Global Food Security 37 (2023) 100686

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Seaweed's contribution to food security in low- and middle-income countries: Benefits from production, processing and trade

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ARTICLE INFO

Keywords:
Seaweed
Agriculture
Food
Nutrients
Trade
Climate change

1. Introduction

Calls are growing for food system transformation to meet human and planetary goals (Bai et al., 2022; Bock et al., 2022). The United Nations Food Systems Summit of 2021, for example, galvanized attention to the need for progress on all 17 Sustainable Development Goals, "each of which relies on healthier, more sustainable and more equitable food systems"(United Nations, 2021). There are, however, many challenges to delivering transformation since such goals require food systems that contribute fewer greenhouse gas emissions (GHG) while meeting the dietary needs of a global population expected to exceed 9 billion before 2050 (Von Braun et al., 2021). Food systems are estimated to contribute roughly one-third of GHG emissions (Crippa et al., 2021). At the same time, food systems can negatively impact freshwater resources, biodiversity, and soil quality, while current patterns of food supply and demand underpin suboptimal diets for billions of people that contribute to an estimated 20% of all avoidable deaths (Global Panel on Agriculture and Food Systems for Nutrition, 2020).

One proposed solution has been to focus more on water-based food systems in general (often referred to as 'blue foods'), and on seaweed in particular. In 2016, the World Bank argued that seaweed "could represent a transformational change in the global food security equation." (World Bank Group, 2016) Since more than half of the anticipated growth in the world's population up to 2050 is to occur in just 8 countries in Africa and Asia, it has been argued that seaweed could become "an important new crop" for low- and middle-income countries (LMICs) (Msuya et al., 2022).[1] Indeed, the United Nations has argued that "increased attention on aquatic foods is beneficial and badly needed." (United Nations Nutrition, 2021) But how realistic are such propositions? This paper explores the potential of seaweed to address food insecurity and poor nutrition in LMICs, alongside its potential to mitigate the carbon footprint of food systems globally.

This paper has five parts. The next section describes the types of seaweeds and major uses, their nutrient content and environmental attributes. Section three explores patterns and trends in the production, trade and consumption of seaweed, globally and within LMICs. A fourth section focuses on practical challenges and constraints to upscaling the use of seaweed in resource-constrained countries and highlights the kinds of investments needed to overcome hurdles. The final conclusions section offers recommendations for policy action.

2. Seaweed attributes

In this paper, the term 'seaweed' is an umbrella term that refers to at least 10,000 different species of macroalgae that grow in the world's diverse saltwater environments (Food and Agriculture Organization, 2018; Barbier et al., 2019). Roughly 220 are currently exploited as having commercial value, although just five species account for around

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[1] The 8 countries are the Democratic Republic of the Congo, Egypt, Ethiopia, India, Nigeria, Pakistan, the Philippines and Tanzania – among which India, the Philippines and Tanzania are already seaweed producers.

https://doi.org/10.1016/j.gfs.2023.100686
Received 27 May 2022; Received in revised form 9 March 2023; Accepted 28 March 2023

95% of total farmed output (Cai et al., 2021).[2] Seaweed has contributed to human diets for centuries. In eastern Asia, for example, seaweed has long been a part of traditional diets and is widely farmed off the coast of countries like China, Japan and Malaysia. In recent decades, demand has grown for seaweed varietals like *nori* (wrappers for sushi) and *kombu* (an ingredient in seasonings), particularly in Europe and North America as well as in Southeast Asia (Koch et al., 2021). Demand has also grown for seaweed's non-food uses, such as additives in the processing of nutraceuticals, cosmetics, livestock feed, fertilizers (particularly in horticulture), bio-packaging and biofuels (Kim et al., 2017; SAPEA, 2017; Shannon and Abu-Ghannam, 2019).

2.1. Types of seaweed and major uses

There are three main types of seaweed - brown, red, and green. Production of brown seaweed has been the main driver of overall growth in seaweed supply, with an almost 11% per annum increase from 1950 to 2019, compared with 8% annual growth in seaweed production overall (Cai et al., 2021). In 2019, the two main varieties of brown seaweed – *Laminaria saccharina* (widely known as kelp) and *Undaria pinnatifida* (known as wakame) - accounted for about 47% of global farmed output, amounting to 35 million metric tons (MT); but none of this was generated by LMICs. Brown seaweed is mainly used in human food products, particularly in the form of agar (a "vegetable gelatin"), used in jellies and candies, alginate (a stabilizing and thickening agent used in making fruit juices, ice cream, jelly, syrups, fruit juices, and certain bakery products, and carrageenan which is used as a water binding agent in dairy products to maintain solids in suspension (Food and Agriculture Organization, 2018). Other uses include livestock feed (low grade kelp as a feed additive for farmed abalone in China, and the potential for fermented seaweed flour in fish feed in Turkey), in producing liquid and dried fertilizers, as well as some pharmaceutical products (Food and Agriculture Organization, 2018; Saade et al., 2020).

In 2019, red seaweed accounted for almost 52% of global seaweed production by weight (Cai et al., 2021) Like the brown variant, red algae are valued for producing carrageen and agar. So-called Irish moss (*Chondrus crispus*) is widely used in producing carrageen, while dulse (*Palmaria palmata*) is sold as a plant-based substitute for bacon (Food and Agriculture Organization, 2018). However, some species such as *Chondracanthus chamissoi* are used in cuisine, including in the preparation of ceviche in Peru (Alemañ et al., 2019).

