in India since the early 1970s and the institute has standardized raft culture methods for five species of native seaweeds (CMFRI, 1987). India is raising its stature as an important country in South Asia cultivating the exotic seaweed species *Kappaphycus alvarezii* with the creation of employment of about 765,000 man-days and a turnover of about each year Rs. 2.0 billion (Mantri *et al*., 2017). The sea-farming of *K. alvarezii*, that yields kappa carrageenan, began in 2000 with the support from PepsiCo India Holdings Ltd with the plantlets brought from Southeast Asia. The cultivation was carried out in the coastal waters of Tamil Nadu, Odisha, Gujarat, and Daman and Diu, with technical assistance from CSIR-Central Salt and Marine Chemicals Research Institute (CSIR-CSMCRI), Bhavnagar. Currently, commercial *K. alvarezii* farming is being done primarily in Tamil Nadu and is concentrated in five coastal districts of the state, engaging nearly 1000-1500 families. Two seaweed farming techniques are in vogue: floating bamboo rafts and tube nets (net sleeves) with an average annual production of 5200 tonnes fresh weight. The present market rate for *Kappaphycus* sp. is approximately Rs. 85-90/kg (dry weight). Farming of native species is, however, very meagre with the annual yield of *Gracilaria edulis* being approximately 60 tonnes (wet weight).

3. PROSPECTS OF SEAWEEDS AND ITS FARMING METHODS

3.1. Seaweed as a Source of Commercial and Bioactive Products for Human Consumption

Seaweeds have evolved with diverse bioactive secondary metabolites as a defense mechanism to thrive in the complex oceanic environment. Several studies have been conducted on these secondary metabolites, and numerous beneficial components have been identified in seaweeds. These components offer a range of health benefits, including antioxidation, anticancer and antibacterial activity, chemoprevention against vascular diseases, and mitigation of complications arising from diabetes (Fahmida Sultana et al., 2023). Seaweeds are regarded as a medicinal food of the 21st century, owing to their exceptional nutritional value and the wealth of bioactive compounds they possess. Recognizing the significance of these bioactive compounds, the ICAR-CMFRI has established a research program dedicated to systematically identifying candidate seaweed species for developing promising bioactive molecules with potential applications in terms of human health and medication. Over a dozen bioactive products with nutraceutical applications have been successfully developed and commercialized by the Institute, targeting lifestyle diseases such as rheumatic arthritis, diabetes, hyperlipidemia, hypothyroidism, hypertension, osteoporosis, non-alcoholic fatty liver disease, and boosting immunity, and reducing post-covid complications (Gopalakrishnan *et al*., 2020). Similarly, the ICAR-Central Institute of Fisheries Technology (ICAR-CIFT) has also made significant progress in developing edible and processed products derived from seaweeds (Gopalakrishnan *et al*., 2020). These innovations hold the possibility for the utilization of seaweeds by the food industry and for upscaling production in a region that traditionally does not consume seaweeds.

3.2. Nutritional Value of Seaweed as the Food of the Millennium

Seaweeds contain essential nutritional components such as proteins, lipids, carbohydrates, vitamins, and minerals. However, the specific composition of these components varies by seaweed species, the time of harvesting, the geological habitat, and the environmental conditions during growth. Seaweeds typically have protein levels ranging from 5-47% on a dry-weight basis. The protein content of seaweeds consists of essential amino acids, making up approximately 42-48% of the total amino acids content. Seaweeds are acknowledged as low-calorie foods due to their reduced lipid content, typically ranging from 0.5-4.5% of the dry weight. These lipid fractions in seaweeds contain various essential fatty acids, enhancing their suitability as a supplemental food or as a balanced diet. Approximately 50% of the lipid content in seaweeds consists are polyunsaturated fatty acids. Seaweeds also have a low ratio of Omega-6 to Omega-3 fatty acids, resulting in seaweeds being good sources of dietary lipids. Seaweeds are also abundant in low molecular weight carbohydrates (Fahmida Sultana *et al*., 2023). The polysaccharides found in seaweeds can be classified into structural polysaccharides and storage polysaccharides, which in turn contribute to the dietary composition of seaweeds.

