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A Global Perspective on Usage of Seaweed – From Abundance to Nutrition and Economy by Extraction

INTRODUCTION

The global perspective on the use of land and ocean to feed the world's growing population has changed in last decade, especially amongst the scientific community. Given the limited availability of land, the exploitation of resources from the ocean has great potential for the foreseeable future and is expected to significantly contribute to the blue economy (FAO, 2024). The blue economy generally refers to all sustainable economic activities related to ocean resources, excluding traditional animal products like fish and seafood. Ocean bioresources include a diverse range of organisms and materials such as macroalgae (Seaweed), marine bacteria and fungi, marine plants, and marine invertebrates. Despite marine invertebrates being animals, they are often considered under bioresources due to their unique biochemical properties and potential for biotechnological applications.

These bioresources are present in abundance and can be the source of various muti-industry products and co-products. The bio-resources obtained can be converted to food products, food additives, bioactive compounds, nutritional supplements, biofuels, aquaculture feeds, pigments, antioxidants, and even nutrients like proteins (Lomartire & Gonçalves, 2022). The relevant industrial sectors which stand to gain from the blue economy include food, pharmaceuticals, cosmetic, biotechnological and biomedical industries. This write-up mainly focuses on seaweed and its utilization for the production of a range of food products and co-products.

Seaweed can be categorized into three main types: brown, red, and green algae. **Brown algae** (Phaeophyceae) are typically large and complex, found in cold-water coastal environments, and include kelp, rockweed, and Sargassum. **Red algae** (Rhodophyta) have vibrant red to purple hues, found in, both, deep and shallow waters, and include nori, dulse, and carrageenan-producing algae. **Green algae** (Chlorophyta) are closely related to land plants, found in marine and freshwater environments, and include sea lettuce, Codium, and Caulerpa. Each type of algae has multiple applications in food, medicine and cosmetics industries.

1. Chemical composition of seaweed

A detailed understanding of the chemical composition and properties of seaweeds is critical because all seaweed species are not suitable for human consumption (Ana, 2022). The most suitable and prevalent seaweeds for human consumption are *Saccharina japonica* (commonly called 'kelp'), *Undaria pinnatifida*, *Porphyra* spp., *Saccharina latissimi*, *Alaria Mariginata* and *Sargassum fusiforme* (Buschmann et al., 2017). Traditionally consumed in Asiatic countries, it is only recently, that consumers in Europe have started to pay more attention to the advantages of such seaweeds (Fleurence, 2016). The use of seaweeds in food remains marginal, and seaweeds are mostly used for cosmetic and medicinal purposes. In Europe, seaweeds are primarily harvested directly from the sea, an activity that depends on climatic conditions and the natural growth rate of seaweed. This contrasts with many Asian countries, where seaweed farming is a well-established practice. However, seaweed farming is now expanding beyond Asia, with a growing presence along the North Atlantic coast of the USA, the Pacific coast of Alaska, the Faroe Islands in Europe, and the British and Irish coasts. Generally, seaweeds contain macro and micro nutrients, and some also contain secondary metabolites (sterols, terpenoids, alkaloids, and phenolic compounds) and pigments, as evident in **Table 1**. The ash content of seaweed is very high, just under 40%. It is also a highly nutritious marine resource, rich in macronutrients such as carbohydrates (30–60%), proteins (5–35%), and lipids (1–5%), along with an exceptionally high ash content (~40%), which reflects its mineral richness. It is particularly abundant in magnesium (~15,000 mg/100 g), calcium, potassium, sodium, iron, zinc, and iodine, making it a valuable dietary source of essential minerals. Additionally, seaweed provides important vitamins like A, B12, C, E, and K, along with beneficial polyunsaturated fatty acids. However, despite its nutritional benefits, certain limiting factors restrict its widespread use in food. Its high iodine content (~2000 mg/kg in some species) can cause thyroid imbalances if consumed in excess, while its naturally high sodium levels may contribute to hypertension. Moreover, seaweed can absorb heavy metals such as arsenic and lead from seawater, necessitating strict quality control. Like all fresh products, after harvesting, seaweeds deteriorate rapidly in a few days making drying an essential step for preserving quality. Thus, most research studies on seaweeds employ dried biomass instead of freshly harvested product. Table 1 illustrating the comparative context of micro-nutrients content in Seaweed relation to the RDA.

