SEAWEEDS AND MICROALGAE: AN OVERVIEW FOR UNLOCKING THEIR POTENTIAL IN GLOBAL AQUACULTURE DEVELOPMENT FAO Fisheries and Aquaculture Circular NFIA/C1229 (En)

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Cover photographs: Cultivation of *Kappaphycus alvarezii* in the Philippines (left; ©A. Hurtado). Production of spirulina in Chad (upper right; ©FAO/M. Marzot). Wild collection of *Ascophyllum nodosum* in Canada (lower right; ©L. Cornish).

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SEAWEEDS AND MICROALGAE: AN OVERVIEW FOR UNLOCKING THEIR POTENTIAL IN GLOBAL AQUACULTURE DEVELOPMENT

by

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PREPARATION OF THIS DOCUMENT

This document is a discussion paper that provides a balanced overview of the algae sector with a focus on its contribution and potential in global aquaculture development. The overview is intended to facilitate discussion on algae-related issues at the Eleventh Session of the Sub-Committee on Aquaculture, the FAO Committee on Fisheries (COFI), which is expected to be held in Mérida, Yucatán, Mexico, from 15 to 18 November 2021. The paper also lays a foundation for more comprehensive, in-depth assessment in the future.

The paper was based on inputs from a number of FAO staff and external experts. They are acknowledged on the title page in the alphabetic order of their surnames, except for the two lead authors. PingSun Leung is acknowledged for his valuable review of the document. Maria Kalentsits is acknowledged for her assistance in literature search. Maria Giannini and Marianne Guyonnet are acknowledged for their assistance in editing and formatting. José Luis Castilla Civit is acknowledged for his assistance in cover design.

ABSTRACT

Algae, including seaweeds and microalgae, contribute nearly 30 percent of world aquaculture production (measured in wet weight), primarily from seaweeds. Seaweeds and microalgae generate socio-economic benefits to tens of thousands of households, primarily in coastal communities, including numerous women empowered by seaweed cultivation. Various human health contributions, environmental benefits and ecosystem services of seaweeds and microalgae have drawn increasing attention to untapped potential of seaweed and microalgae cultivation. Highly imbalanced production and consumption across geographic regions implies a great potential in the development of seaweed and microalgae cultivation. Yet joint efforts of governments, the industry, the scientific community, international organizations, civil societies, and other stakeholders or experts are needed to realize the potential. This document examines the status and trends of global algae production with a focus on algae cultivation, recognizes the algae sector's existing and potential contributions and benefits, highlights a variety of constraints and challenges over the sector's sustainable development, and discusses lessons learned and way forward to unlock full potential in algae cultivation and FAO's roles in the process. From a balanced perspective that recognizes not only the potential of algae but also constraints and challenges upon the realization of the potential, information and knowledge provided by this document can facilitate evidence-based policymaking and sector management in algae development at the global, regional and national levels.

CONTENTS

ABBREVIATIONS AND ACRONYMS

ANSES	French Agency for Food, Environmental and Occupational Health & Safety
ASFIS	Aquatic Sciences and Fisheries Information System
DHA	docosahexaenoic acid
EFSA	European Food Safety Authority
FAM	freshwater aquatic macrophyte
FAO	Food and Agriculture Organization of the United Nations
IIMSAM	The Autonomous Intergovernmental Institution for the Use of Micro-algae Spirulina Against Malnutrition
IMTA	integrated multitrophic aquaculture
IUCN	International Union for Conservation of Nature
JECFA	Joint FAO/WHO Expert Committee on Food Additives
NDA	The Panel on Nutrition, Novel Foods and Food Allergens
nei	not elsewhere included
NOAA	National Oceanic and Atmospheric Administration
PMP/AB	Progressive Management Pathway for Improving Aquaculture Biosecurity
SDG	Sustainable Development Goal
UCTV	University of California Television
UN	United Nations
UNGA	The United Nations General Assembly
USD	United States Dollar
WAPI	World Aquaculture Performance Indicators

1. INTRODUCTION

Algae referred to in this document include seaweeds (i.e. marine macroalgae) and microalgae, which are photosynthetic aquatic organisms. Algae play a vital role in the aquatic ecosystem by forming the energy base of the food web for all aquatic organisms; they provide various environmental benefits and ecosystem services, such as eutrophication mitigation, carbon capture or sequestration, ocean acidification amelioration, habitat provision and shoreline protection, among others.

Consideration of other photosynthetic aquatic plants, such as seagrass, halophytic plants and freshwater aquatic macrophytes (FAMs), is beyond the scope of this document. While the cultivation of FAMs has become a substantial aquaculture sub-sector, particularly in Asia, there is a general lack of systematic information and knowledge regarding the sector (FAO, forthcoming).

Algae, particularly seaweeds, are an important component of global aquaculture. In 2019, algae cultivation, measured in wet weight,[1] contributed nearly 30 percent of the 120 million tonnes of world aquaculture production,[2] and red seaweeds (Rhodophyta) and brown seaweeds (Phaeophyceae) were, respectively, the second- and third-largest species groups in global aquaculture, only smaller than “Carps, barbels and other cyprinids” (FAO, 2021a).

Being mostly low-value commodities, seaweeds accounted for 5.4 percent of the USD 275 billion of world aquaculture production value in 2019. Still, the 5.4 percent value share remained higher than that of “Tilapias and other cichlids” or “Catfishes”, and was only lower than that of four species groups: (i.e. “Carps, barbels and other cyprinids”; “Marine shrimps and prawns”; “Salmons, trouts, smelts”; and “Crayfishes”) (FAO, 2021b).

Seaweeds, however, are not well known in many parts of the world, as their production is mostly concentrated in Eastern and South-eastern Asia.[3] On the demand side, while in Eastern Asia seaweeds have become widely and frequently consumed human foods, in other parts of the world seaweeds are largely niche or novel foods, mostly eaten in some coastal communities as traditional foods or by a relatively small number of consumers for various purposes, which could be dietary (e.g. as exotic foods from Oriental cuisine), nutritional (e.g. supplementing micronutrients), environmental (e.g. as products with a low environmental footprint) and/or social (e.g. plant-based diets for animal welfare).

Seaweeds have multiple other uses in food and non-food industries, such as food additives, animal feeds, pharmaceuticals, nutraceuticals, cosmetics, textiles, biofertilizer/biostimulants, bio-packaging, and biofuel, among others (McHugh, 2003; FAO, 2018). However, knowledge of their contribution to these products is generally confined to seaweed-related industries and the scientific community.

With their various social, environmental and economic contribution and benefits (Bjerregaard *et al*., 2016), the potential contributions of seaweeds to multiple Sustainable Development Goals (SDGs) (e.g. SDG 1, SDG 2, SDG 3, SDG 8, SGD 10, SDG 12, SDG 13 and SDG 14) have been recognized, for example, in a “Seaweed Manifesto”.[4] There is a growing interest in seaweeds from several sectors, with a particular focus on their potential as a source of nutritious food to feed the growing human population and for the ecosystem services they provide, particularly in reducing greenhouse gases (Parodi *et*

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[1] Unless specified otherwise, in this document production tonnage is measured in wet weight.
[2] Unless noted otherwise, aquaculture and fisheries production statistics presented in this document are from FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ). www.fao.org/fishery/statistics/software/fishstatj/en
[3] Unless noted otherwise, country grouping in this document follows the United Nations M49 standard.
[4] https://unglobalcompact.org/library/5743

al., 2018; Duarte *et al*., 2020). The existence of vast marine areas suitable for seaweed farming makes champions of seaweeds envision a forthcoming "Seaweed Revolution".[5]

There is a growing consensus that wild resources will not be able to supply enough seaweeds to satisfy future demand despite the robust management strategies in many areas (Steen *et al*., 2016; Monagail *et al*., 2017; Lauzon-Guay *et al*., 2021). Aquaculture is the primary means to ensure safety and traceability and to help unlock the great potential of seaweeds. However, the sustainable development of seaweed cultivation faces various issues, constraints and challenges that entail joint efforts of policy-makers, stakeholders and experts to address or overcome.

Microalgae cultivation appears much smaller than seaweeds – commercial microalgae cultivation recorded in FAO statistics contributed less than 0.2 percent of global algae cultivation tonnage in 2019. Microalgae cultivation, however, plays crucial roles in the farming of aquatic animal species (e.g. as direct hatchery/nursery feeds or essential part of primary nutrient cycles operating within a pond culture system for rearing finfish, shrimp or other animal species), although such intermediate products or services provided by microalgae are usually not recorded in official statistics. Similar to seaweeds, microalgae also have great potential in various food and non-food applications (Khan, Shin and Kim, 2018); many of which nevertheless entail significant joint efforts to become fully commercialized.

Sustainable algae sector development entails the recognition of not only its potential contributions and benefits but also constraints and challenges upon the realization of the potential. This paper provides a balanced overview of the algae sector, which includes (i) examination of the status and trends of global algae production (section 2); (ii) assessment of the sector's social, economic and environmental contributions (section 3); (iii) highlight of issues, constraints and challenges in the algae sector development (section 4); and (iv) discussion of lessons learned and way forward to unlock full potential in algae cultivation and FAO's roles in the process (section 5).