Seaweed species possess unique storage polysaccharides, including agar, carrageenan, and alginate, which are highly valued components with significant economic importance. Seaweeds provide a considerable amount of dietary fibre while being consumed as food. Seaweeds are abundant sources of water-soluble and fat-soluble vitamins, offering a diverse range of essential nutrients. Notably, seaweeds stand out as one among the select few vegan suppliers of Vitamin B12, making them an essential dietary source for vegetarians and vegans to meet their nutritional requirements.

Seaweeds are excellent sources of minerals and trace elements, comprising about 8-12% of their dry weight. They are particularly exceptional as a natural and bioavailable source of dietary iodine. Seaweed species contain significantly higher levels of calcium (Ca) compared to cow'smilk, up to 10 times more, and are readily absorbed by the human body. Available literature indicate that pregnant and breastfeeding women and, individuals experiencing malnutrition can benefit from regular seaweed consumption to ensure an adequate intake of these essential minerals (Fahmida Sultana *et al*., 2023).

Green algae like *Ulva* spp. and *Caulerpa* spp. can be consumed directly with the benefits of proteins, essential amino acids, minerals, vitamins, and low fat content. It is reported that *Ulva lactuca* consumption may help to lower cholesterol levels and is proven to have anti-tumor, anti-influenza, and anti-coagulant activities. Food Safety and Standards Authority of India (FSSAI) is in the process of finalizing safety standards for the human consumption of green edible seaweed (Johnson *et al*., 2023b).

3.3. Prospects of Seaweeds for Ensuring Food Security

Seaweeds represent a concentrated nutrient source as they are created and used following safety standards. By promoting the cultivation and consumption of seaweeds, we can address three critical challenges to sustainable productivity: the availability of cultivable land, freshwater resources, and the need for fertilizers. Most types of seaweed are considered edible and offer a significant and sustainable supply of essential macro- and micronutrient composition in the human diet (Fahmida Sultana *et al*., 2023). Consequently, seaweed farming offers promise to not only supplement traditional agriculture but also serve as a viable alternative. It is estimated that cultivating just 2% of the ocean's surface covered by species of seaweed could effectively double the current food output of traditional agriculture (Fahmida Sultana *et al*., 2023). This expansion in seaweed farming would contribute to increased food production and provide additional environmental benefits and services.

3.4. Seaweed Farming and Climate Change Mitigation

While climate change affects the entire world, its impacts are particularly severe on developing nations that lack resources to afford expensive climate change mitigation measures. Coastal and marine ecosystems that can absorb and sequester carbon can play a vital function in global mitigation efforts. Seaweed farming presents a viable solution for coastal countries to lessen the effects of climate change, as it requires minimal investment and offers numerous additional benefits. Large-scale seaweed mariculture has been recognized as a climate-resilient aquaculture technique that can mitigate ocean acidification. Both natural seaweed beds and cultivated seaweed farms serve as significant carbon dioxide (CO_2) sinks playing an active role in reducing and adapting to climate change. They have been considered as effective "Blue Carbon" sinks, on par with other coastal and marine macrophytes. Along the coast of India alone, it is estimated that the biomass of seaweeds possesses the capacity to absorb and utilize 3017 tonnes of CO_2/day. In comparison, the emission stands at 122 tonnes of CO_2/day, resulting in a net carbon credit of 2895 tonnes/day. The specific rate of sequestration of CO_2 per gram seaweed dry weight was 0.018673 g day^{-1} (0.02557 × 0.19915 × 3.667). The specific rate of sequestration (per unit mass of seaweed per unit time) of CO_2 was estimated as 19 kg CO_2/day/tonne dry weight of *K. alvarezii* (= 760 kg CO_2/day/tonne dry weight/ha) (Johnson *et al*., 2023b).