Green seaweed varieties are used as 'sea vegetables' in salads; but demand for 'fresh' (unprocessed) seaweed is only found in populations with an established tradition of seaweed in the diet, and because of high prices: US$ 0.79/kg (wet weight) in 2019 for green seaweed compared with US$ 0.47/kg for brown and US$ 0.39/kg for red (Cai et al., 2021). Indeed, output of green algae has been falling steadily since a peak in 1992, accounting for merely 0.05% of overall seaweed supply (17,000 MT) in 2019 (Food and Agriculture Organization, 2020; Koch et al., 2021).

2.2. Nutrient attributes

Macro algae are a relatively good plant source of vitamins, such as riboflavin, niacin, pantothenic acid, folic acid, and carotenoids (Demarco et al., 2022; Peñalver et al., 2020). Measurable concentrations vary considerable by species and where they are harvested. Some species contain cobalamin (a vitamin compound associated with the B12 complex) at much higher levels than terrestrial plants. For example, *Pyropia yezoensis* produces cobalamin that is "biologically available" to the consumer (Watanabe et al., 2014) in amounts averaging 1g per kg fresh weight (Castillejo et al., 2018). Some (e.g., *Porphyra umbilicalis*) provide water-soluble vitamins, such as vitamin C, at concentrations that are higher than in peas and potatoes (by weight), but much lower than in grapefruits or strawberries (Nielsen et al., 2021). The values of β-carotene (pro-vitamin A) found in *Codium fragile and Gracilaria chilensis* have been reported at levels that exceed those in carrots (Ortiz et al., 2009).

Seaweed also contains minerals such as calcium, chloride, and magnesium (Peñalver et al., 2020), bioactive molecules and enzymes of interest to pharmaceutical makers (Imchen, 2021), potassium at levels higher than in sirloin steak (Roe et al., 2015), and of course iodine. Being a plant derived from seawater, concentrations of iodine in certain seaweed species can be relatively high, although the amount absorbed by consumers varies considerably according to seaweed type, bioavailability, and losses in cooking or other processing. Regular high intake of the iodine-rich algae (such as *Laminaria* and *Ascophyllum*) has the potential for adverse effects on thyroid function (due to excess dietary iodine intake), particularly among pregnant women and neonates (Aakre et al., 2020; Sebastiani et al., 2019). Although (Circuncisão et al., 2018) found that iodine's bioavailability in brown seaweed to be "moderate". Either way, in LMICs where iodine deficiency is a greater population-wide health threat, seaweed products also have the potential to contribute to local daily needs, particularly in countries in which household consumption of iodized salt remains lower than desirable (Smyth, 2021).

On average, seaweed has a relatively high average crude protein concentration of around 16.7% (Boyd et al., 2022; Kim et al., 2017). The amino acid profile of this protein is similar to other plant-based sources, and with a high digestibility of 78–89% (SAPEA, 2017). Some analysts have therefore highlighted the potential for seaweed to become a more significant aquatic protein to complement terrestrial plant protein sources (Bjerregaard et al., 2016; World Bank Group, 2016). That said, consumers would need much higher intake of seaweed than today for this source to become a major supplier of protein to the diet. As a result, the main contribution of seaweed to total protein intake would likely be as an extracted ingredient in processed foods.

Similarly, seaweed does not represent a major source of energy (kilocalories), because it is not consumed in amounts that would qualify as a staple food (like rice or tubers). Thus, seaweed is unlikely to reduce food insecurity in LMICs through its direct contribution to dietary intake. Instead, algae of many kinds represent a source of nutrient-rich extracts used as additives in meals or used in processing to enhance the healthfulness of food products. For example, carrageenan from red algae is added to burgers and sausages, where it plays a dual function in providing antioxidants to preserve the quality of meat, and as a lipid (fat) substitute (Fasolin et al., 2019; Palmieri and Forleo, 2020).

In fact, much remains to be understood about the net benefits of eating seaweed as food versus the value of seaweed as ingredients in other processed foods. There is epidemiological evidence for links between algae intake and health outcomes in Asia. For example, Murai et al. (2021) noted that studies of Japanese adults show an inverse statistical association between diets that include seaweed and the incidence of ischemic heart disease and mortality from stroke. Similarly, a review by (Shannon and Abu-Ghannam, 2019) determined that populations regularly consuming seaweed in their diet have significantly less obesity and diet-related diseases. Nevertheless, there are challenges in determining the biological pathways involved, and in quantifying the bioavailability of nutrients and health benefits associated with one species versus another, produced in one season versus another, and in one coastal context versus another, because the nutrient and chemical makeup of seaweed varies hugely according to such parameters.

2.3. Environmental attributes

Beyond the intrinsic nutrient content of seaweed, there are two newer domains of interest. The first relates to environmental resource

[2] The main farmed species in 2019 were *Laminaria/Saccharina* and *Undaria* (brown seaweed), accounting for ~ 42% of production, and *Kappaphycus/Eucheuma*, *Gracilaria* and *Porphyra* (red seaweed), accounting for 51% (Cai et al., 2021).

degradation and climate change. Macroalgae grow using sunlight and inorganic nutrients naturally found in marine environments. They require no land, fresh water or inorganic inputs to grow and produce, thereby providing macro- and micronutrients without a major carbon footprint. Macroalgae and other marine plants may account for around 70% of the world's carbon storage (Barbier et al., 2019). What is more, it has been estimated that carbon dioxide-removing farms growing perennial brown algae could draw down approximately 10 tons of CO_2 per hectare of sea surface per year (Chung et al., 2013). However, it is not well understood if the harvesting of farmed product, or indeed collection of wild seaweed, releases CO_2 into the atmosphere, thereby short-circuiting the desired "carbon sink" function of algae (Mongin et al., 2016; Troell et al., 2022).