2. STATUS AND TRENDS OF GLOBAL ALGAE PRODUCTION

World seaweed production is primarily supported by aquaculture. In 1969, the 2.2 million tonnes of world seaweed production was evenly divided between wild collection and cultivation. A half century later, however, while wild collection remained at 1.1 million tonnes in 2019, cultivation increased to 34.7 million tonnes, which accounted for 97 percent of world seaweed production in 2019 (Cai *et al*., 2021).

There is a strong regional imbalance in seaweed production. In 2019, seaweed production in Asia (99.1 percent from cultivation) contributed 97.4 percent of world production, and seven of the top ten seaweed producing countries were from Eastern or South-eastern Asia (Table 1).

The Americas and Europe contributed, respectively, 1.4 percent and 0.8 percent of world seaweed production in 2019. Seaweed production in these two regions was primarily fulfilled by wild collection, and cultivation only accounted for 4.7 percent and 3.9 percent of total seaweed production, respectively (Table 1).

In contrast, cultivation was the main source of seaweed production in Africa (81.3 percent) and Oceania (85.3 percent), although their contribution to world seaweed production was only 0.4 percent and 0.05 percent, respectively (Table 1).

[5] https://seaweedrevolution.live.ft.com

Table 1: Global seaweed production, 2019

Country/area	Total seaweed production (farmed and wild)		Seaweed cultivation	
	Tonnes (wet weight)	Share of world production (%)	Tonnes (wet weight)	Share in farmed and wild production (%)
World	**35 762 504**	**100.00**	**34 679 134**	**96.97**
Asia	**34 826 750**	**97.38**	**34 513 223**	**99.10**
1. China	*20 296 592*	*56.75*	*20 122 142*	*99.14*
2. Indonesia	*9 962 900*	*27.86*	*9 918 400*	*99.55*
3. Republic of Korea	*1 821 475*	*5.09*	*1 812 765*	*99.52*
4. Philippines	*1 500 326*	*4.20*	*1 499 961*	*99.98*
5. Democratic People's Republic of Korea	*603 000*	*1.69*	*603 000*	*100.00*
7. Japan	*412 300*	*1.15*	*345 500*	*83.80*
8. Malaysia	*188 110*	*0.53*	*188 110*	*100.00*
Rest of Asia (7 countries/territories)	42 047	0.12	23 344	55.52
Americas	**487 241**	**1.36**	**22 856**	**4.69**
6. Chile	*426 605*	*1.19*	*21 679*	*5.08*
Peru	36 348	0.10	-	-
Canada	12 655	0.04	-	-
Mexico	7 336	0.02	10	0.14
United States of America	3 394	0.01	263	7.75
Rest of the Americas (6 countries)	904	0.00	904	100.00
Europe	**287 033**	**0.80**	**11 125**	**3.88**
9. Norway	*163 197*	*0.46*	*117*	*0.07*
France	51 476	0.14	176	0.34
Ireland	29 542	0.08	42	0.14
Russian Federation	19 544	0.05	10 573	54.10
Iceland	17 533	0.05	-	-
Rest of Europe (5 countries)	5 741	0.02	217	3.78
Africa	**144 909**	**0.41**	**117 791**	**81.29**
10. United Republic of Tanzania	*106 069*	*0.30*	*106 069*	*100.00*
Zanzibar	104 620	0.29	104 620	100.00
Tanzania (mainland)	1 449	0.00	1 449	100.00
Morocco	17 591	0.05	273	1.55
South Africa	11 155	0.03	2 155	19.32
Madagascar	9 665	0.03	8 865	91.72
Rest of Africa (2 countries)	430	0.00	430	100.00
Oceania	**16 572**	**0.05**	**14 140**	**85.32**
Solomon Islands	5 600	0.02	5 600	100.00
Papua New Guinea	4 300	0.01	4 300	100.00
Kiribati	3 650	0.01	3 650	100.00
Australia	1 923	0.01	-	-
Rest of Oceania (3 countries)	1 099	0.00	590	53.66

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).
Notes: The top 10 seaweed producing countries are indexed. "-" indicates zero or no data.

Seaweeds are broadly classified into three taxonomic groups: brown seaweeds (around 2 000 species under Phaeophyceae), red seaweeds (over 7 200 species under Rhodophyta) and green seaweeds (more than 1 800 macroalgae species under Chlorophyta).[6,7]

Seaweed cultivation is concentrated on a relatively small number of species. FAO statistics record only 27 different ASFIS[8] (Aquatic Sciences and Fisheries Information System) seaweed species items cultivated in 2019, a fraction (6.1 percent) of the total 443 ASFIS species items in global aquaculture, even though seaweeds accounted for nearly 30 percent of world aquaculture production in terms of wet weight (FAO, 2021d).

It should be noted that FAO statistics may not record or distinctly reveal some aquaculture species (including seaweed species) because of underreporting, confidentiality or other reasons. Despite such data imperfections, it can be concluded with high confidence that seaweed cultivation tends to have relatively low species diversity in contrast to the aquaculture of animal species.

2.1 Brown seaweeds

World cultivation of brown seaweeds increased from 13 000 tonnes in 1950 to 16.4 million tonnes in 2019; the average 10.9 percent annual growth during 1950–2019 was higher than the 7.9 percent growth in world aquaculture of all species.

In 2019, brown seaweeds accounted for 47.3 percent of world seaweed cultivation in terms of tonnage and 52 percent in terms of value. Brown seaweed cultivation has concentrated on two cold-water genera: *Laminaria*/*Saccharina* (also known as kelp) and *Undaria* (also known as wakame).

In 2019, the 12.3 million tonnes of *Laminaria*/*Saccharina* (primarily *Laminaria* [*Saccharina*] *japonica*[9]) cultivation (35.4 percent of all seaweeds) was supplied by seven countries, comprising four countries in Eastern Asia and three countries in Europe (Table 2). The 2.6 million tonnes of *Undaria* (primarily *U. pinnatifida*) cultivation (7.4 percent of all seaweeds) was supplied by four countries, comprising three countries in Eastern Asia and one country in Europe (Table 3).

Table 2: *Laminaria*/*Saccharina* cultivation production, 2019

Country/area	*Laminaria*/*Saccharina* cultivation	
	Tonnes (wet weight)	Share of world (%)
World	**12 273 748**	**100.00**
1. China	10 978 362	89.45
2. Republic of Korea	662 557	5.40
3. Democratic People’s Republic of Korea	600 000	4.89
4. Japan	32 600	0.27
5. Faroe Islands	156	0.00
6. Norway	73	0.00
7. Spain	0.14	0.00

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).

[6] www.seaweed.ie
[7] www.americanscientist.org/article/the-science-of-seaweeds
[8] ASFIS – Aquatic Sciences and Fisheries Information System – species items in FAO statistics could refer to either individual species, hybrids or groups of related species, such as families (when identification to species is impossible). www.fao.org/fishery/collection/asfis/en
[9] In order to avoid confusion, the document follows taxonomic nomenclatures used in FAO statistics even when there are more updated taxonomic names; e.g. *Laminaria japonica* is used instead of *Saccharina japonica*; *Porphyra* is used instead of *Pyropia* or *Neoporphyra*.

Table 3: *Undaria* cultivation production, 2019

Country/area	*Undaria* cultivation	
	Tonnes (wet weight)	Share of world (%)
World	**2 563 582**	**100.00**
1. China	2 023 930	78.95
2. Republic of Korea	494 947	19.31
3. Japan	44 600	1.74
4. France	105	0.00

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).

Other minor brown seaweed species under cultivation include:

- 1.25 million tonnes of unidentified brown seaweeds cultivated in four countries: China (1.24 million tonnes), the Russian Federation (11 000 tonnes), the United States of America (241 tonnes) and Mexico (10 tonnes);
- 304 000 tonnes of *Sargassum* (primarily *S. fusiforme*) cultivated in two Eastern Asian countries: China (270 000 tonnes) and the Republic of Korea (34 000 tonnes);
- 105 tonnes of *Alaria esculenta* (also known as bladderlocks, dabberlocks or winged kelp) cultivated in three Northern European countries: Norway (44 tonnes), Ireland (42 tonnes) and the Faroe Islands (19 tonnes);
- 90 tonnes of *Cladosiphon okamuranus* (also known as mozuku) cultivated in Tonga – the cultivation of *C. okamuranus* in Okinawa, Japan (Sato *et al.*, 2021), is not distinctly recorded in FAO statistics but may be embedded under "Seaweeds nei"; and
- 2 tonnes of *Macrocystis pyrifera* (also known as giant kelp) cultivated in Chile.

Cultivated brown seaweeds are mostly used as human foods (e.g. kombu soup and wakame salads) as well as abalone feed.[10] They are also used as raw materials to produce (i) alginate (a hydrocolloid for various food and non-food uses); (ii) animal feeds; (iii) biofertilizer or biostimulants; (iv) pharmaceutical or nutraceutical products; and (v) compostable bio-packaging; among others (McHugh, 2003; FAO, 2018).