The concept of Blue Carbon, which involves utilizing coastal ecosystems in order to lessen climate change while delivering co-benefits such as coastal preservation and improved fisheries, has gained global attention. Biofuels derived from seaweed offer a more environmentally sustainable alternative to biofuels produced from terrestrial crops. Large-scale conversion of seaweed into bio-ethanol would provide significant climate resilience advantages. The inclusion of fermented seaweed (approximately 2% of specific seaweed species) in cattle feed can enhance ruminant digestion and significantly reduce methane gas production by up to 99%. This has important implications for reducing the amount of greenhouse gases released from the agricultural sector. In agriculture, applying highly nutritious seaweed biochar or compost can enhance soil quality, leading to improved crop productivity. This can help to avoid the emissions resulting from the manufacturing of artificial fertilizers. Moreover, the presence of extensive seaweed farms strategically located can offer coastal protection by attenuating wave energy and reducing physical damage caused by intensifying storms resulting from climate change (Johnson *et al*., 2023b).

3.5. Integrated Multi-Trophic Aquaculture (IMTA)

The adverse effects of climate change along with high fishing pressure in coastal waters have started affecting the livelihoods of fishers. Though harvests are declining, demand for seafood is on the rise owing to its crucial role in ensuring the food and nutritional security of the population. Thus, there is a necessity to augment marine fish production through farming of promising commercial fish species in the sea. Realizing this as important priority, ICAR-CMFRI has developed and standardized technologies for seed production and farming of marine finfish and shellfish in open sea cages. A possible issue with increased sea cage farming is the potential enhancement in organic and inorganic load in the water which could result in disease problems. To overcome this, integrated culture with different groups of aquatic species with differing feeding habits can be explored. This approach known as Integrated Multi-Trophic Aquaculture (IMTA) can result in bio-mitigation along with enhanced production. ICAR-CMFRI has successfully conducted trials and demonstrated IMTA by integrating seaweed with sea cage farming of marine finfishes/shellfishes in Tamil Nadu, Gujarat, and Andhra Pradesh. This has resulted in increased production of seaweeds, which has improved farmers' livelihoods and contributed to the country's carbon credit. During 2014-20, the institute successfully demonstrated the IMTA by integrating cobia culture in cages with seaweed culture in rafts at Munaikadu, Palk Bay, Tamil Nadu. Sixteen bamboo rafts (12 × 12 feet) with 60 kg of seaweed per raft were integrated for 4 cycles (45 days/cycle) along with one cobia farming cage. The rafts were positioned semi-circularly, 15 feet away from the cage to allow the seaweed to absorb the dissolved inorganic and organic nutrient wastes that move from the cage along the water current.

Currently, through IMTA, seaweed rafts integrated with cobia farming cages had a better average yield of 390 kg per raft, while in the non-integrated raft, the yield was 250 kg per raft. Through the integration with cobia cage farming, an additional 140 kg of seaweed per raft (56% more yield) was achieved. A supplementary net income of Rs. 86,000 was realised by integrating rafts of seaweed with cobia cages. Carbon dioxide sequestration (per unit mass of seaweed/day/16 rafts/4 crops) by the cultivated seaweed in the integrated and non-integrated rafts was 47.4 kg CO_2/day/tonne dry weight of *K. alvarezii* vs 30.4 kg CO_2/day/tonne dry weight, respectively. Hence, an additional 17.0 kg of CO_2/day/tonne dry weight credit was achieved by integrating 16 seaweed rafts (4 cycles) with one cobia farming cage (per crop). In one hectare of area, 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 for ensuring a steady source of income to the coastal fishers and has been successfully taken up by more than 40% of sea cage farming entrepreneurs in Tamil Nadu, Karnataka, and

Andhra Pradesh. Moreover, it is a crucial mitigating strategy for reducing the adverse impacts of climate change and generates income for the country and earning carbon credit (Johnson *et al*., 2023b).

