Potential of Seaweeds as a Source of Chemicals and Other Useful Products

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Abstract

Seaweeds, often termed the "Blue Gold" of the oceans, represent a largely untapped reservoir of high-value phytochemicals and sustainable industrial feedstocks. The article explores the transition of seaweeds from traditional sources of phycocolloids (agar, alginate, carrageenan) to next-generation bio-resources for the pharmaceutical, nutraceutical and chemical industries. We examine the potential of Indian seaweed species in yielding novel bioactive compounds such as sulphated polysaccharides, polyphenols and pigments which have demonstrated efficacy in managing lifestyle diseases. Furthermore, the article delves into the concept of the "Seaweed Biorefinery," a cascading processing model that integrates the extraction of high-value specialty chemicals with the production of biofuels and agricultural biostimulants. By aligning advanced chemical processing with sustainable mariculture practices like Integrated Multi-Trophic Aquaculture (IMTA), the Indian chemical industry stands at the precipice of a Blue Economy revolution that promises both economic resilience and environmental sustainability.

Introduction

The global pursuit of sustainable and renewable alternatives to fossil-based resources has increasingly shifted attention toward the oceans. Among marine resources, seaweeds (marine macroalgae) have gained prominence as a high-value biomass, often referred to as "Blue Gold." Global seaweed production (2022) is 37.8 million tons (FAO, 2024). Top producers are China, Indonesia, Republic of Korea and Philippines. India production in 2023 (wet weight) is 72,000 tons (CMFRI, FRAEED, 2024). With a coastline exceeding 11,000 km and a rich repository of more than 800 documented seaweed species, India is uniquely positioned to spearhead a "Blue Revolution." In India, seaweeds were traditionally viewed mainly as sources of basic hydrocolloids or as niche food products. Recent advances in marine chemistry and biotechnology, however, have revealed their far greater potential. Seaweeds function as sophisticated biological systems capable of producing a wide spectrum of distinctive chemicals, biopolymers and bioactive compounds that are rarely, if ever, synthesised by terrestrial plants.

Seaweed Value Chain: From Cultivation to Industry – Global Status

According to the estimated global mass flow of cultivated seaweeds from the origin, type, species, then industry and end use in 2019 highlights the dominance of cultivated seaweeds, which account for about 97 percent out of the total 35.76 million tons produced worldwide. Red seaweeds (51%) are primarily utilised

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for carrageenan and agar extraction, while brown seaweeds (46%), particularly *Laminaria/Saccharina* and *Undaria*, contribute significantly to alginate production and direct food uses. Red seaweeds were found to be the largest contributors to the hydrocolloids industry, for both food and non-food applications. A substantial proportion of seaweed biomass is converted into food hydrocolloids (35%) for applications in meat, dairy, confectionery and bakery products, alongside non-food hydrocolloids (21%) used in pharmaceuticals, personal care products, pet food and other industrial sectors. Direct human consumption of seaweeds accounts for about 36 percent, underscoring their importance in traditional diets, especially in Asian countries. (Liam Janke, 2024, Journal of Industrial Ecology, 28 (5): 1256-1269).

Seaweed Value Chain: From Cultivation to Industry – India Status

India's seaweed industry stands at a critical inflection point. Although production capacity has grown in recent years, a substantial share of the biomass is presently utilised for bio stimulant formulations. Market assessments, however, clearly indicate that the greatest opportunities for value addition and import substitution lie in the production of phycocolloids.

ITC-HS Code	Seaweed imports to India (quantity in tons)			Seaweed imports to India (value in lakhs)		
	2019-2020	2020-2021	2021-2022	2019-2020	2020-2021	2021-2022
Seaweeds for human consumption (12122110)	28.46	85.60	0.02	47.45	98.84	2.35
Kappa carrageenan (13023240)	421.27	79.16	15.45	4100.13	687.75	177.72
Sodium alginate (39131010)	2148.17	1665.78	1361.46	7454.11	4999.46	6379.12
Agar-agar (13023100)	437.82	412.94	410.30	6897.52	6632.36	5486.74

Source: Tradestat, 2022 & Anilkumar, P. K., TIFAC, 2022

The import data clearly indicate India's continued dependence on seaweed-derived products. With clearly defined HS codes covering products ranging from seaweeds for human consumption (12122110) to industrial-grade kappa carrageenan (13023240) and sodium alginate (39131010), the regulatory framework is already in place. Market demand for these products is well established. Bridging the gap between raw seaweed biomass and high-value derivatives now requires species-specific cultivation strategies and adequate processing infrastructure to reduce import dependence.