Table 1: Illustrating the micro-nutrient content of Seaweed and compares the nutrients consumption per 5g consumption of Seaweed against RDA.

Nutrient	Seaweed Content (per 100g dried)	RDA (Adults)	% RDA per 5g Serving	Limiting Factor
Iodine (I)	~2000 mg/kg (2000 µg/g)	150 µg (RDA) / 1100 µg (UL)	~667% RDA / ~9% UL	Upper intake limit (UL) restricts daily consumption
Magnesium (Mg)	~15,000 mg	310–420 mg	~180%–240% RDA	Limited by iodine restriction
Calcium (Ca)	~7,000 mg	1000–1200 mg	~30%–35% RDA	No direct limiting factor, but iodine restriction affects intake
Potassium (K)	~9,000 mg	2600–3400 mg	~13%–17% RDA	High sodium content may impact balance
Sodium (Na)	~4,000 mg	2300 mg (UL)	~9% UL	Excess sodium intake risk
Iron (Fe)	~100 mg	8–18 mg	~28%–63% RDA	Bioavailability may be reduced by phytates

2. Cultivation and Farming

According to a latest FAO report (FAO, 2024), global seaweed production of seaweeds was approximately 37.8 million tonnes in 2022. This represents a significant increase compared to previous years, highlighting the growing importance and expansion of the seaweed industry worldwide.

Seaweed cultivation practices differ markedly across regions. In Asian countries such as China, Japan, South Korea, Indonesia, and the Philippines, seaweed is often farmed and grown under controlled conditions. Techniques include the longline system, raft system, and pond systems (United Nations, 2024). These methods involve cultivating seaweed on ropes or nets in coastal waters or ponds, often using hatcheries and nurseries to start seedlings in controlled environments before transferring to sea farms. The focus here is on intensive farming with high-density planting and multiple harvest cycles per year to maximize yields. Technological advancements like automated seeding and harvesting machinery are also increasingly used to enhance efficiency.

In contrast, European and Scandinavian countries primarily harvest seaweed from the wild. This approach relies on natural seaweed beds found along coastlines. Wild harvesting is less controlled than aquaculture and often depends on the natural abundance and seasonal growth cycles. However, there is growing interest in developing seaweed farming in these regions to ensure a sustainable supply and reduce pressure on natural populations. Efforts are being made to adapt cultivation techniques used in Asia to the colder and different coastal environments of Europe, North America and Scandinavia.

Globally, seaweed is predominantly used for hydrocolloid extraction, including carrageenan from *Eucheuma spp*., and *Kappaphycus alvarezii*, and agar from *Gracilaria spp*. These hydrocolloids have various applications in the food, pharmaceutical, and cosmetic industries, driving the demand for greater seaweed production.

3. Economic Opportunities

Seaweed cultivation and industrial applications offer significant economic opportunities across various sectors. The entire value chain, from farming and harvesting to processing and research, supports economic development and employment in multiple regions.

4.1 Seaweed Farming and Harvesting

Seaweed farming is labour-intensive and provides jobs to coastal communities, particularly in Asia. For example, Indonesia and the Philippines are major producers of carrageenan seaweeds, employing thousands in coastal areas. Seaweed farming is also considered to be environmentally sustainable, as it does not require arable land, freshwater, or fertilizers. This sustainability adds to the long-term economic viability of the industry.