3.6. Seaweed Farming and Women Empowerment

In low-income and developing nations, implementing seaweed farming has shown to be a powerful strategy for empowering coastal women. By engaging in seaweed cultivation, women can generate income while balancing their traditional household responsibilities. This has a significant positive impact on their socio-economic status as observed in various countries such as Tanzania, Indonesia, Kenya, and others. The income earned through sustainable seaweed farming has enabled women to improve their living standards by providing resources for their children's education, healthcare, housing, and clothing. In India, governmental and non-governmental organizations have established seaweed culture projects in coastal regions, focusing on ensuring women's participation. For instance, the "Tamil Nadu Women's Empowerment Project" in Tamil Nadu, India was an internationally funded initiative that specifically aimed to promote seaweed farming and ensured the participation of women, with a target of 50% female involvement (Fahmida Sultana *et al*., 2023). Hence, it is envisaged that expanding seaweed farming in the country will further enhance the socio-economic status of coastal fishermen and farmers, contributing to the overall empowerment of coastal communities.

3.7. Potential areas of seaweed production on the coast of India

The commercial expansion of seaweed production in India can create significant rural employment opportunities and contribute to the growth of the rural economy. Given India's extensive coastline, there is ample scope for developing seaweed farming activities. The ICAR-CMFRI has identified 24,252 hectares of potential seaweed farming area (spatial map of 333 locations with geo-coordinates on the coast of India within 1 km distance from the lowest low tide line) through coastal surveys and remote sensing data analysis (Johnson *et al*., 2020; Johnson *et al*., 2023a). Out of 333 sites, trial farming activities are being carried out at 78 sites. The identified sites alone possess the potential to produce 9.7 million metric tonnes of seaweed (wet weight) annually. Recognizing the potential of seaweed cultivation and the by product industry in India, the Pradhan Mantri Matsya Sampada Yojana (PMMSY) of the Department of Fisheries, Government of India has allocated a budget of Rs. 640 crores for developing seaweed farming. The PMMSY with its various components and schemes aims at promoting seaweed farming, aiming to provide direct and indirect employment to about 0.5 million people in the initial stage. Under the PMMSY, the objective is to transform the seaweed farming sector by significantly increasing seaweed cultivation in the country. The target is to reach 1.12 million tonnes of seaweed (wet weight) within 5 years. The PMMSY is being implemented in a mission mode, providing financial, marketing as well as logistic assistance to small fisher populations, especially women and households led by fisherwomen. The support includes the establishment of tissue culture sections, nurseries, processing and marketing, seed banks for seaweed, and many more. By promoting seaweed farming under the PMMSY, the objective is to not only increase production but also to ensure income and welfare improvement for small fisher communities. This is expected to contribute to the overall development and growth of the seaweed farming sector in India.

4. NEED FOR PRIORITIZING SEAWEED RESEARCH

Seaweed faces significant challenges in terms of accessibility, consumer acceptance, and nutritional considerations. Accessibility and affordability of seaweed food products are crucial aspects that need to be addressed. Additionally, it is necessary to overcome the unfamiliarity and confusion among consumers regarding the nutritional value of seaweed compared to traditional foods. Introducing seaweed as a new food ingredient can be a complex process, requiring time for societal acceptance on a global front. Therefore, achieving consumer acceptance for using seaweed as a primary agricultural food product poses a considerable challenge. To overcome these obstacles, concerted research efforts involving social scientists are necessary to understand consumer preferences and attitudes. It is important to remember that the health benefits associated with seaweed may not be universally applicable, as the digestibility and nutritional composition can vary across different species. Hence, species-specific nutritional research is essential, alongside cultivation and product development research. Furthermore, the high mineral content of seaweed raises concerns about potential health risks associated with excessive consumption, highlighting the importance of establishing guidelines and educating consumers on proper intake levels. Addressing these challenges requires a multidisciplinary approach, encompassing scientific research, cultivation techniques, product innovation, consumer studies, and effective communication strategies to promote the nutritional benefits and safe consumption using seaweed as a staple food.