2.2 Red seaweeds

World cultivation of red seaweeds increased from 21 000 tonnes in 1950 to 18.3 million tonnes in 2019; the 10.3 percent annual growth was slightly lower than that of brown seaweeds, yet still much higher than the 7.9 percent growth for world aquaculture of all species.

In 2019, red seaweeds accounted for 52.6 percent of world seaweed cultivation in terms of tonnage and 47.6 percent in terms of value. Red seaweed cultivation is concentrated on two warm-water genera (*Kappaphycus/Eucheuma* and *Gracilaria*) and one cold-water genus (*Porphyra*, also known as nori).

The 11.6 million tonnes of *Kappaphycus/Eucheuma* cultivation in 2019 (33.6 percent of all seaweeds) was provided by 23 countries or territories, comprising nine countries in Asia, four countries or territories in Eastern Africa, four Pacific Island states, and six countries in Latin America and the Caribbean (Table 4).

[10] In China, high-quality kelp (*Laminaria japonica*) is usually used for human consumption, whereas low-grade kelp (including scraps) is used as abalone feed (FAO, 2020a).

Table 4: *Kappaphycus/Eucheuma* cultivation production, 2019

Country/area	*Kappaphycus/Eucheuma* cultivation	
	Tonnes (wet weight)	Share of world (%)
World	**11 622 213**	**100.00**
Asia	**11 491 956**	**98.88**
Indonesia	9 795 400	84.28
Philippines	1 498 788	12.90
Malaysia	188 110	1.62
China	4 200	0.04
Cambodia	2 000	0.02
Viet Nam	1 700	0.01
Timor-Leste	1 500	0.01
Sri Lanka	247	0.00
Myanmar	11	0.00
Africa	**115 334**	**0.99**
United Republic of Tanzania	106 069	0.91
Zanzibar	104 620	0.90
Tanzania (mainland)	1 449	0.01
Madagascar	8 865	0.08
Kenya	400	0.00
Oceania	**14 050**	**0.12**
Solomon Islands	5 600	0.05
Papua New Guinea	4 300	0.04
Kiribati	3 650	0.03
Fiji	500	0.00
Latin America and the Caribbean	**874**	**0.01**
Brazil	700	0.01
Saint Lucia	103	0.00
Ecuador	45	0.00
Grenada	20	0.00
Belize	3	0.00
Venezuela (Bolivarian Republic of)	3	0.00

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).

In 2019, the 3.6 million tonnes of farmed *Gracilaria* (10.5 percent of all seaweeds) was contributed by 11 countries, comprising six countries or territories in Eastern and South-eastern Asia, two countries in South America, two countries in Northern Africa, and one country in Southern Europe (Table 5). The 3 million tonnes of farmed *Porphyra* (8.6 percent of all seaweeds) was contributed by five countries or territories in Eastern Asia (Table 6).

Besides the three major red seaweed genera, FAO statistics also record a small amount of unidentified red seaweeds cultivated in 2019 by two countries, comprising 5 300 tonnes in India (Ranjan, 2021) and 5 tonnes in Chile (Buschmann *et al*., 2021).

Gracilaria are mostly used for agar production and abalone feed, whereas *Kappaphycus*/*Eucheuma* are mostly used to extract carrageenan (McHugh, 2003; FAO, 2018). As with alginate extracted from brown seaweeds, agar and carrageenan are seaweed-based hydrocolloids widely used in food and non-food industries. *Gracilaria* and *Kappaphycus*/*Eucheuma* are also consumed as human foods (e.g. salads and pickles) by coastal communities where they are produced. *Porphyra* are mostly used as human foods (e.g. soup ingredient and sushi wrap).

Table 5: *Gracilaria* cultivation production, 2019

Country/area	*Gracilaria* cultivation	
	Tonnes (wet weight)	Share of world (%)
World	**3 639 833**	**100.00**
Asia	**3 617 828**	**99.40**
China	3 480 850	95.63
Indonesia	123 000	3.38
Viet Nam	11 150	0.31
Republic of Korea	1 769	0.05
Taiwan Province of China	976	0.03
Philippines	83	0.00
Latin America and the Caribbean	**21 702**	**0.60**
Chile	21 672	0.60
Brazil	30	0.00
Africa	**303**	**0.01**
Morocco	273	0.01
Tunisia	30	0.00
Europe	**0.13**	**0.00**
Spain	0.13	0.00

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).

Table 6: *Porphyra* cultivation production, 2019

Country/area	*Porphyra* cultivation	
	Tonnes (wet weight)	Share of world (%)
World	**2 984 123**	**100.00**
Asia	**2 984 123**	**100.00**
China	2 123 040	71.14
Republic of Korea	606 873	20.34
Japan	251 200	8.42
Democratic People's Republic of Korea	3 000	0.10
Taiwan Province of China	10	0.00

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).

2.3 Green seaweeds (excluding green microalgae)

Cultivation of green seaweeds has been small and on a downward trend since the early 1990s. The 16 696 tonnes of world green seaweed cultivation in 2019 (merely 0.05 percent of all seaweeds) was less than half of the peak level in 1992 (38 556 tonnes), as opposed to the rapid growth in the cultivation of brown seaweeds (3-fold) and red seaweeds (15-fold) between 1992 and 2019.

FAO statistics record eight green seaweed ASFIS species items cultivated during 1950–2019; six of them had non-negligible production (i.e. greater than a half tonne) in 2019. The 16 696 tonnes of world green seaweed cultivation in 2019 primarily comprised five ASFIS species items (i.e. *Caulerpa* spp; *Monostroma nitidum*; *Enteromorpha* [*Ulva*] *prolifera*; *Capsosiphon fulvescens*; and *Codium fragile*), whose 2019 production was lower than their peak levels during 1950–2019 (Table 7).

During 1950–2019, the 6 404 tonnes of average annual aquaculture production of *Caulerpa* spp. was the highest among all green seaweeds, yet the production (almost entirely contributed by the Philippines) declined from 28 704 tonnes in 1998 to 1 090 tonnes in 2019.

In 2019, the 6 321 tonnes of world cultivation of *Monostroma nitidum* (also known as green laver) was the highest among green seaweeds, yet the production (entirely contributed by the Republic of Korea) was much lower than its highest level during 1950–2019 (i.e. 17 248 tonnes in 1992).

Table 7: World green seaweed cultivation, 1950–2019

<table>
<tr><th rowspan="2">Species</th><th rowspan="2">Average annual cultivation during 1950–2019 (wet tonnes)</th><th colspan="2">Maximum annual cultivation during 1950–2019</th><th colspan="2">Cultivation in 2019</th></tr>
<tr><th>Wet tonnes</th><th>Year</th><th>Wet tonnes</th><th>Producing countries</th></tr>
<tr><td>Green seaweeds</td><td>14 019</td><td>38 556</td><td>1992</td><td>16 696</td><td>Total 6 countries</td></tr>
<tr><td>1. Caulerpa spp.</td><td>6 404</td><td>28 704</td><td>1998</td><td>1 090</td><td>Philippines (100%)</td></tr>
<tr><td>2. Monostroma nitidum</td><td>3 991</td><td>17 248</td><td>1992</td><td>6 321</td><td>Republic of Korea (100%)</td></tr>
<tr><td>3. Enteromorpha prolifera</td><td>1 367</td><td>12 540</td><td>2008</td><td>-</td><td>-</td></tr>
<tr><td>4. Capsosiphon fulvescens</td><td>1 134</td><td>7 000</td><td>2018</td><td>3 386</td><td>Republic of Korea (100%)</td></tr>
<tr><td>5. Ulva spp.</td><td>515</td><td>2 900</td><td>2005</td><td>2 155</td><td>South Africa (100%)</td></tr>
<tr><td>6. Codium fragile</td><td>494</td><td>5 550</td><td>2014</td><td>3 258</td><td>Republic of Korea (100%)</td></tr>
<tr><td>7. Green seaweeds nei</td><td>114</td><td>863</td><td>1988</td><td>486</td><td>Viet Nam (92.62%)
Portugal (7.2%)
Spain (0.18%)</td></tr>
<tr><td>8. Caulerpa racemosa</td><td>0.06</td><td>2</td><td>2015</td><td>-</td><td>-</td></tr>
</table>

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).
Notes: Green seaweeds exclude green microalgae. Species items are ranked according to the average annual production during 1950–2019. “-” indicates zero or no data. nei = not elsewhere included.

The 2 155 tonnes of world cultivation of *Ulva* (also known as sea lettuces) in 2019 was also lower than its highest level during 1950–2019 (i.e. 14 074 tonnes in 2008). The decline primarily reflects the decrease of *Enteromorpha* (*Ulva*) *prolifera* cultivation in China from 12 540 tonnes in 2008 to a negligible level in 2019, whereas world cultivation of *Ulva* in 2019 comprised 2 155 tonnes of *Ulva* spp. cultivated in South Africa (Table 7).

The Republic of Korea’s 12 965 tonnes of green seaweed cultivation in 2019, which comprised *Monostroma nitidum*, *Capsosiphon fulvescens* and *Codium fragile* (Table 7), was 78 percent of the world total.