4.2 Processing Industry

Hydrocolloids: Seaweeds are a primary source of hydrocolloids like agar, carrageenan, and alginates, used in food, pharmaceutical, and cosmetic products (Saji et al., 2022). These products have low market value, on larger scale these commodities are driving industrial demand and innovation. On the other hand, the high value product from Seaweeds such as fucoidan, a bioactive sulfated polysaccharide from brown seaweed, is widely used in pharmaceuticals, nutraceuticals, cosmetics, and biomedical applications due to its antioxidant, anti-inflammatory, anticancer, and immune-boosting properties (Bulya et al., 2024). The global fucoidan market, valued at approximately **$150–$250 million** in 2023, is expected to grow at a **6-10% CAGR**, driven by rising demand for natural health products. Pharmaceuticals and nutraceuticals dominate the market, with increasing applications in functional foods and skincare. The Asia-Pacific region, particularly Japan, China, and Korea, leads in production and consumption, while North America and Europe show strong demand for high-purity fucoidan.

Biofuels and Bioplastics: Research into converting seaweed biomass into biofuels and bioplastics is gaining traction (Baghel, 2023). These sustainable alternatives to fossil fuels and conventional plastics offer substantial economic benefits as industries move towards greener solutions.

4.3 Scientific Research and Development

Biotechnology: Seaweed-derived compounds are being researched for their potential in medicine, including anti-inflammatory and anti-cancer properties (Hofmann et al., 2024). This ongoing research fosters collaborations between academic institutions and biotech companies, creating high-skilled jobs and intellectual property.

Nutraceuticals and Functional Foods: Seaweed is rich in vitamins, minerals, and antioxidants, making it valuable for developing health supplements and functional foods (Wassie et al., 2021). The growing health and wellness market provides a significant economic incentive for continued research and product development.

4.4 Human nutrition opportunities

Globally, nutritional deficiencies in both macro and micronutrients are increasing, particularly in developing economies. These regions often face limited access to diverse and nutrient-rich foods, leading to widespread deficiencies in essential nutrients like proteins, fats, vitamins, and minerals. Malnutrition can result in stunted growth, weakened immune systems, and higher susceptibility to diseases, disproportionately affecting children and women. Addressing these deficiencies requires sustainable solutions like employing seaweeds, which is nutrient-dense and can be cultivated in abundance. Seaweed boasts a rich nutritional profile, providing essential proteins, fats, carbohydrates, and micronutrients, making it a cost-effective and valuable dietary ingredient. However, its consumption is limited by the presence of heavy metals (such as lead and arsenic) and high iodine content. Therefore, while seaweed is a nutritious food source, its benefits must be evaluated alongside recommended daily intake limits to ensure safe consumption.

4. Products and Uses

Seaweed biomass is a versatile resource that can be processed through extraction, fermentation, and pyrolysis to produce a wide array of products with applications in various industries. Phycocolloids such as alginates, agars, and carrageenan’s are extracted from brown and red seaweeds, serving as thickening, gelling, and stabilizing agents in food processing, pharmaceuticals, and textiles. Additionally, seaweeds can also yield biochemicals, methane, alcohols, esters, acids, and other chemicals used in pharmaceuticals, cosmetics, and renewable energy. It is also utilized as animal fodder providing essential nutrients to improve livestock health, and as biofertilizers for promoting plant growth and soil health. Moreover, seaweed is a nutritious food source in many cultures, particularly in Asian cuisine, offering vitamins, minerals, fibre, and protein. This broad spectrum of applications underscores seaweed's significant potential in fostering sustainable and innovative solutions across multiple industry sectors.