The current technology used in seaweed farming relies on simple structures that can only be deployed in relatively sheltered areas, limiting the potential farming zones. Therefore, it is necessary to develop suitable structural designs that can sustain seaweed farms in open seas, expanding the reach of the farming sector. Spatial planning is also necessary to prevent adverse interactions with other coastal users, such as navigation, and minimize the potential environmental impacts of seaweed farming. The possible consequences of introducing exotic seaweed species must be carefully evaluated. It is necessary to assess these species, their ecological impacts, and potential invasiveness to ensure the sustainability of seaweed farming practices.

The increase in seaweed production may lead to a decrease in market prices, discouraging farmers from participating in this industry. To address this issue, developing multiple value chains within the seaweed industry is vital, promoting diverse uses and applications for seaweed products to create sustainable economic opportunities for farmers. Despite extensive research, seaweed-based biofuels have not yet been commercially viable or reached the market. Therefore, further research efforts are needed to overcome the existing challenges and explore the potential of seaweed-based biofuel production. The ongoing research efforts are necessary to address the various challenges associated with seaweed cultivation, including pollution risks, technological advancements, spatial planning, market competitiveness, as well as the creation of new value chains. This will contribute to the sustainable growth and use of seaweed resources that benefit both the industry and the environment.

5. WAY FORWARD

The availability of high-quality seed materials is a primary requisite for successful seaweed farming. The promotion of commercial seaweed culture in India, therefore, requires the assured supply of quality seed materials of important cultivable seaweed species. Import of improved stocks of *K. alvarezi* from the major seaweed-producing countries *viz*., Indonesia and the Philippines and the development of seed-banks at different locations in the potential regions is of paramount importance. Additionally, expanding the range of cultivars by introducing species like *Spinosum* and higher agar-yielding *Gracilaria* species will require conducting ecological sensitivity studies to ensure their compatibility with local ecosystems. Developing *In vitro* cell culture methods is crucial for seaweed farming enabling year-round mass production of seed materials under controlled conditions. This approach ensures a consistent supply of high-quality seeds and reduces reliance on seasonal fluctuations. To further advance seaweed farming in Indian waters, it is important to focus on the creation of novel and improved strains of seaweed through techniques such as strain development, hybridization, and protoplast fusion. Introducing promising exotic seaweed species with high yield, adaptability, and utility is also crucial for enhancing productivity. Adequate financing and insurance coverage against crop losses caused by natural calamities is necessary to provide support and security to Indian seaweed farmers.

To foster the growth of the seaweed farming sector, it is necessary to establish strong linkages between the farm sector and the seaweed-based products industry. This will ensure that the sector growth is demand-driven rather than solely focused on supply. Leveraging recent innovations in secondary metabolites, nutraceuticals, processed products, plant growth promoters, and fertilizers, it is necessary to promote start-up ventures and develop a thriving post-harvest industry. The development of an alternative seaweed-based cattle feed industry holds promise in lowering the amount of methane released from the livestock sector. Creating successful farm-industry linkages will require establishing a favourable business environment around major seaweed farming areas, with initial support from the government regarding technical assistance, financial aid, and policy framework. Key focus areas should include leasing and licensing policies in coastal and offshore regions, business incubation for technology ideas, regulated contract farming arrangements, value chain studies, credit and insurance support for industrial units, and environmental and green certification, packaging, branding, and logistics for business development. Exploring international technology partnerships, business collaborations, and foreign trade opportunities may further support the growth and expansion of the seaweed farming sector in India.