Cultivated green seaweeds can be used as sea vegetables to prepare salads and other dishes. As manifested by their common or commercial names, *Monostroma nitidum* (also known as green laver) and *Caulerpa lentillifera* (also known as sea grape or green caviar) are considered delicacies. Similar to brown and red seaweeds, green seaweeds have many other applications, such as animal feeds (e.g. *Ulva* spp. cultivated in South Africa to feed abalone), biofertilizer/biostimulants, pharmaceuticals, cosmetics and waste treatment (McHugh, 2003; FAO, 2018).

2.4 Stylized facts of seaweed cultivation

In 2019, average first-sale prices were USD 0.47/kg (wet weight) for brown seaweeds, USD 0.39/kg for red seaweeds and USD 0.79/kg for green seaweeds. The USD 0.89/kg of average price for *Porphyra* was the highest among the five major seaweed genera under cultivation, followed by *Undaria* (USD 0.75/kg), *Gracilaria* (USD 0.54/kg), *Laminaria*/*Saccharina* (USD 0.37/kg) and *Kappaphycus*/*Eucheuma* (USD 0.21/kg).

On the supply side, economies of scale can help lower production cost, which is reflected by the lowest prices for the two largest seaweed genera, *Laminaria*/*Saccharina* and *Kappaphycus*/*Eucheuma*. In addition, low labour and capital costs are key to reducing the cost of seaweed cultivation (Cai, Hishamunda and Ridler, 2013), as indicated by the lower price of *Kappaphycus*/*Eucheuma* compared to *Laminaria*/*Saccharina*. On the demand side, generally speaking, seaweeds used as human foods tend to be more valuable than those employed for industrial applications.

Many seaweeds collected from wild habitats have yet to be cultivated substantially; furthermore, not all wild seaweeds are suitable for cultivation. FAO statistics recorded 36 seaweed ASFIS species items with non-negligible wild production in 2019, among which 21 species items had no corresponding cultivation production.[11] These 21 species items include several brown seaweeds that accounted for nearly half of wild seaweed production in 2019. Most of them were kelp species under the order Laminariales, including:

- 247 312 tonnes of *Lessonia* kelps, which were collected in two countries in South America: Chile (245 269 tonnes) and Peru (2 043 tonnes).
- 75 155 tonnes of *Ascophyllum nodosum* (also known as North Atlantic rockweed), which were collected in three countries in Northern Europe and one country in Northern America: Ireland (28 000 tonnes), Norway (18 949 tonnes), Iceland (15 551 tonnes) and Canada (12 655) tonnes.
- 51 624 tonnes of *Laminaria hyperborea* (also known as North European kelp), which were collected in five European countries: Norway (36 771 tonnes), France (12 939 tonnes), Ireland (1 400 tonnes), the Russian Federation (430 tonnes) and Iceland (84 tonnes).
- 40 100 tonnes of *Laminaria digitata* (also known as sea tangle), which were collected in two European countries: France (38 202 tonnes) and Iceland (1 898 tonnes).

In 2019, the 11.7 million tonnes of world production of carrageenan-containing seaweeds (carrageenophytes) was almost entirely supplied by *Kappaphycus*/*Eucheuma* cultivation in tropical areas. There were 62 961 tonnes of wild collection of another five carrageenophytes in South America:

- 28 672 tonnes of *Sarcothalia crispata* collected in Chile.
- 26 644 tonnes of *Gigartina skottsbergii* collected in Chile;
- 2 937 tonnes of *Mazzaella laminarioides* collected in Chile;
- 2 364 tonnes of *Gymnogongrus furcellatus* collected in Chile; and
- 2 344 tonnes of *Chondracanthus chamissoi* collected in Peru (1 511 tonnes) and Chile (833 tonnes).

These five carrageenophytes have no record of cultivation production in FAO statistics, which indicate that they have not been substantially cultivated.

Similarly, the 3.7 million tonnes of world production of agar-containing seaweeds (agarophytes) in 2019 was almost entirely supplied by *Gracilaria*, which were mostly provided by cultivation with a small amount (53 955 tonnes) resulting from wild collection in Chile. Another three agarophytes had only wild collection but no cultivation production recorded in FAO statistics:

- 1 284 tonnes of *Gelidium* spp. collected in South Africa (735 tonnes), Chile (309 tonnes), Spain (232 tonnes) and Taiwan Province of China (8 tonnes);
- 158 tonnes of *Gelidium corneum* collected in France; and
- 1 tonne of *Pterocladia lucida* collected in New Zealand.

[11] This could partly reflect imperfect data (e.g. existing cultivation production not recorded or distinctly revealed in FAO statistics). Yet such cases are usually associated with low or concentrated production.

2.5 Microalgae

Microalgae are microscopic algae usually invisible to the naked eye. While seaweeds are marine organisms, microalgae are phytoplankton found in both freshwater and marine systems. Microalgae comprise a variety of unicellular algae species, such as green microalgae (Chlorophyceae; e.g. *Chlorella* spp.) (Dixon and Wilken, 2018), diatoms (Bacillariophyceae),[12] *Nannochloropsis* spp. (Chua *et al*., 2020), *Schizochytrium* spp. (EFSA NDA Panel, 2020), *Crypthecodinium* spp. (Mendes *et al*., 2009), to name a few closely related to aquaculture. Cyanobacteria (also known as blue-green algae), such as spirulina[13] (including about 15 species under two genera, *Spirulina* and *Arthrospira*; Habib *et al*., 2008), are usually deemed part of microalgae (Hill, 2017).

Commercial microalgae production is rather small compared to seaweeds. The only wild production of microalgae recorded in FAO statistics was that of *Spirulina* (*Arthrospira*) in Mexico from 1962 until 1993, with a maximum production of 4 375 tonnes in 1989.

Substantial microalgae cultivation recorded in FAO statistics started in 2003 with 16 483 tonnes of *Spirulina* (*Arthrospira*) cultivated in China. Global microalgae cultivation reached 93 756 tonnes in 2010, yet it declined to 56 456 tonnes in 2019, which mostly reflected the change of spirulina cultivation in China.

The 56 456 tonnes of world microalgae production in 2019 was supplied primarily by 56 208 tonnes of *Spirulina* (*Arthrospira*), cultivated in ten countries, and four green microalgae (a total of 248 tonnes), cultivated in four countries (Table 8).

It should be noted that as microalgae cultivation tends to be regulated and monitored at the national or local level, separately from aquaculture, FAO statistics may miss substantial microalgae production in some countries, including Australia, Czechia, Iceland, India, Israel, Italy, Japan, Malaysia, Myanmar and the United States of America (FAO, 2020a).

Table 8: Microalgae cultivation, 2019

Country/area	Microalgae (tonnes)	*Spirulina*/ *Arthrospira* (tonnes)	Green microalgae (tonnes)				
			Total	*Haematococcus pluvialis*	*Chlorella vulgaris*	*Tetraselmis* spp.	*Dunaliella salina*
World	**56 456**	**56 208**	**248**	**242**	**4.77**	**1.45**	**0.22**
1. China	54 850	54 650	200	200			
2. Chile	903	861	42	42			
3. France	207	201	6.22		4.77	1.45	
4. Greece	142	142					
5. Tunisia	140	140					
6. Burkina Faso	140	140					
7. Central African Republic	50	50					
8. Chad	20	20					
9. Bulgaria	2.65	2.65					
10. Spain	1.52	1.30	0.22				0.22

Source: FAO. 2021c. Fishery and Aquaculture Statistics. Global production by production source 1950–2019 (FishStatJ).

[12] www.biologyonline.com/dictionary/diatom

[13] Under currently accepted taxonomic classification, main species in spirulina cultivation belong to the genus *Arthrospira*. However, the name of "spirulina" remains widely used, and FAO statistics maintain the use of "*Spirulina*" despite the reclassification (e.g. *Spirulina platensis* instead of *Arthrospira platensis*; *S. maxima* instead of *A. maxima*). For narrative convenience, this document refers to the genera *Spirulina* and *Arthrospira* collectively as "spirulina" (similar to the practice in Habib *et al*., 2008) or as "*Spirulina* (*Arthrospira*)".

As opposed to seaweed cultivation that is mostly conducted in marine areas, commercial microalgae cultivation is primarily land-based operation. Three landlocked developing countries in Africa (Burkina Faso, Central African Republic and Chad) have microalgae productions recorded in FAO statistics (Table 8).

Most commercial microalgae cultivation is focused on the production of dried microalgae biomass (e.g. *Chlorella* or spirulina powder) as functional foods or dietary supplements and the extraction of various bioactive or biochemical compounds, such as (i) pigments as nutritional supplements (e.g. carotenes from *Dunaliella* and astaxanthin and canthaxanthin from *Haematococcus*); (ii) docosahexaenoic acid (DHA) from *Crypthecodinium*; (iii) polysaccharides as an additive to cosmetic products; and (iv) natural food colourants (e.g. spirulina as natural blue food colouring) (Spolaore *et al*., 2006; Barkia, Saari and Manning, 2019).

Microalgae have other promising applications in, for example, wastewater treatment, algae meal and algae oils, carbon sequestration and biofuels (Spolaore *et al*., 2006; Khan, Shin and Kim, 2018; Barkia, Saari and Manning, 2019; Ragaza, 2020). While these applications may not be fully commercialized, markets for many of them are growing and rapidly expanding. Substantial microalgae cultivation occurs in other aquaculture operations to produce feeds for animal species (see section 3.4), yet such production is usually not recorded in official statistics.