5. Extraction methods used

As illustrated in the previous sections, seaweeds are a valuable biomass for producing a wide range of products across various applications, with extraction being a key process employed (Matos et al., 2021). Extraction methods researched on seaweeds include conventional solvent extraction, as well as intensified methods such as microwave-assisted extraction, ultrasound-assisted extraction, enzymatic-assisted extraction, supercritical fluid extraction, pressurized and elevated temperature extraction and electro-assisted techniques such as pulsed electric fields. The process intensified extractions mentioned here are claimed to offer significant advantages such as reduced time, energy, and solvent usage, although these claims are yet to be objectively verified. In terms of productivity, Ultrasound-Assisted Extraction has been found to be highly effective, but only in small-scale experiments. The technology struggles with uniform energy distribution issues and equipment wear on a larger scale. Likewise, Microwave-Assisted Extraction is reported to offer very high productivity, but here again, the technology has not been studied on industrial scale and it is unclear whether the advantages reported in laboratory scale can be replicated. Supercritical Fluid Extraction, on the other hand, provides high productivity suitable even on an industrial scale, although the economic viability depends on the specific product being extracted. Enzyme-Assisted Extraction enhances productivity by targeting specific cell components but can be slower and more variable depending on enzyme activity, presenting moderate scalability. The technology also requires careful enzyme management to be attractive. Pulse Electric Field Extraction (PEF) is also reported to be promising based on laboratory scale experiments, but operations on commercial scale requires significant investment in specialised equipment. Addressing the technological challenges related to the use of intensified processes is necessary before declaring the relevant processes to be efficient and sustainable. As of now, conventional extraction under optimised conditions remains a practical approach for transformative advancement in extraction processes for separating components from seaweeds. The growing number of research publications on extraction from seaweeds is given in. **Figure 1**

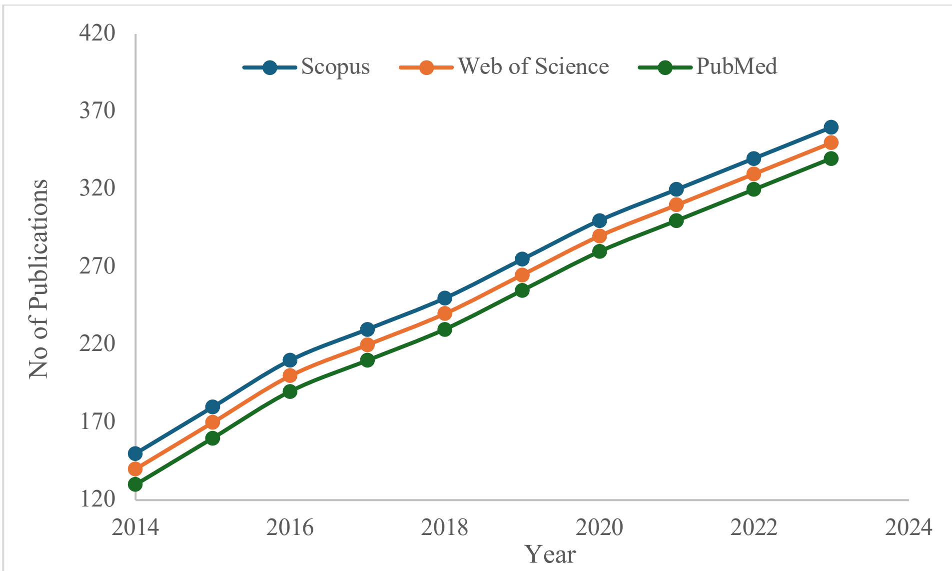

Figure 1: Number of publications on seaweed extraction 2014-2023

6. Environmental Benefits

As mentioned in section 4, utilizing seaweed as a sustainable solution to obtain various products and co-products offers numerous environmental benefits. Seaweed cultivation does not require arable land or freshwater resources, making it an eco-friendly alternative to traditional agriculture. Additionally, seaweed farms can help mitigate climate change by absorbing large amounts of carbon dioxide and releasing oxygen, thus acting as natural carbon sinks. The nutrient uptake by seaweeds can also help combat coastal eutrophication, reducing the occurrence of harmful algal blooms and improving water quality.

Moreover, seaweed farming supports marine biodiversity by providing habitats for various marine organisms. The possibility of producing biofuels and bioplastics from seaweed reduces dependence on fossil fuels, contributing to a reduction in greenhouse gas emissions. Using seaweed-derived fertilizers and animal feed promotes sustainable agricultural practices, reducing the need for chemical inputs and enhancing soil and animal health. Seaweed-based products, such as biochemicals and phycocolloids, offer renewable and biodegradable alternatives to synthetic chemicals, reducing environmental pollution and promoting a circular economy.