Other potential environmental benefits include the removal of inorganic nutrients in the seas (Peng et al., 2021) reducing nitrogen and phosphorous pollution and emissions (by shifting to algae-based bio-fertilizers from inorganic products) (Chatterjee et al., 2017; Mahapatra et al., 2018), and promoting greater marine biodiversity (Duarte et al., 2021). It has also been argued that seaweed farming elevates the pH of coastal waters and supplies oxygen, thereby reducing the effects of acidification and de-oxygenation locally (Duarte et al., 2017). For example, Racine et al. (2021) proposed that as seaweed farming removes large quantities of phosphorus and nitrogen from coastal ecosystems, there is potential for such production systems to tackle eutrophic conditions and manage 'clean up' processes through such nutrient assimilation. At the same time, concerns have been expressed about potentially negative effects of seaweed farming on local habitat integrity and biodiversity (SAPEA, 2017).

The second growing interest relates to the search for 'alternative proteins'; that is, ones that have a significantly lower carbon footprint than proteins derived from terrestrial livestock under conventional production technologies. For example, macroalgal biomass can be used as an additive to livestock and other animal feeds aimed at reducing enteric methane emissions (Vijn et al., 2020), and as a diet supplement for poultry (Barbier et al., 2019; Peng et al., 2021). Considerable investment has been directed recently towards non-conventional animal sources (such as insects and microorganisms) as well as vegetable sources (fungi), but there is potential for seaweed to provide a larger share of nutrients to the world's food supply in ways that do not generate significant GHG emissions (Fasolin et al., 2019; Leandro et al., 2020).

3. Production, trade and consumption of seaweed

3.1. Seaweed production

The supply of seaweed has been growing rapidly, almost tripling in terms of output from roughly 11 million metric tons (MT) wet weight in 2000 to over 30 million MT in 2019 (see Fig. 1). Non-farmed seaweed output (collection of wild seaweed) amounted to around 1 million MT fresh weight in 2019 (Food and Agriculture Organization of the United Nations, 2022a). However, collecting non-farmed seaweed remains a locally-important activity in certain parts of the world, especially on the coasts of Brazil, Mexico, and Peru (Food and Agriculture Organization, 2020; Rebours et al., 2014).

While China is currently the largest producer of farmed seaweed (accounting for roughly 57% of world output), one LMIC (Indonesia) has been an important driver of increased supply over recent decades, becoming a principal exporter of two species (*Kappaphycus alvarezii* and *Eucheuma* spp.) that produce carrageenan (Boyd et al., 2022; Food and Agriculture Organization, 2018). In 2019, Indonesia alone produced roughly 10 million MT, in wet weight, compared with a combined quantity of seaweed farmed across Africa of just 118,000 MT (Food and Agriculture Organization of the United Nations, 2022a). In other words, LMICs other than Indonesia (which was still officially designated as a lower-middle income country by the World Bank in 2021) play a minor role in global production (Troell et al., 2022).

That said, numerous LMICs do farm seaweed in certain favorable contexts. The technologies used in small-scale coastal seaweed production and harvesting are relatively straightforward, in that no complex farm technologies are required. A harvest can be gathered in roughly six to eight weeks. Wet material needs to be gathered but can be sun-dried rather than requiring separate energy inputs. However, training in off-shore farm management is necessary, and labor and time allocation are not insignificant for planting, maintenance of lines and harvest. While the adoption of seaweed farming has apparently benefited women's income and status in countries as diverse as the Philippines, Ghana, and Vietnam (Msuya et al., 2007; Valderrama et al., 2015), women's pre-existing time demands and livelihood opportunities must be taken into account when promoting seaweed cultivation. Similarly, because seaweed farming tends to take place in accessible intertidal zones there is potential for competition with other forms of marine aquaculture (including caged fish and shellfish production), and this should be assessed carefully before investments in new ocean-based production of plants.

Almost 12 million MT of *Kappaphycus/Eucheuma* were produced in 2019 (34% of all seaweed by weight) by 23 countries or territories, including Tanzania (106,000 MT), Timor-Leste (1500 MT), Kenya (400 MT), Sri Lanka (247 MT) and Ecuador (45 MT) (Cai et al., 2021). Production has increased a little from very low levels since the 1980s, including in Tanzania, South Africa, Morocco and Namibia. For example, roughly 300 MT of a red algae species (*Gracilaria*) were harvested in Tunisia and Morocco, in 2019, representing just 0.01% of the world's total (Food and Agriculture Organization, 2020).

However, output in Africa has stagnated since around 2010. As of 2019, Tanzania was the largest producer in Africa (Fig. 2), supplying carrageen-rich red seaweed, but even in that country output has been on a downward trajectory, falling from 132,000 MT in 2010 to 106,000 MT in 2019 (Food and Agriculture Organization, 2020). Declining output is also reported in South Africa, which dropped from second largest African producer in 2010 to third in 2019; its output of 11,000 MT in 2019 represented just 0.03% of global output (Food and Agriculture Organization, 2020). The decline in production since 2010 in Tanzania and South Africa is largely ascribed to "pathogen outbreaks, which hinder growth" (Ndawala et al., 2021), although some point to increasing challenges to marine environments ascribed to climate change (Msuya et al., 2022). The productivity of algae cultivation can be negatively impacted by viruses, parasites or contaminants, often requiring significant investments in measures such as remediation, new stock, and improved protection of farm environments (Barkia et al., 2019; Cai et al., 2021). Poorer smallholders are severely constrained in both knowledge and resources when faced with such threats.