Phycocolloids	Current demand	Actual production	Seaweed (Dry Weight) requirement to meet phycocolloid demand	Current seaweed production through culture/ collection (dry weight)
Agar (tons)	400	120	4000	5000
Alginate (tons)	1,000	400	5,000	4000 – 5000
Carrageenan (tons)	1,500 – 2,000	150 – 200	4,500 – 6,000	600

At present, there is a high demand for carrageenan, agar and alginate, of which only about 10%, 30% and 40%, respectively, are met through domestic production. Consequently, India's pharmaceutical, food and cosmetic industries remain heavily dependent on imports of these critical inputs. Notably, even seaweed-based biofertilizer raw materials such as *Ascophyllum nodosum* powder are imported, underscoring a strategic gap that could be effectively bridged through the development and utilisation of suitable indigenous seaweed resources. While seaweed availability is nearly sufficient to meet agar and alginate requirements, it remains inadequate for carrageenan, indicating a strong opportunity for emerging domestic industries to capitalise on this potential and generate revenues of nearly ₹175 crore annually.

Marine Chemical Resources Beyond Phycocolloids

Traditionally, the industrial exploitation of seaweeds has centred on the extraction of phycocolloids namely agar, alginate and carrageenan which serve as essential gelling, thickening and stabilising agents in the food, textile and pharmaceutical industries. Agar and agarose, obtained from red seaweeds such as *Gracilaria* and *Gelidiella*, are indispensable for microbiological culture media and have gained increasing importance in molecular biology applications, while alginates derived from brown seaweeds like *Sargassum* and *Turbinaria* are widely used as viscous gums in textile printing, wound dressings and related biomedical applications; carrageenan, another red seaweed based polysaccharide, plays a critical role in dairy and processed meat products. Although these phycocolloids continue to form the backbone of the seaweed industry, the modern chemical sector is progressively shifting its attention toward high-value, low-volume metabolites.

Thriving in harsh, saline and highly competitive marine environments, seaweeds have evolved to produce a diverse array of unique secondary metabolites such as sulphated polysaccharides (including fucoidans and laminarins), polyphenols, terpenes and sterols which exhibit significant biological activities and offer promising avenues for advanced industrial and biomedical applications.

> **Seaweed mariculture is among the few industrial activities that can be described as nature-positive. Seaweeds are autotrophic organisms and do not require freshwater, cultivable land, or external fertilizers for growth. More importantly, they function as effective carbon sinks.**

Pharmaceuticals and Nutraceuticals: A Marine Pharmacy

One of the most promising areas for chemical engineers and biotechnologists is extracting health-promoting compounds from seaweeds. Research at ICAR-CMFRI has shown that marine macroalgae are rich sources of bioactive substances with anti-inflammatory, anti-diabetic, anti-microbial and antioxidant properties. The Indian nutraceuticals market has recorded a strong compounded annual growth rate of about 20% over the past three years (ICAR-CMFRI, 2022), with significant expansion in functional foods, antioxidants and immunity-enhancing products. It is projected that by the end of 2025, the market will expand from approximately $4 billion to nearly $18 billion (Yadav & Mehta Malik, 2020).

Several nutraceutical products have already been developed and commercialised by ICAR-CMFRI for human well-being and to treat lifestyle diseases and metabolic disorders, including Cadalmin TMAntidiabetic extract for use against type-2 diabetes (ADe), CadalminTM LivCure extract for use against non-alcoholic fatty liver disease/NFALD (LCe), CadalminTM Green Algal extract (GAe), anti-arthritic nutraceutical for joint pain/arthritis, anti-hypothyroidism-extract for use against hypothyroid disorders (AHe), CadalminTM Antiosteoporotic (AOe) and Immuno-boost-extract (IBe), CadalminTM Antihypertensive-extract for use against hypertension (AHe), CadalminTM Immunalgin extract (IMe) to improve immunity against delta variant of SARS CoV-2 virus and Antihypercholesterolemic-extract (ACe) for use against dyslipidemia. CadalminTM Antibacterial extract as topical skin care ointment (CadalminTM ABe) from seaweed and Probiotic Nutraceutical to Improve Intestinal Gut Microflora: CadalminTM Cardiocto extract (CadalminTM COe) nutraceutical to combat cardiohypertrophy.

The chemical industry supports this progress by developing eco-friendly extraction methods, such as supercritical fluid extraction and ultrasound-assisted extraction, which help recover these sensitive compounds without damaging their effectiveness. Important seaweed-derived compounds include fucoidan, a sulphated polysaccharide from brown algae with anti-cancer and anti-viral potential; fucoxanthin, a brown algal pigment known for its anti-obesity benefits; and polyphenols like phlorotannins, which show very strong antioxidant activity, often higher than that found in tea or wine.

Seaweed Biorefinery: A Zero-Waste Approach

Crop-based biofuels such as biodiesel from oilseeds and ethanol from sugarcane or corn are often unsustainable because they compete with food crops for land, water and fertilizers. In contrast, marine algae offer a promising alternative for biofuel production due to their very fast growth rates, which are 8–10 times higher than those of land plants. To make seaweed utilisation economically viable for producing bulk chemicals and energy, it is necessary to shift from a single-product extraction approach to a biorefinery model. Similar to a petroleum refinery that separates crude oil into products such as naphtha, diesel and gasoline, a seaweed biorefinery processes the same biomass in a stepwise manner to recover multiple value-added products.