7. Challenges and Considerations

Processing seaweed biomass presents several challenges, limitations, and considerations that need to be addressed to optimize efficiency and sustainability. One of the major challenges is the design of biorefineries. Unlike traditional refineries, seaweed biorefineries need to integrate various processes and equipment to efficiently produce multiple products while aiming for zero waste. This integration is complex and requires comprehensive mass and energy balance analyses for each step of the process, as well as the use of advanced process simulation tools. Another significant limitation is the environmental impact of seaweed cultivation and processing. Seaweed farming must take into account global climate change factors. Moreover, sustainable seaweed production needs to ensure no harm to natural environments and ecosystems, including wild seaweed populations. This requires careful marine spatial planning and energy- and cost-efficient cultivation approaches based on full life-cycle assessments. Furthermore, regulatory and food safety considerations are paramount. The processing of seaweed for food and feed products must comply with various international standards and guidelines, such as the EU Regulation (EC) number 852/2004 on food hygiene. However, there is a lack of specific guidelines for certain types of seaweed, such as Ulva species, which necessitates the development of more tailored regulations and safety assessments. Technological challenges also exist, especially in the preservation and stabilization of seaweed biomass post-harvest. Methods like drying, salting, and fermentation must be optimized to retain the nutritional and physicochemical properties of seaweed while preventing spoilage and contamination. Each method has its own set of advantages and drawbacks, requiring careful selection based on the intended use of the seaweed. Lastly, the presence of chemical and biological hazards, such as heavy metals and microbial contaminants, poses a significant risk. The levels of these hazards can vary based on the species and cultivation site, making it crucial to harmonize analytical methods for their identification and quantification. This harmonization is essential for assessing the risks and ensuring the safety of seaweed products for consumers.

8. Examples of Seaweed based Blue Economy Initiatives in research and industry

The global seaweed market achieved a capital of $17 billion dollar in 2023, and this ignited research & development, investment and start-ups in this field. The current market values is estimated to increase to 5-fold of the present value by 2030 (Zhang et al., 2022). The dominance of seaweed production by Asian countries have furthered the cause of boosting blue economy and economic growth. The list of top ten countries with highest production and exports of seaweed is given in **Table 2**. In Europe, growth since 2017 has been driven by the Russian Federation, which produced 23.8 thousand tons by 2021. In the Americas, seaweed production is dominated by Chile and Peru, whose production peaked at 88 thousand tons in 2009 before declining to 17 thousand in 2021 due to various reasons such as climate change, overharvesting, economic factors and technological advancements (FAO, 2024). As observed in Table 2, the world's largest producer of the seaweed is China; however, the Republic of Korea tops annual exports, as shown in Figure 2.

Table 2: List of countries with maximum production of seaweed worldwide (Source: FAO, 2024)

Countries	**Production in tons**
China	21,584,175
Indonesia	9,091,307
Republic of Korea	1,845,682
Philippines	1,343,707
Democratic Republic of Korea	603,000
Japan	342,100
Malaysia	178,897
United Republic of Tanzania	81,104
Russian Federation	23,863
Chile	17,004