3.2. Processing and trade of seaweed products

Globally, the seaweed industry had an estimated commercial value of roughly US$16.6 billion per year leading up to 2020 (Food and Agriculture Organization, 2018; GrandviewResearch, 2021; Loureiro et al., 2015). The share of this captured by LMICs remains very small. For example, in 2019, the total monetary value from seaweed sales by Indonesia amounted to US$218 million, whereas in The Philippines it was US$38 million, and US$22 million in Peru (Cai et al., 2021). Income from seaweed-based hydrocolloids (agar, carrageenan and alginate) added US$214 million to the economy of the Philippines, and US$110 million to Indonesia (Cai et al., 2021). The biggest importers of hydrocolloids in 2019 were the United States of America and Germany.

Some market research companies predict more than 12% per annum growth globally, rising to over US$30 billion by 2025 (MarketsandMarkets, 2020), possibly reaching US$37.8 billion by 2028 (GrandviewResearch, 2021). While most of this additional economic value will be captured by well-established large-scale production and processing systems in Southeast Asia (including China), even a small growth in market share in LMICs could generate considerable foreign

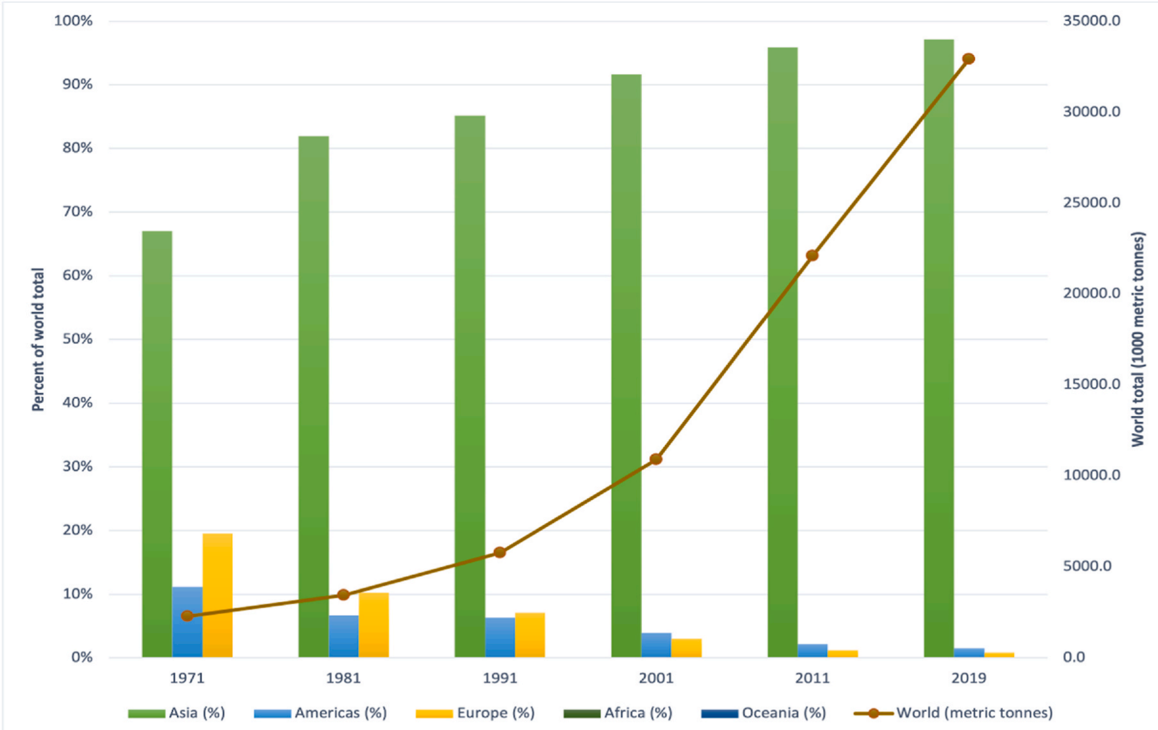

Fig. 1. Global trends in aquatic plant supply, 1971–2019[31].
Source: (Food and Agriculture Organization of the United Nations, 2022a, b). Data for this figure were tabulated using FAO STAT Food Balance data (1971–2013, old methodology and population) and Food Balance data (2010–2019). Total production from the latter sources amount to 32,924,340 metric tons, which, it should be noted, differs from FAO Yearbook data and Cai et al., 2021 who report total world production as 35,762,504 metric tons.