3. SOCIAL, ECONOMIC AND ENVIRONMENTAL CONTRIBUTION OF ALGAE

3.1 Contribution to food, nutrition and human health

Because most seaweed species have no intrinsic toxins, they are edible. Human consumption of seaweeds dates back centuries, with about 700 edible seaweed species (including around 195 brown seaweeds, 345 red seaweeds and 125 green seaweeds) documented (Pereira, 2016).

Coastal communities in many countries have cultural traditions of eating seaweeds. *Laminaria*/*Saccharina*, *Porphyra* and *Undaria* have become common foods in Eastern Asia and are widely and frequently consumed as soup ingredients, salads, sushi wraps and snacks, among others. They have been introduced in other countries as part of Asian cuisine and have gained increasing global popularity. Many seaweeds can be tasty foods when prepared and eaten properly, and they can be adapted to or integrated into modern culinary and dietary habits (Rhatigan, 2009; Mouritsen, 2013; Tinellis, 2014; Pérez Lloréns *et al*., 2018).

Being nutritious aquatic foods generally rich in dietary fibres, micronutrients and bioactive compounds (Holdt and Kraan, 2011), seaweeds are often treated as healthy, low-calorie food, particularly favoured by people who prefer low-carbohydrate or plant-based diets (Shannon and Abu-Ghannam, 2019). Some seaweed species, such as *Palmaria palmata* (also known as dulse) and *Porphyra tenera*, are known for their high protein content (Holdt and Kraan, 2011).

Multiple health benefits of seaweed consumption (e.g. improving gut health and reducing the risks of non-communicable diseases such as obesity and Type II diabetes) have been demonstrated by a large body of published research (Zhang *et al*., 2007; Wan-Loy and Siew-Moi, 2016; Pirian *et al*., 2017; Cherry *et al*., 2019; Gómez-Zorita, 2020).

In addition to direct human consumption, seaweeds are also processed into food additives or food supplements (McHugh, 2003; FAO, 2018). Japanese kelp (*Laminaria japonica*) was one of the earliest raw materials for producing monosodium glutamate, which is widely used as a flavour enhancer for umami taste (Milinovic *et al*., 2021). Agar extracted from *Gracilaria* and other agarophytes, carrageenan extracted from *Kappaphycus*/*Eucheuma* and other carrageenophytes, and alginate extracted from *Laminaria*/*Saccharina* and other brown seaweeds are seaweed-based hydrocolloids widely used as food additives to enhance the quality of a variety of foods. Additionally, seaweed extracts, such as iodine, fucoidan, fucoxanthin and phlorotannins, are used as food supplements for health benefits.

Non-toxic microalgae can be directly consumed as human foods. In Chad, the consumption of spirulina harvested from Lake Chad, primarily as a source of proteins and micronutrients, has helped improve the nutritional status of people in the landlocked, low-income country (Piccolo, 2012). The nutritional value and health benefits of microalgae have been well recognized (Jensen, Ginsberg and Drapeau, 2001; Habib *et al*., 2008). Various microalgae extracts are used as dietary supplements or food additives (see more details in section 2.5).

3.2 Contribution to income, livelihood and social cohesion

In 2019, the 34.7 million tonnes of world seaweed cultivation production for various food and non-food uses generated USD 14.7 billion first-sale value, primarily attributed to *Laminaria*/*Saccharina* (USD 4.6 billion), *Porphyra* (USD 2.7 billion), *Kappaphycus*/*Eucheuma* (USD 2.4 billion), *Gracilaria* (USD 2 billion) and *Undaria* (USD 1.9 billion).

Seaweed cultivation operations are usually labour intensive and employ many part-time or occasional workers. Thus, a large portion of the USD 14.7 billion of first-sale value became wages or incomes that supported the livelihoods of numerous households in coastal communities. Activities further downstream (e.g. post-harvest handling, distribution, processing and marketing) tend to generate more income and employment. For example, in the Philippines, it was estimated that the seaweed industry involved 100 000–150 000 seaweed farmers, 30 000–50 000 local consolidators, and more than 20 000 small traders (Hurtado, 2013). The seaweed-carrageenan industry also created a large number of supportive and administrative jobs in laboratories and government offices.

According to UN Comtrade statistics, 98 countries earned USD 2.65 billion of foreign exchange in 2019 through exporting seaweeds (USD 909 million) and seaweed-based hydrocolloids (USD 1.74 billion) (Table 9).

Table 9: Export of seaweeds and seaweed-based hydrocolloids, 2019

Seaweeds and seaweed-based hydrocolloids			Seaweeds[1]			Seaweed-based hydrocolloids[2]		
Exporter	Million USD	Share of world (%)	Exporter	Million USD	Share of world (%)	Exporter	Million USD	Share of world (%)
1. China	578	21.79	1. Rep. of Korea	278	30.55	1. China	523	30.00
2. Indonesia	329	12.39	2. Indonesia	218	24.01	2. Philippines	214	12.28
3. Rep. of Korea	320	12.08	3. Chile	86	9.43	3. Spain	138	7.91
4. Philippines	252	9.52	4. China	55	6.03	4. Chile	123	7.06
5. Chile	209	7.87	5. Philippines	38	4.23	5. France	114	6.53
6. Spain	145	5.48	6. Ireland	33	3.60	6. Indonesia	110	6.34
7. France	124	4.68	7. Peru	22	2.43	7. United States of America	84	4.82
8. United States of America	102	3.85	8. Japan	21	2.33	8. Germany	76	4.39
9. Germany	82	3.11	9. United States of America	18	1.98	9. United Kingdom	65	3.75
10. United Kingdom	78	2.93	10. Canada	18	1.97	10. Rep. of Korea	43	2.45
Rest of the world	432	16.30	Rest of the world	122	13.45	Rest of the world	252	14.47
World	**2 652**	**100.00**	**World**	**909**	**100.00**	**World**	**1 743**	**100.00**

Source: UN Comtrade (accessed on 7 April 2021).
Notes: 1. Seaweeds include cultivated and wild collected commodities under HS120220, HS120221 and HS120229. 2. Seaweed-based hydrocolloids include HS130231 (agar), HS130239 (primarily carrageenan) and HS391310 (alginate).

The export of seaweeds and seaweed-based hydrocolloids accounted for a substantial portion of the export value of all fisheries and aquaculture products from the Philippines (22 percent) and the Republic of Korea (15 percent).

Seaweed cultivation makes a significant contribution to community cohesion and women's empowerment (Valderrama *et al*., 2013; Suyo *et al*., 2020; Suyo *et al*., 2021). The characteristics of seaweed cultivation (particularly the tropical species *Kappaphycus*/*Eucheuma*), such as labour intensive, low capital investments and simple farming technology, allow for the participation of many resource-poor households or vulnerable individuals (Lentisco and Needham, 2013).

Women often play a significant or leading role in seaweed cultivation and the value chain (Cai, Hishamunda and Ridler, 2013). In India, women were the first and primary adopters of seaweed farming, which offered them an income within a safe environment (Krishnan and Narayanakumar, 2013). In the United Republic of Tanzania, women have taken the initiative in seaweed farming, and are leaders both in seaweed cultivation and in adding value (Msuya, 2013). In the Philippines, women played significant roles in seaweed farming, especially in seeding and post-harvest treatments; they accounted for about 44 percent of the regular seaweed farming labour force and were the main source of casual labour (Hurtado, 2013).

3.3 Environmental benefits and ecosystem services

Seaweeds and microalgae provide important environmental benefits and ecosystem services (Campbell *et al*., 2019a). Seaweed cultivation does not need to directly use terrestrial land, freshwater, feed or fertilizer. Microalgae can be grown in freshwater or marine environments and cultivated in marginal land in desert and arid areas (Winckelmann *et al*., 2015).

By extracting nutrients (nitrogen and phosphorus) from surrounding waters and absorbing carbon dioxide, the photosynthetic process of seaweeds and microalgae can mitigate eutrophication, treat wastewater, reduce ocean acidification and capture/sequester carbon (Muraoka, 2004; Racine *et al*. 2021).

Seaweed and microalgae cultivation can contribute to the urgent need to address climate change through various mechanisms, including, among others, (i) algae-based products (e.g. human foods, animal feeds and fertilizers) that have a relatively low carbon footprint; (ii) capturing or sequestering carbon; and (iii) reducing methane emissions from cattle farming that uses certain seaweeds as feed supplement (Duarte *et al*., 2017; Hoegh-Guldberg *et al*., 2019; Roque *et al*., 2021). The potential of the contribution is, nevertheless, dependent upon multiple technical and socio-economic factors (see section 4.7).

Other direct or indirect environmental benefits and ecosystem services of seaweeds and/or microalgae include (i) providing habitats for fish and other marine organisms; (ii) serving as a buffer against strong wave action to protect the shoreline; (iii) reducing overfishing through providing alternative livelihoods to fishing communities; (iv) improving soil conditions and potentially reducing agricultural pesticides through seaweed-based biofertilizer or biostimulants (Nabti, Jha and Hartmann, 2017; El Boukhari *et al*., 2020); and (v) producing readily biodegradable goods and packaging (Chia *et al*., 2020); among others (Hasselström *et al*., 2018; Barbier *et al*., 2019).