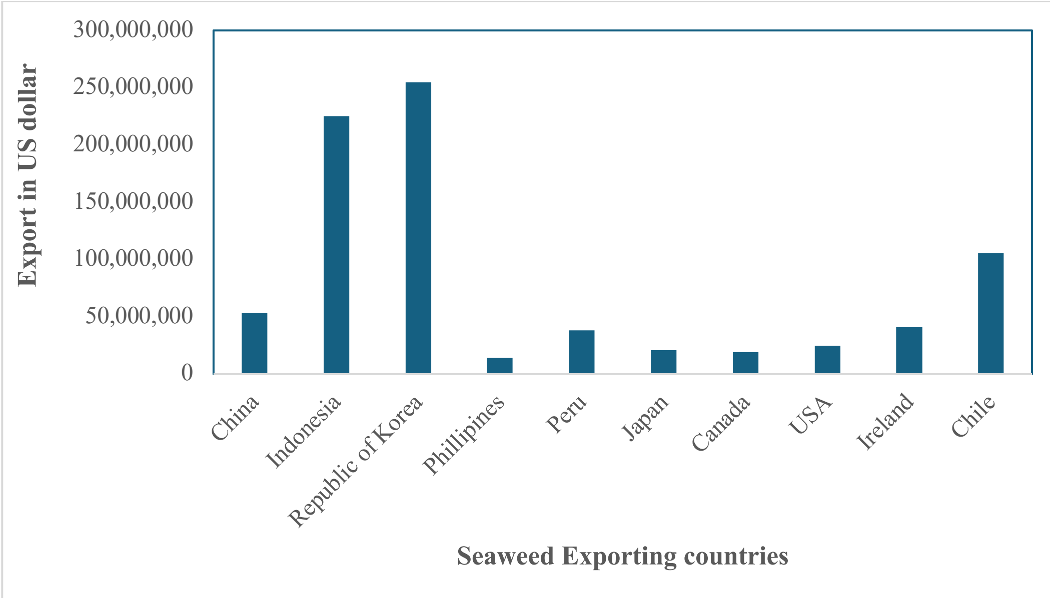

Figure 2: Illustration of top 10 seaweed exporting countries worldwide (Source: FAO, 2024)

Blue Economy focuses on the sustainable use of ocean resources for economic growth, improved livelihoods, and ocean ecosystem health. Within this framework, seaweed has emerged as a significant resource due to its potential in various industries, from food and pharmaceuticals to biofuels and environmental management. Here is a selection of some notable examples of seaweed-related Blue Economy initiatives in both research and industry as shown in Table 3.

Table 3: List of organisation working on Seaweed process and product development for better sustainability

Initiative Types	Name & Acronym	Locations
Research Initiatives	European Marine Biological Resource Centre (EMBRC) Seaweed Research	France, Italy, Greece, Portugal, and the UK
	Marine Agronomy Research Program at the University of Connecticut	Storrs, Connecticut, USA
	Seaweed for Europe Coalition	Brussels, Belgium
Industry Initiatives	Ocean Rainforest	Faroe Islands
	Algaia	Paris, France, with operations in Brittany, France

	GreenWave	New Haven, Connecticut, USA
	Cargill's Seaweed Initiative	Minneapolis, Minnesota, USA
	Sea6 Energy	Bangalore, India
Environmental and Social Impact	Blue Ocean Barns	Kailua-Kona, Hawaii, USA
	The Seaweed Company	The Netherlands, with operations in Ireland, Morocco, and India
Academia-Industry Collaborations	The Global Seaweed STAR Program	Sweden
	The Seaweed Biorefinery Platform	Aarhus University, located in Aarhus, Denmark

Suggested Readings:

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Biographical sketch of Authors

Professor Keshavan Niranjan, better known as Niranjan, is the Professor of Food Bioprocessing at the University of Reading (UK). He is:

- the Editor-In Chief (Food) of the journal Food and Bioproducts Processing;
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Professor Niranjan has a strong publication track record with around 180 peer-reviewed research papers. He has also authored a textbook on food engineering principles.

Dr. Rahul Kumar, PhD (University of Reading) earned his PhD from the University of Reading, UK, where he led waste-intensive projects on the UK vegetable supply chain, quantifying regional environmental footprints (GHG emissions, water, land, fertilizer) using spatially explicit models and statistical techniques. He has experience working with industry and academic partners through projects funded by Innovate UK, BBSRC, and international collaborations in Spain and Portugal.

With 11 peer-reviewed publications and multiple international conference presentations, Dr. Kumar is an active contributor to the scientific community. Kumar is particularly interested in actor-level food system analysis, sustainable transitions, and data-driven policy development.

This SIB was independently reviewed and approved by the IUFoST Scientific Council.