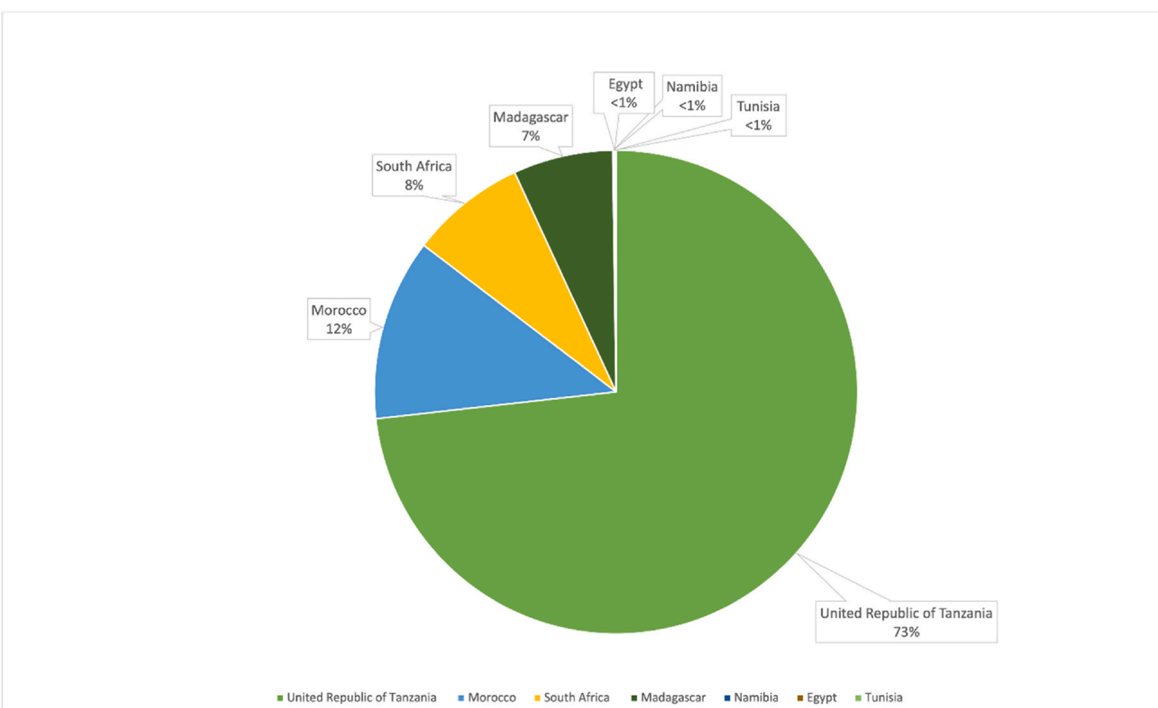

Fig. 2. Share of total Africa-wide production of aquatic plants* (farmed and wild catch), by main producing countries, 2019
Source: Food and Agriculture Organization of the United Nations, 2022a

exchange from new exports.

The government of India is planning to invest almost US$87 million to raise annual national farmed production from the current 2500 MT to one million MT, by 2026, thereby creating up to one million new jobs (Flatt, 2021; HinduTimes, 2021). Seaweed farming has already been promoted as a way of diversifying the livelihoods of artisanal fisherfolk, (women as well as men) in parts of India, for example, in Tamil Nadu, Gujarat, Maharashtra and Andra Pradesh (Mantri et al., 2017).

However, jobs and income growth are also associated with downstream activities in the supply chain, in processing and packaging, government jobs and shipping (Cai et al., 2021). For example, South Korea exported seaweed (*Pyropia*) products to 110 countries in 2018, worth US$ 525 million, as well as US$ 75 million of products from other seaweed species (Hwang et al., 2020). For example, in The Philippines, seaweed-related activities employed 50,000 local consolidators and more than 20,000 small traders in 2010 (Hurtado et al., 2013). India's small-scale post-production industries use roughly one-third of the country's seaweed production, mainly in generating gels and emulsifiers that are used in processing other food products (Dhargalkar, 2014).

In Africa, value-addition through processing remains limited. Yet, with appropriate investments in training and infrastructure, the processing and packaging of seaweed products (dried, fermented, liquid, concentrate or powdered) could support local food industry growth as well as exports. For example (Mirera et al., 2020), found that some smallholder producers of seaweed in Kenya have branched out into value-added production of shampoos and soaps as well as fish feed for pond aquaculture. Similarly, in Namibia where harvesting of wild seaweed has been undertaken for several decades, there are start-up businesses exploring seaweed processing for cosmetic and nutritional supplement use, following the lead of companies in South Africa, as well as feed for pond-based abalone farming (Rothman et al., 2020). In Indonesia, which produces more seaweed than all of Africa, there are over 30 processing companies producing carrageenan and agar (Food and Agriculture Organization, 2018).

3.3. Dietary intake of seaweed

Coherent, high-quality data on actual intake of seaweed around the globe do not yet exist. While data on seaweed production remain limited for many parts of the world, information on the contribution of seaweed to diets – either in its integral form or as ingredients in other foods – is vanishingly small outside of Japan, Korea, and a few other Asian nations. This is because seaweed is mainly consumed as a high-value food commodity that is processed and retailed by private sector food companies that do not make their data publicly accessible. As a result, trends and patterns in intake can only be surmised.

Over 70 species of algae have been approved by national food safety authorities around the world as food (Bizzaro et al., 2022). Many factors, including taste and color, risks of contamination by heavy metals, and relatively high prices for good quality algae products, impede the acceptability of seaweed as a component of diet (Barkia et al., 2019). Neophobia (personal beliefs or preferences that exert influence on consumers' acceptance of new products) certainly affects the intention to consume algae in many contexts. In Spain, for example, it was found that consumers can be willing to experiment with seaweed as food if they strongly believe in advertized health benefits, but if they do not accept those benefits, they avoid the novelty of an unfamiliar food (Losada-Lopez et al., 2021). In many LMICs where fish plays a limited role in local food culture, the assumption that seaweed could play a role in enhancing dietary patterns is overly-optimistic; even more so in the case of land-locked food deficit countries.