3.4 Contribution to aquaculture

Besides the direct contribution to aquaculture production, seaweeds and microalgae also help facilitate other aquaculture activities. The ability of seaweeds to metabolize carbon dioxide and extract inorganic nutrients (nitrogen and phosphorus) from surrounding waters makes integration of seaweed cultivation with the farming of animal species an appealing production system, capable of increasing environmental and economic benefits through better nutrient recycling and more efficient use of farming areas. The potential of seaweeds as restorative aquaculture species has helped improve the public image of aquaculture and enhance the acceptability of aquaculture in environmental groups.[14]

The integrated multitrophic aquaculture (IMTA) system has the potential to generate not only environmental benefits but also economic profits (Soto, 2009). Some successful examples are (i) growing *Gracilaria* in shrimp or finfish ponds (Diatin, Effendi and Taufik, 2020); (ii) farming kelps and bivalves (e.g. mussels, oysters or scallops) together in open oceans, sometimes adding deposit feeders such as sea cucumbers (Mao *et al*., 2019; Fernández, Leal and Henríquez, 2019); and (iii) conducting mega-scale integrated aquaculture with over 240 000 tonnes of annual production of more than 30 species (including kelp, scallops, oysters, abalone and sea cucumbers) in over 100 km^2 of farming area that occupies two-thirds of a bay area (Fang *et al*., 2015). However, the application of IMTA faces multiple constraints and challenges (see section 4.4 for more information).

Seaweeds are used as main feed materials for abalone (Naidoo *et al*., 2006), sea urchins (Onomu *et al*., 2020) and, to a lesser extent, sea cucumbers (Xia *et al*., 2012). Seaweeds are also used as supplemental fish feed ingredients that provide necessary amino acids, beneficial polysaccharides, fatty acids, antioxidants, vitamins and minerals (Ismail, 2019).

Microalgae with high contents of lipids can be used to produce algae oils as a unique substitute of fish oils (Armenta and Valentine, 2013). Astaxanthin extracted from *Haematococcus pluvialis*, a green microalgae species, is used as a pigmentation enhancer in the salmon farming industry (Ambati *et al*., 2014).

Many hatcheries rely on microalgae cultivation to provide live feed organisms, directly or indirectly (e.g. through cultivating zooplankton), as a first feed and for nursing the larvae of fish, molluscs, crustaceans or other aquatic animals (Lavens and Sorgeloos, 1996). Microalgae produced as such are intermediate aquaculture products that are usually not recorded in official statistics.

Indeed, an important part of pond culture management is to monitor and cultivate microalgae to maintain good water quality and provide natural food for target species (Hill, 2017; Tacon, 1988). As pond culture is the main aquaculture grow-out system in freshwater or brackish-water environments for many major aquaculture species (e.g. carp, tilapia, catfish and shrimp), the hidden microalgae production, while not recorded in official statistics, tends to be enormous.

4. ISSUES, CONSTRAINTS AND CHALLENGES

There are vast areas suitable for seaweed and microalgae cultivation (Lehahn, Ingle and Golberg, 2016; Theuerkauf *et al*., 2019).[15] Reported experiences in Eastern and South-eastern Asia indicate that seaweed and microalgae cultivation can become robust industries that generate benefits and contributions. However, further development of seaweeds and microalgae in global aquaculture faces multiple issues, constraints and challenges.

[14] www.3blmedia.com/News/Oceans-2050-Leads-Global-Effort-Quantify-Seaweed-Carbon-Sequestration

[15] Researchers in Norway believe that mid-Norway alone has enough marine areas available to cultivate 20 million tonnes of seaweed biomass a year. https://www.sintef.no/en/latest-news/2020/seaweeds-may-become-a-profitable-piece-in-the-green-transition-jigsaw/#:~:text=Researchers%20believe%20that%20in%20Mid,will%20be%20required%20for%20cultivation.

4.1 Limited or uncertain demand for seaweeds

Expansion in seaweed production would need to be accommodated by increases in seaweed demand. One way is to increase seaweed consumption as human foods, which tends to utilize seaweeds efficiently and generate more income for seaweed farmers.

Although most seaweed production in Eastern Asia is consumed directly as human foods, people outside Eastern Asia generally have low or little exposure to or preference over seaweed consumption. The versatility and variety of many seaweeds suggest that they can be utilized in a broad range of food products, adding healthy, low calorie, nutrient dense opportunities for food manufacturers and distributors. However, demand for these applications remains low in spite of seaweed's nutritional value and health benefits and various ongoing efforts in promoting its consumption, particularly in Europe and Northern America (van den Burg, Dagevos and Helmes, 2021; UCTV, 2019).

Food safety concerns have been a primary issue deterring the consumption of aquatic foods (Ahern, Thilsted and Oenema, 2021). The consumption of wild and cultivated seaweeds and microalgae could also contribute to the exposure of certain food safety hazards (e.g. heavy metals or microcystin contaminations) or incur health risks from excessive intake of certain elements (e.g. iodine) (Bouga and Combet, 2015).

Many factors can affect the presence of food safety hazards in seaweeds and microalgae, including species/strain, physiology, season, location, harvesting method and post-harvest treatment, among others (Banach, Hoek-van den Hil and van der Fels-Klerx, 2020). Concerns and uncertainties over the safety of algae products pose a great challenge to the promotion of their consumption in new markets where food safety guidelines or regulations tend to be stringent for precautionary purposes (Lähteenmäki-Uutela, Rahikainen and Camarena-Gómez *et al*., 2021; ANSES, 2020).

While the cultivation of many seaweed species (e.g. *Porphyra*, *Undaria* and *Laminaria*/*Saccharina*) has been mostly driven by direct human consumption, the development of *Kappaphycus*/*Eucheuma* cultivation indicates that significant development of seaweeds (or algae in general) could be driven by applications other than direct human consumption. However, it is difficult to replicate the success of *Kappaphycus*/*Eucheuma* for all seaweeds because of the lack of key elements, such as (i) being a competitive raw material to produce a unique product with widespread applications that are difficult to replace with substitute products and (ii) availability of abundant farm sites and a large suitable labour force to produce the material at low cost.

Many non-food applications of seaweeds (e.g. pharmaceutical, nutraceutical, cosmetic, animal feed, biofertilizer/biostimulant, bio-packaging, textile fibre, carbon capture or sequestration, biofuel, among others) are promising, yet they face technical, economic and/or market constraints and challenges. It is unclear which of the application(s) will become the main driving force(s) behind the next major breakthrough in seaweed development, comparable to the success of *Laminaria*/*Saccharina* or *Kappaphycus/Eucheuma* (Cai *et al*., 2021).

4.2 Limited or reduced availability of suitable farm sites nearshore

Most seaweeds are grown close to the surface of the water in order to have sufficient sunlight for photosynthesis; therefore, they are usually cultivated in nearshore areas for operational and logistic conveniences. Nearshore operations tend to be less expensive in terms of both investment and operating costs. However, multiple factors pose constraints or challenges to seaweed cultivation in nearshore areas, including, among others, (i) competition for nearshore areas from urban development, recreation, fishing, fish farming and/or other activities; (ii) pollution in nearshore waters; and (iii) rising seawater temperatures.

Cultivating seaweeds further offshore can help overcome the nearshore constraints, and seaweed cultivation could be integrated with other offshore activities such as wind energy generation (van den Burg *et al*., 2016). However, seaweed cultivation in the open ocean faces the challenges of technical feasibility (e.g. strong cultivars are needed to withstand strong waves; novel farming systems, such as the tube net for *Kappaphycus*/*Eucheuma* cultivation, are needed to protect seaweeds from strong waves; new skills, such as swimming, are needed to operate in deep-water farm sites; and enhanced management capacity is needed to safeguard and monitor the operation), economic viability, and the general lack of regulations on offshore aquaculture (Msuya, 2013; van den Burg *et al*., 2016; Liu *et al*., 2019; Bak, Gregersen and Infante, 2020).

4.3 Shortage of labour

Seaweed cultivation usually entails a large amount of labour in planting, daily maintenance, harvesting and post-harvest handling, with a seasonal or occasional demand (e.g. a large number of workers are needed for a short time period to harvest seaweeds at the optimal time to ensure desirable quality).

Plantation-style *Kappaphycus*/*Eucheuma* farms were established (e.g. in India and the Philippines) by carrageenan processors to gain better control over the raw material production. Yet they did not survive the competition of small, family-run farms. One of the main reasons was that highly flexible labour is needed to cultivate seaweeds on the cyclical time scales of tides and the moon, which made it difficult to pay workers stable wages (Valderrama *et al*., 2013).

The lack of suitable labour (low cost, flexible and stable supply) has been a major constraint over seaweed cultivation in developed regions (McHugh, 2003). Labour shortages also pose challenges to seaweed cultivating countries in developing regions on their paths towards a more developed and urbanized economy, as economic developments create more attractive employment opportunities in other sectors (e.g. tourism) than laborious and strenuous jobs in seaweed farming, particularly for the younger generation (Davis, 2021). More automated farming systems and technologies can help address labour shortages and improve occupational health but would tend to increase production costs (Liu *et al*., 2019).