Over the previous few decades, scientific advances in seaweed farming technology have brought significant improvement in the seaweed sector. However, challenges still have to be addressed to ensure sustainable production, diversified uses, and societal acceptance. The cultivation process begins with the careful selection of suitable species and appropriate culture sites in coastal waters, considering things like the quality of water nutrient availability, and ecological impact. This ensures that seaweed can be produced sustainably at an affordable cost while maximizing the benefits. Furthermore, maintaining a market price that incentivizes farmers to participate in seaweed farming is essential for its continued growth. This requires a balance between production costs, market demand, and profitability. Regulations should be established to enhance the quality of some seaweed species and their derived products for human consumption. This includes setting standards for cultivation practices, harvesting methods, and processing techniques to ensure food safety and nutritional value. Determining the optimal daily intake of seaweed or seaweed products in order to maintain a healthy diet is an important area of research. Understanding the nutritional composition and bioactive substances in different seaweed species can help establish guidelines for consumption and maximize the health benefits they provide. Promoting best management practices is significant for the success of seaweed farming. Disseminating these practices among stakeholders, including farmers, researchers, policymakers, and consumers, is important to ensuring their adoption and implementation. The industry of seaweed cultivation can further develop and contribute to sustainable food production, economic development, and environmental conservation by addressing these scientific and practical challenges. Continued research, collaboration, and knowledge exchange among scientists, industry players, and policymakers are vital for advancing and integrating seaweed farming into global food systems.

6. KEY RECOMMENDATIONS

- Establishment of facilities for round-the-year quality planting material production and supply of all economically significant species of seaweed in different coastal states to be given utmost priority. Micro-propagation techniques for large-scale planting material production may be up-scaled, including establishing pan-India cold chain transportation of seaweed seed material.
- For the final earmarking of the most suitable seaweed farming areas along the coast of India, pilot-scale seaweed farming may be initiated in potential cultivation areas that ICAR-CMFRI has already identified in consultation with the state and local administration, fishermen associations, NGOs, and religious organizations. Such areas may be demarcated as the ‘right to use’ locations for the cultivation of seaweed.
- Alternate high-yielding native and exotic species need to be evaluated and brought under farming to reduce the dependency on single species – *Kappaphycus alvarezii* farming.
- The efficacy of native seaweed species as a fodder supplement for lowering the amount of methane released from livestock may be studied, and large-scale cultivation of such species may be given top priority.

- Offshore farming, experiments on land-based cultivation of seaweed, and integrated multi-trophic aquaculture (IMTA) with native seaweed species may be promoted.
- Efforts to develop FSSAI guidelines for seaweed products/recipes (including dried products) for human consumption and guidelines for the import and assessment of non-native seaweed species may be hastened.
- The necessity for strengthening research on the development of more bioactive compounds and bio-stimulants and branding of these specialized products with the handholding of GoI departments and other sister organizations. There is also an urgent need to improve the market share of these products at Indian and global levels.
- Developing efficient genomic resources and genome editing tools for the Indian macroalgal species to characterize their genes are the need of the hour. These would ultimately help in breeding programmes to develop seaweed strains that have better yields, produce more commercially valuable compounds, and showing improved resilience to the impacts of climate change.
- Surplus seaweed material may be purchased directly by the Government at a minimum support price to promote seaweed cultivation. Also, steps may be initiated to introduce insurance schemes with affordable premiums to protect seaweed farming against natural calamities and harvest loss due to diseases.
- To promote seaweed consumption in India, nationwide seaweed consumption campaigns, seaweed product festivals, and even a day for seaweeds, such as "National Seaweed Day", are to be organized.

7. CONCLUSION

Seaweed culture and utilization offer a sustainable and multifaceted approach addressing environmental challenges, enhancing food security, and promoting economic development. Through careful planning, research, and policy support, the cultivation and application of seaweeds can be harnessed to foster a greener and more sustainable future. By embracing this opportunity and implementing effective policies, the vast potential of seaweed culture and utilization can be unlocked, benefiting both present and future generations.

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