It has been argued that consumer demand for seaweed can be promoted by highlighting its health properties (Palmieri and Forleo, 2020). However, there is little evidence that promotion of a novel food would support significant growth in consumer demand, particularly among low-income households. Theoretically, some market in-roads could be made among less poor urban consumers who are concerned about diet-related non-communicable diseases. Many health claims are made for algae with regard to potential regulation of blood glucose (sugar) levels; lowering cholesterol; boosting immune systems; nourishing the skin; as well as anti-hypertensive, antimicrobial and anti-cancer properties (Lomartire et al., 2021). Some of these claimed effects have been documented in relation to seaweed extracts, i.e., bioactive peptides extracted from algae (Bizzaro et al., 2022), but there is much less evidence for the health benefits of consuming whole seaweed (Cherry et al., 2019).

In LMICs, the potential for seaweed to enter local diets is limited, at least in the short-term. While sushi restaurants are proliferating in African cities such as Dakar, Lagos and Pretoria, these address demand from high-income consumers. The search for foods deemed by consumers to be 'healthy' in the context of concerns about rising rates of diet-related non-communicable diseases, such as diabetes, is growing in LMICs. This has led to the 'rediscovery' of traditional crops like finger millets, Bambara nuts and manioc (Tadele, 2019). However, the addition of a novel food like seaweed into dietary patterns can be a challenge. As noted by Chapman et al. (2015), "traditional cultural frameworks and prejudices" are the main reasons preventing uptake and upscaling of seaweed as food. As a result, Cai et al. (2021) conclude that "people outside Eastern Asia generally have low or little exposure to or preference over seaweed consumption [and that demand globally for seaweed as food] remains low in spite of seaweed's nutritional value and health benefits."

That said, potential exists for introducing extracted seaweed ingredients into locally processed products. If the processing of seaweed into dried or liquid nutrient extracts could be undertaken reasonably close to coastal production there is potential for food manufacturers to focus on carageen-type ingredients used in food processing or on extracts used in seaweed-enriched dishes, including noodles, baked products and processed meat formulations. In other words, the real contribution of seaweed to food security in most LMICS would arguably be through household income growth associated with new jobs in seaweed value chains rather than as a novel food per se (Theuerkauf et al., 2019). Income growth is strongly associated globally with more diversity and quality of diets (Pechey and Monsivais 2016; Darmon and Drewnowski 2015). The latter often relies on market purchases supported by employment in high income earning activities (Ickowitz et al., 2019; Masters et al., 2018). In the case of seaweed, product development using seaweed extracts and ingredients has important potential to generate revenue for local companies across Africa and Asia under the right policy and market conditions.

4. Challenges and opportunities for seaweed in LMICs

To contribute significantly to income growth, appropriate enabling policies, infrastructure and investments would be needed to support new or expanded seaweed production and value-addition. While seaweed fills important agricultural niches around the world, this kind of farming has yet to gain a fraction of the attention garnered by fish or shrimp aquaculture. Outside of Tanzania, Madagascar and South Africa, seaweed farming is largely invisible in Africa's policy agenda on food and agriculture. Changing this requires realistic assessments of business models, strong evidence of export growth potential as well as in-country demand, more supportive policy frameworks that promote targets and facilitate partnerships with food industry, and investments in processing and packaging capabilities for seaweed products, while generating post-harvest jobs. Concretely, the major constraints to a significant bolstering of a seaweed agenda in LMICs lie in two main areas, each with multiple facets, described below. However, there are opportunities to be explored as well (see Table 1 which summarizes opportunities as well as challenges associated with seaweed from production to consumption).

While the greatest problems of hunger and food insecurity are currently faced by food-deficit countries such as Afghanistan, Chad,

[3] While FAO's definition of aquatic plants includes water chestnut, lotus, and water cress, they also note that the production of aquatic plants is "mostly marine macroalgae (seaweeds)" (Food and Agriculture Organization of the United Nations, 2019).

Table 1
Opportunities and challenges associated with seaweed-related activities in low- and middle-income countries (LMICs).

Seaweed - related activities	Opportunities	Challenges
Farmed production	• Many LMICs have coastal conditions suited to farmed production • Potential for women smallholders to develop new sources of income • Potential for marine aquaculture to mitigate coastal eutrophication and pollution	• Limited experience, extension services, localized public research to tap into • Labor supply could be a seasonal constraint due to existing farm and household demands • Unknown impacts of climate change on ecosystem viability to support seaweed farming
Processing and value addition	• Processed seaweed ingredients of many kinds can contribute to enhanced food products • Processing and packaging of seaweed products for wider markets represents potential new income streams	• Limited sources of investment capital • Value chain infrastructure currently underdeveloped in most LMICs • Food safety and quality standards need to be established and monitored to facilitate private investment and marketing
Trade (exports)	• Global demand for seaweed products and extracts is expected to grow • Seaweed can be a new form of high value export commodity	• Not all algae species commanding high prices can be produced everywhere • Lack of domestic market regulations and policies needed to facilitate exports of seaweed products
Consumption and nutrition	• Novel food ingredients of high nutrient density could become part of locally processed food products • Fresh 'sea vegetables' could complement local diets of LMIC coastal communities over time • Dietary diversity may be enhanced through fresh seaweed produce • Diet quality overall improved through market purchases supported by income from seaweed farming and processing	• Unknown potential for seaweed to enter local LMIC diets where seafood products do not already exist • Seaweed cannot be consumed in sufficient quantities that provide high levels of kilocalories or protein • Seaweed product prices likely to be high relative to other local vegetables thereby constraining demand

Nepal, and Nicaragua, it is not clear how seaweed farming could help in landlocked nations, or indeed how seaweed products could enter local diets as a novel food. Part of the continued optimism relates to the long coastlines of Africa and South Asia, much of which may be conducive to farming macroalgae. For example, India's coastline is roughly 7500 km in length, along which at least 840 seaweed species are found (Dhargalkar, 2014). The most recent assessment identified 317 locations along India's shore, offering roughly 24,000 ha of seaweed farming potential (Johnson et al.). Latin America has almost 60,000 km of coastline, which is already home to a wide diversity of ecosystems that support diverse seaweed species (Alemañ et al., 2019). In Africa, there is potential for expanded seaweed production along 640 km of Kenya's coastline and for 5600 km of Madagascar's coast (Froehlich et al., 2019).