High-Value Extraction: The process begins with the recovery of high-value, low-volume compounds such as pigments, proteins and bioactive molecules for pharmaceutical and cosmetic applications.

Hydrocolloid Recovery: The residual biomass is subsequently used for the extraction of polysaccharides, including alginate or agar.

Bioenergy Production: The final leftover biomass, rich in carbohydrates and naturally low in lignin compared to terrestrial plants, serves as an excellent feedstock for energy production. It can be fermented to produce bioethanol or anaerobically digested to generate biogas (bio-methane).

This cascading utilisation strategy enhances the economic value obtained from each kilogram of seaweed while minimizing waste. For the chemical processing industry, it offers both challenges and opportunities to develop integrated reactor systems capable of efficiently handling wet, saline biomass and enabling sequential extraction processes.

Agriculture and Biostimulants

The earlier "Green Revolution" depended largely on inorganic fertilizers, which over time contributed to soil degradation, whereas the emerging "Blue Economy" offers a more sustainable alternative through seaweed-based biostimulants. Seaweed extracts contain natural plant growth regulators such as auxins, cytokinins and gibberellins, along with essential macro and micronutrients and amino acids. The manufacture of seaweed biostimulants is an expanding area within the chemical industry, involving carefully controlled hydrolysis processes that break down algal cell walls to release beneficial compounds while preserving their biological activity.

Seaweed-based biostimulants are a natural and rich source of potassium, which is essential for plant growth, root development, water regulation and stress tolerance. Their application improves photosynthesis, flowering and yield while helping crops withstand drought and salinity. Because potassium from seaweed is easily absorbed by plants, these biostimulants can reduce the need for inorganic potash fertilizers, lowering soil degradation and environmental impacts. Moreover, by decreasing reliance on imported potassium fertilizers, seaweed-based biostimulants support sustainable farming and enhance agricultural self-reliance.

In India, seaweed-based biostimulants are regulated by the Fertilizer (Inorganic, Organic or Mixed) (Control) Order, 1985 (FCO) under the Essential Commodities Act. The Department of Agriculture and Farmers Welfare (DA&FW) has notified specific standards for biostimulants, including those derived from seaweeds, covering composition, permissible raw materials, heavy metal limits, efficacy claims and labelling requirements. Manufacturers or marketers must obtain registration and licensing from the state agriculture department.

Sustainability and Carbon Sequestration

Seaweed mariculture is among the few industrial activities that can be described as nature-positive. Seaweeds are autotrophic organisms and do not require freshwater, cultivable land or external fertilizers for growth. More importantly, they function as effective carbon sinks.

Carbon sequestration: Seaweeds actively absorb carbon dioxide, nitrogen and phosphorus from seawater, thereby helping to reduce ocean acidification and control nutrient enrichment (eutrophication).

Methane reduction: Studies by ICAR-CMFRI and ICAR-NIANP evaluated nine red and brown seaweed species for their methane-mitigation potential under in-vitro conditions. Inclusion of *Kappaphycus alvarezii* at 3 – 5% of dietary dry matter resulted in a notable 31 – 42% reduction in methane production. Similarly, supplementation with *Sargassum wightii* at 4 – 5% dry matter led to a 36 – 48% decrease in methane emissions (Malik, et. al., 2025, Microorganisms, 13, 123). Another red seaweed, *Asparagopsis taxiformis*, known for its high content of anti-methanogenic compounds and strong methane-reducing potential in ruminants, has also been reported from the Kerala coast.

Integrated Multi-Trophic Aquaculture (IMTA): ICAR-CMFRI is promoting IMTA systems in which seaweeds are cultivated alongside fish cages. In this system, seaweeds absorb inorganic nutrients such as ammonia released from fish waste, acting as a natural bio-filter while simultaneously generating an additional income (ICAR-CMFRI study reported that 56% additional yield and 18% additional income to the farmer).

For the chemical industry, these attributes indicate a raw-material supply chain that is not only carbon-neutral but potentially carbon-negative. Utilising feedstocks derived from seaweed farming supports corporate sustainability and ESG objectives while contributing to the decarbonisation of industrial value chains.

Conclusion

The potential of seaweeds as a source of industrial chemicals is enormous but remains largely untapped in India when compared to countries such as China and Indonesia. Unlocking this potential requires close collaboration between marine scientists and the chemical industry. Key needs include engineering solutions for large-scale harvesting and processing of seaweeds, standardised extraction methods to manage variations in chemical composition across species and seasons and substantial investment in coastal biorefineries. At ICAR-CMFRI, we are committed to providing strong scientific support by developing reliable seed banks and standardised mariculture practices. It is the right time to tap into this "blue gold" and move towards a future where chemicals, fuels and medicines are produced from the ocean's renewable and regenerative resources instead of relying on fossil fuels.