4.4 Constraints over integrated farming systems

Notwithstanding its conceptual appeal and successful applications (see section 3.4), technical, economic and institutional constraints complicate the integration of seaweed cultivation with other aquaculture activities (Barrington, Chopin and Robinson, 2009; Troell, 2009; Hughes and Black, 2016). A recent study on the suitability of integrated multitrophic aquaculture (IMTA) in Europe identified constraints over IMTA in various aspects, including biological, conflicts, environmental, interest, legislation, market, operational, research and development, and vandalism (Kleitou, Kletou and David, 2018).

Technically, IMTA is a complex aquaculture system whose performance is dependent upon the balance of a wide range of interactions among cultivated species or between the organisms and their physical and chemical environment (Granada *et al.*, 2018). A finfish or bivalve farmer may lack expertise or experience to cultivate seaweeds (and vice versa), let alone adopting appropriate farming protocols for all integrated species (e.g. stocking densities and biosecurity measures) to maintain a well-functioning ecosystem (Hughes and Black, 2016).

In an IMTA system, infrastructure and operation needed for cultivating one species may impede that of another integrated species. For example, the suspended system for cultivating seaweeds may alter water flow in a way that is undesirable to finfish cage farming nearby; seaweed longlines may interfere with the access of large vessels to finfish cages; finfish cages may attract herbivorous fishes grazing on seaweeds; and bivalves and their growing facilities may damage the fronds of seaweeds (Hughes and Black, 2016; Lance *et al*., 2017; Campbell *et al*., 2019a).

Economically, IMTA systems, particularly large-scale operations, encounter the challenge of marketing multiple products along different value chains. While a diversified species composition in an IMTA system may help reduce the impacts of price fluctuations of individual species, the aforementioned complexities of the system would tend to increase the operational costs, and low-valued seaweeds may not offer enough financial incentive for finfish farmers to alter their business models (Troell, 2009).

An IMTA system also tends to have less flexibility in planning production according to market demands. For example, when facing an increase in seaweed price and a decline in bivalve price, an IMTA farmer may not have the same flexibility as in monoculture systems to increase the stocking density of seaweed and reduce that of bivalves, as doing so could disrupt the balanced ecosystem needed for a well-functioning IMTA system.

Institutionally, finfish farmers tend to lack incentives to integrate seaweeds into their farming systems if regulations do not force them to internalize the cumulative impacts of their farming operations on the ecosystem at larger scale (fjords, channels or whole bays) and do not allow them to benefit from the positive impacts of seaweeds on water quality (e.g. increasing the number of fish allowed to be reared) (Barrington, Chopin and Robinson, 2009; Troell, 2009). Integration may also be hindered by a lack of regulations that facilitate collaboration between site owners who produce different species.

4.5 Low or declined seedling quality

Seedling production is key to successful and sustainable seaweed farming. Large-scale *Porphyra* cultivation became feasible only after its unusual life cycle (particularly the shell-boring Conchocelis phase) was understood in the early 1950s and the technology of growing *Porphyra* seedlings on oyster shells in land-based facilities was developed (McHugh, 2003). The breakthrough in rearing summer seedlings in hatcheries helped jump-start rapid growth of kelp farming in China in the late 1950s, and continuing efforts in improving kelp seedlings (e.g. through hybridization) have not only increased the productivity of kelp cultivation but also expanded kelp cultivation to geographical areas with warmer seawater temperatures (e.g. Fujian Province in South-eastern China) (Hu *et al*., 2021).

The quality of seedlings has become increasingly crucial under deteriorating farming environments, such as rising seawater temperatures and more frequent and severe disease outbreaks. Outsourcing good quality seed stocks from specialized hatcheries is a common practice in aquaculture, yet mainstreaming the business model could be difficult for some seaweeds (e.g. *Kappaphycus*/*Eucheuma*) cultivated by numerous smallholder farmers who can easily obtain cultivars through vegetative propagation from their own harvest.

Improper management or constraints over seedling production, including the use of inbred stocks or repeated vegetative propagation, can lead to trait degeneration and the consequent loss of agronomic value of a farmed type[16] due to possible reduced growth, lowered quality and higher susceptibility to diseases, among others (Loureiro, Gachon and Rebours, 2015). Low or declined quality of seedlings could motivate the introduction of non-native seaweed species or genotypes, which pose risks to biodiversity and biosecurity.

Genetic improvement technologies, such as strain selection (Hwang, Ha and Park, 2017), selective breeding (Hwang *et al*., 2019), hybridization (Su *et al*., 2020), micropropagation (also known as tissue culture) (Reddy *et al*., 2017) and genetic markers (Yong, Chin and Rodrigues, 2016), can help improve

[16] A farmed type is a cultured aquatic organism that could be a strain, variety, hybrid, triploid, monosex group, another genetically altered form, or wild type.

seedling quality and production efficiency. However, these tend to be technical and financially demanding and often require public support.

While seaweed breeding programmes and progress have played a vital role in the development of seaweed cultivation in Eastern Asia (Hwang *et al*., 2019), a lack of genetic improvement persists in tropical red seaweeds (e.g. *Kappaphycus*/*Eucheuma*) that are primarily multiplied by vegetative propagation. While distinct morphotypes of *Kappaphycus*/*Eucheuma* are recognized, the genetic basis of these morphotypes is inadequately researched and poorly understood.

4.6 Miscellaneous issues or constraints over seaweed cultivation and value chains

Other significant issues hindering seaweed cultivation and value chains include (i) deteriorating farming environments because of climate change, such as rising seawater temperatures, increasing extreme weather conditions and more voracious grazing of predators (Smith, 2017); (ii) more frequent and severe disease outbreaks (Ward *et al*., 2020); (iii) high transportation costs; (iv) high intermediary costs; (v) low and fluctuating market prices, including uncertain export prices due to exchange rate fluctuations; (vi) low incomes for seaweed farmers; (vii) suboptimal practices (e.g. premature harvesting) owing to financial constraints or unstable market conditions; (viii) low quality due to inappropriate post-harvest handling; and (ix) lack of value addition (Cai, Hishamunda and Ridler, 2013).

4.7 Environmental/ecosystem impacts or risks

As extractive aquaculture species, seaweeds tend to be more eco-friendly than fed aquaculture species. However, improperly managed seaweed cultivation could negatively affect the environment or ecosystem through (i) spreading diseases and parasites; (ii) releasing reproductive materials of domesticated or non-native species that may contaminate the genetic integrity of local species; (iii) slowing water flow, which may hinder sediment transport and alter marine chemistry; (iv) competing for light and nutrients with other marine organisms; (v) causing environmental degradation through the construction of the farming system (e.g. destroying mangroves for wooden stakes or damaging the benthic ecosystem by clearing up the sea floor or using stakes or anchors); and (vi) causing pollution during operation (e.g. loss/discard of cultivation materials or generation of noise) (Campbell *et al*., 2019a; Hurtado, Neish and Critchley, 2019).

The environmental benefits and ecosystem services of seaweed cultivation may be discounted by the environmental or ecological footprint along the seaweed supply chain. For example, while seaweed cultivation normally does not need to use freshwater, seaweed processing, such as washing seaweeds or extraction of target compounds (e.g. agar), can be freshwater-intensive operations (McHugh, 2003).

Fast-growing seaweeds can capture carbon more quickly than trees; however, a large portion of captured carbon may not be permanently sequestered if seaweeds are harvested after a relatively short growing cycle (usually less than one year) (Krause-Jensen and Duarte, 2016). Cultivating seaweeds and burying them in the deep ocean can help realize their full potential in carbon sequestration, yet such operations face the challenges of economic viability and uncertain environmental impacts.

4.8 Issues and constraints over microalgae cultivation

Despite efforts in promoting microalgae as a new source of human food to fight hunger and malnutrition (UNGA, 2015; IIMSAM, 2021), including the efforts of FAO (Habib *et al*., 2008; Piccolo, 2012), global human consumption of microalgae mostly occurs through high-end food supplement products (e.g. *Chlorella* or spirulina powder) supplied by the nutraceutical industry (see details in section 2.5).

Factors that constrain the use of microalgae in human foods include (i) unappealing taste or colour; (ii) potential heavy metals and/or microcystins contaminations under poorly managed cultivation;

(iii) potential side effects caused by microalgae intake (e.g. allergies and gastrointestinal problems); and (iv) relatively high prices of quality microalgae products (Barkia, Saari and Manning, 2019).

While microalgae can grow very fast under suitable conditions, the productivity of large-scale microalgae cultivation in open systems (e.g. ponds or raceways) tends to be hampered by various technical factors, including (i) contaminants (i.e. non-target microalgae); (ii) viruses, pathogens, parasites and predators; (iii) insufficient nutrients or carbon dioxide; (iv) insufficient sunlight due to self-shading from high cell density; (v) photooxidation and death due to excess accumulation of oxygen during the day; and (vi) significant shifts in culture pH with photosynthesis (absorbing carbon dioxide) during the day and respiration (releasing carbon dioxide) at night (Barkia, Saari and Manning, 2019).