However, little is known about actual ecosystem conditions (local levels of pollution, for example) and the investment requirements in areas that currently suffer the highest rates of food insecurity and malnutrition. For example, a review of the potential for aquatic food contributions to income and diets in countries as diverse as Ghana, Peru, India, and Nigeria only considered fish and crustaceans because "although aquatic plants, seaweed, and aquatic animals other than fish and shellfish are important for food and nutrition security in certain locations, they are not included in our analysis due to data limitations" (Naylor et al., 2021).

A global assessment by the World Bank (2016) made broad estimates of likely habitats conducive to seaweed farming, suggesting strong possibilities for brown seaweed around the coast of southern Africa, and for red seaweed along the east coast of Africa (including Madagascar), North Africa, Central America, the southern coastline of India and around Sri Lanka, as well as parts of Malaysia and Indonesia. A more recent study identified 48 million km^2 globally as being ecologically suitable for seaweed farming, including large stretches of the coasts of West Africa and the Horn of Africa as well as most of Central America and the Caribbean and North Africa (Froehlich et al., 2019). However, greater specificity is needed to permit concrete assessments by governments and investors of cost-effective investments. More broadly, the lack of globally comparable datasets relating to all dimensions of seaweed production, trade and consumption remains a major constraint to understanding trends and patterns, and this continues to impede higher levels of public investment in seaweed-related activity.

4.1. Risks associated with seaweed production

First, while the short maturation time to harvest (roughly 6 weeks) reduces the time of exposure of seaweed crops to environmental hazards (especially compared to most terrestrial grain crops), there are still many issues to contend with. For example, so-called 'ice-ice disease' syndrome occurs when bacteria cause bleaching and tissue loss, thereby reducing biomass at harvest and resulting carrageen (Ward et al., 2022). Changes in salinity and water acidity, water temperature and light intensity all generate stress that causes seaweed to be prone to bacterial infections. Climate change is expected to increase such risks (Koch et al., 2021). Even in the short-term, inter-seasonal variability in ocean temperature, and salinity can affect the protein level in seaweed (high temperature and salinity being negatively correlated with protein quality), which has implications for post-harvest processing (SAPEA, 2017).

Second, seaweed farms can in certain locations compete for limited space along the shoreline. Location is key for farming seaweed. There must be enough light (loss of yield is linked to depth and darkness of the water) and access to free-flowing nutrients, but such locations can compete with traditional fishing, tourism, or with the outlets of wastewater or industrial effluents (SAPEA, 2017).

Third, seasonal labor constraints can be a major hurdle, particularly outside of Asia. Seaweed aquaculture can require significant amounts of labor for planting, maintenance of the lines, harvest and post-harvest handling. Large farms have flourished in countries like China, Indonesia and the Philippines, in part because of good availability and flexibility of labor needed to manage production cycles on time, which reduce cost (Cai et al., 2021). One assessment of the economics of production in six LMICs concluded that "although seaweed farming is repeatedly portrayed as a coastal enterprise suitable for small-scale family farms, the analysis highlighted the importance of achieving economies of scale as indicated by the superior economic performance of the Indonesian "industrial-scale" farms relative to the family-run operations in India and Tanzania. In the case of Tanzania, the small farming plots generated a level of income that fell short of the international and national poverty lines." (Valderrama et al., 2015).

Fourth, as with terrestrial crops, the quality of seedstock matters to yields (Hwang et al., 2020). A continuing lack of public agricultural research dedicated to enhancing, adapting, and maintaining seaweed stock has discouraged innovation and led to propagation from a limited pool of parent plants which, over time, increases susceptibility to disease and declining yields (SAPEA, 2017).

4.2. Investments in seaweed economic value chains

Theuerkauf et al. (2019) suggest that market-based approaches "could be an important pathway for low or lower-middle income nations to initiate or grow aquaculture production." Seaweed already accounts for one-third of aquaculture output globally and demand continues to grow (Cai et al., 2021; Food and Agriculture Organization, 2020). Establishing supply chains that meets international demand for perishable products (like seaweed) requires appropriate investments in drying, processing and packaging, good market infrastructure, clustered industry services, functional ports, appropriate legislation supporting quality assurance and insurability, as well as contractual stability.

In the domain of quality assurance, food safety stands out. Algae bind metal ions and can therefore gather toxins, including heavy metals (SAPEA, 2017). Certain seaweed varieties are also being known to amass biotoxins, metabolites, and radioisotopes (Wells et al., 2017). These attributes make seaweed useful as sentinel plants for monitoring water pollution, but can also inhibit demand (Cherry et al., 2019). Msuya et al. (2022), for example, note that "biosecurity policies are lacking in Tanzania" and that responses to pollution or disease outbreaks "are not well coordinated and control measures, in most cases, are not practiced by farmers." This can erode consumer trust in any product and makes guaranteeing that seaweed products are safe and of high enough quality for integration into food supply chains an essential underpinning of successful businesses in this sector. Appropriate food safety regulations and effective monitoring and reporting systems will need to be built up in LMICs that lack these, and relevant policies and institutions will have to help identify and overcome legal and risk barriers that would impair investments by local companies (Free et al., 2022).

For markets to function well, trust is key - whether it is about food quality and safety, price forecasts, logistical bottlenecks, input availability, or simply, where opportunities for farming should be prioritized. For example, in their calculations of how much ocean is suitable globally for aquaculture, Oyinlola et al. (2018) did not include seaweed because of the lack of "data on seaweed mariculture locations". Similarly, the analysis by Naylor et al. (2021) on demand for aquatic foods did not include seaweed, "due to data limitations." This signals an important data gap faced by national policymakers as well as for modelling. Inaction in terms of investments and research can in part be ascribed to a lack of basic knowledge, and any thoughts of wealthy nations remunerating LMICs to farm algae as a way of reaching global carbon sequestration targets (akin to carbon trading) will remain theoretical, until there is more granular understanding of what can actually be produced and where. This supports growing calls for improved information on aquatic foods of all kinds to be incorporated into national and global data collection and collation systems.

5. Conclusions

Seaweed farming requires little fresh water, inorganic fertilizers, and land. In terms of greenhouse gas emissions, seaweed absorb nitrogen, phosphorous and carbon dioxide, at least until harvest when most of these may be released. The vitamin, mineral and protein content of many types of seaweed is high. It is not surprising, therefore, that the potential for seaweed to assume a greater role in nourishing the world, with minimal negative impacts on the environment, has been widely proclaimed (Duarte et al., 2021).

However, there are three major hurdles to be overcome. First, much more needs to be understood about the potential net nutrition and health benefits of seaweed, particularly in undernourished or at-risk populations in LMICs. There remain significant evidence gaps relating to claimed health effects of regular dietary intake of seaweed as well as justifiable concerns about potential toxin impacts and exceeding upper tolerable limits for certain nutrients. The review of evidence by Murai et al. (2021) concluded that "further epidemiological studies including observational and interventional studies are necessary to clarify the effects of seaweeds on disease and health." Similarly, Wells et al. (2017) argued that while some health benefits are known, there are still "considerable challenges in quantifying these benefits, and in assessing potential adverse effects." At the same time, while the positive role played by algae (macro and micro) in carbon sequestration and emissions control are demonstrable, potential constraints to future expansion of seaweed production because of negative climate change impacts are not well understood. Filling such important evidence gaps represents an important opportunity for researchers globally and in LMICs.

Second, since there is so little production or consumption of seaweed in LMICs where food insecurity is high, building up domestic capacity for farming, processing and trading seaweed will require significant public and private investment in the coming years. The food security contribution of promoting a new seaweed-based farm and food sector in LMICs could be large, primarily deriving from new income streams accruing i) at the household level (smallholder producers in coastal communities), ii) among small- and medium-sized enterprises involved in processing and packaging, ingredient extraction, or using derived ingredients in food, cosmetic and pharmaceutical products, and iii) among traders who export processed and unprocessed products to global markets. These income streams would involve new jobs, higher labor productivity, and enhanced local livelihoods that would support enhance local diets through greater purchasing power.

A challenge is that most food-deficit LMICs are characterized by a chronic lack of investment in conventional forms of agriculture sector, with poor extension services, limited local research and development, weak institutional support and underdeveloped infrastructure. Pivoting to novel forms of agriculture like seaweed farming will require a serious ambition to develop such an industry. Of course, none of these challenges are insurmountable, nor even unique to seaweed. But, for LMICs to capture a larger market share, constraints must be tackled realistically. To enhance LMIC production, processing, and trade will require significant investments in technical know-how, infrastructure, safety standards, and processing capabilities.

It will also require an enabling policy environment. Governments will need to work closely with development partners and private businesses to: a) establish coherent sectoral strategies and targets (as India has done recently); b) ensure appropriate legislative, food safety, and policy environments supporting investments; c) establish required infrastructure and market hubs to facilitate commercial processing facilities and supply chains for export as well as domestic demand; d) link existing government land agriculture and marine fisheries interests with new coastal inter-tidal portfolios of action, including support for local training, technology adoption and trade; and e) promote long-term agendas through applied research in national institutions on seaweed species, resilience to diseases and pests, production technology innovations, and cost efficiencies.

A third challenge is that official data on seaweed production, trade and consumption are notoriously poor in terms of accuracy and coverage. As a result, national and global statistics on patterns and trends should be treated cautiously. Given the attention now paid to seaweed, appropriate investments are urgently needed to improve the quantity, quality and comparability of data as a basis on which governments and businesses can make informed decisions about future investments.

Demand for environmentally sustainable forms of agriculture in coming decades argues for more focused attention to seaweed as having potential for supporting food security and nutrition in coastal LMICS, mainly through income growth. But many key questions need be answered quickly and concretely, particularly those relating to the supply and cost of labor in coastal communities where alternative livelihoods already exist, to climate-induced changes in water quality and temperature that may impede seaweed farming in coming decades, and to the potential for small producers of farmed output to gain sufficient market share through trade to make commercial investments viable and sustainable.

Declaration of competing interest

The authors declare the following financial interests/personal

relationships which may be considered as potential competing interests: Patrick Webb reports financial support was provided by the United States Agency for International Development. Patrick Webb reports a relationship with United States Agency for International Development that includes: a funding grant for the Feed the Future Food Systems for Nutrition Innovation Lab.

Data availability

No data was used for the research described in the article.

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