Closed cultivating systems (e.g. photobioreactors) provide better controlled cultivation environments, but they are expensive to build and operate (Barkia, Saari and Manning, 2019). The high cost of harvesting (i.e. dewatering) and refining cultivated microalgae biomass is another factor contributing to the high production cost of microalgae, which is a main constraint over viable commercialization of microalgae biofuel production (Lam and Lee, 2012).

4.9 Algae blooms

The fast-growing nature of algae, desirable in aquaculture notwithstanding, can cause algae blooms in wild habitats. Harmful microalgae blooms, such as red tides along coastal regions (Anderson, Cembella and Hallegraeff, 2012; NOAA, 2021) and blue-green algae (cyanobacteria) blooms in inland waters (Jia, Zhang and Dong, 2019), can deteriorate water quality, disrupt aquatic ecosystems and cause water and food contaminations that endanger the health of aquatic animals and humans (Sanseverino *et al*., 2016).

Macroalgae blooms, such as *Sargassum* blooms aka golden tides (Byeon, Oh and Kim *et al*., 2019) and *Ulva* blooms aka green tides (Gladyshev and Gubelit, 2019), can also lead to costly environmental nuisances. For example, holopelagic *Sargassum* blooms that began in the southern tropical Atlantic have caused massive amounts of *Sargassum* to intermittently wash ashore on African and Caribbean coasts since 2011 (Wang *et al*., 2019; Desrochers *et al*., 2020; Godínez-Ortega *et al*., 2021), causing detrimental impacts on coastal ecosystems, tourism and fisheries. In the open ocean, floating *Sargassum* mats, primarily composed of a mix of *S. fluitans* and *S. natans*, are considered as a natural reserve, attracting many species of marine fauna and flora and acting as a nursery. However, when reaching coastal areas, the huge amount of *Sargassum* biomass becomes a menace to the tourist industry, disturbs fisheries and nearshore ecosystems, and negatively affects coastal communities' livelihoods.

Most algae blooms are caused by a rapid proliferation and accumulation of wild algae under conducive conditions for growth (temperatures, salinity, sunlight, nutrients, etc.). Nutrient pollution, which can come from diverse sources (e.g. agricultural runoff, aquaculture effluent, urban waste, industrial pollution, and fossil fuel combustion),[17] tends to be a main culprit leading to algae blooms.

Removing large amounts of algae biomass caused by blooms tends to be difficult and costly. Utilizing the biomass to produce feed, fertilizer, human foods and other products can offset some of the expenses incurred to manage the blooms. However, multiple constraints and challenges, such as the lack of markets, inadequate processing capacity, and uncertain quantity and undesirable quality of the biomass (e.g. the high arsenic contents in wild *Sargassum* along the Caribbean coasts), complicate the development of an industry based on biomass from algae blooms (Desrochers *et al*., 2020; Devault *et al*., 2020).

[17] www.wri.org/our-work/project/eutrophication-and-hypoxia/sources-eutrophication#urban

Measures to reduce nutrient pollution, such as preventing soil erosion (e.g. caused by deforestation), managing nutrient supply by mass balance (i.e., crop supplied precisely with what it needs) and appropriate wastewater treatment, are fundamental means to address algae blooms. Algae cultivation, through its biosorption and bioremediation impacts on eutrophication, can help prevent or mitigate wild algae blooms. In addition, development of the algae sector can generate market demand and processing capacity to facilitate the economic utilization of biomass from wild algae blooms.

However, improper practices in seaweed cultivation could contribute to macroalgae blooms. For example, the recurrent blooms of *Enteromorpha* (*Ulva*) *prolifera* in the Yellow Sea and the East China Sea originated from the coastal area that accounted for 95 percent of *Porphyra yezoensis* cultivation in China (Hu *et al*., 2010; Zhang *et al*., 2019a). *E. prolifera* is a nuisance species that grows on bamboo rafts and rope nets used to cultivate *P. yezoensis*. Cleaning of the cultivating rafts or heavy storms can release considerable amounts of *E. prolifera* into the water. As the *P. yezoensis* farming area more than doubled between 2007 and 2008, a massive *E. prolifera* bloom (covering 2 400 km^2) occurred in the Yellow Sea in 2008 and caused significant economic losses (Hu *et al*., 2010).

Eco-friendly practices, such as forbidding improper introduction of invasive alien species and avoiding disposal of large amount of epiphytes into the water, can help minimize the potential contribution of seaweed cultivation to algae blooms. For example, adjustments of harvest timing and methods of *P. yezoensis* cultivation has helped reduce the scale of *E. prolifera* blooms in the Yellow Sea (Zhang *et al*., 2019b).

Microalgae cultivation, which usually rears non-toxic microalgae in self-contained farming systems, presents low risks of causing harmful algae blooms in wild habitats. However, precautionary measures should be taken to minimize such risks, especially as genetic modification has been considered as a means to increase the productivity of microalgae cultivation (Henley *et al*., 2012; Kumar *et al*., 2020).

5. LESSONS LEARNED AND WAY FORWARD

5.1 Governance as foundation

Science- and evidence-based laws, regulations and guidelines (environmental regulations, spatial planning, food safety standards, occupational health requirements, technical guidelines and good aquaculture practices, among others) on seaweeds and microalgae are essential to laying a solid foundation for the sector's sustainable development.

While it is usually the jurisdiction of individual countries to establish or adopt these criteria according to their socio-economic and environmental conditions and developmental priorities, the international and scientific communities can help generate and share global knowledge and experiences to facilitate informed decision-making in the process.

Governments, civil societies, international organizations and/or the industry can establish or facilitate community-based management (e.g. farmer groups) and market-based schemes (e.g. certification), which can become equally or more effective governing mechanisms in certain areas (e.g. fostering good practices, such as adopting proper stocking density, avoiding the littering of cultivation materials in the ocean, and not adding impurities during the post-harvest handling).

5.2 Market demand as driving force

Market demand has been a key driving force behind algae sector development. The kelp boom in Scotland during the eighteenth century, an industry which employed over 100 000 people at peak time, was driven by demand for raw materials to produce soda (sodium carbonate) and potash (potassium carbonate) (Kenicer, Bridgewater and Milliken, 2000).

Demand for raw materials to produce carrageenan created the Irish moss (*Chondrus crispus*) boom in Canada, starting around 1950 and lasting through the mid-1970s (Craigie, Cornish and Deveau, 2019), and later also fuelled the *Kappaphycus*/*Eucheuma* booms in the Philippines (from the mid-1970s to the early 2010s) and in Indonesia (from around 2000 to the mid-2010s) (Bixler and Porse, 2011).

Demand for healthy and tasty aquatic food has been the primary driving force behind the kelp boom in Eastern Asia, primarily China and the Republic of Korea, from the 1950s to the present day. The boom has been sustained or reinforced along the way by other market forces, such as the demand for brown seaweed extracts (iodine, alginate, mannitol, fucoidan, etc.) and the demand for fresh seaweeds to feed abalone (Hwang, Ha and Park, 2017; Zhang, 2018).

Nutritious, eco-friendly and versatile algae have great potential in a variety of food and non-food applications, yet the potential may not turn into immediate market demand because of a variety of constraints, such as low consumer exposure or preference, high production costs, market competition and stringent regulations. One example is the lack of commercial success in algae-based biofuel production (primarily because of high production costs and low fossil fuel price) in spite of much interest and substantial investments in the sector from the private and public sectors (van Iersel and Flammini, 2010; Lam and Lee, 2012; Chen *et al*., 2015).

Though attracting attention, many potential contributions of algae (e.g. health contributions, environmental benefits and ecosystem services) may not automatically lead to immediate market demand or subsequent business opportunities to attract profit-seeking private investments in the sector. Similarly, the valuable global externalities of seaweeds and microalgae (e.g. mitigating climate change through carbon sequestration) may not give local governments enough incentive to prioritize algae in development planning.

Therefore, market-based mechanisms, including carbon credits, nitrogen credits, blue bonds and green finance, among others, could be established to facilitate internalization of the positive externalities of algae (Jones, 2021). Coordinated support from governments, donors, civil societies and international organizations is crucial to facilitating algae sector development and integration into global food systems.

Another crucial lesson learned from the history of global algae development is that over-reliance on a narrow range of applications (particularly industrial commodities) can be risky or unsustainable. For instance, the aforementioned kelp boom in Scotland went into a speedy decline in the early 1800s, as more economic ways to produce soda and potash were discovered (Kenicer, Bridgewater and Milliken, 2000). The rapid expansion of *Kappaphycus*/*Eucheuma* cultivation in tropical areas, which supplies much cheaper raw materials for carrageenan production, has rendered the Irish moss industry in Canada a similar boom-bust experience, and the decline of the industry (starting in the mid-1970s) has caused significant socio-economic repercussions (Eamer, 2016).

Utilization of algae (especially seaweeds) as human foods, particularly for local consumption, tends to be the most stable market force that can serve as a stabilizer for algae sector development. However, the inertia of dietary habits and consumer behaviours poses a major challenge to the development of markets for algae food products, especially in places with little algae production, consumption and culinary traditions. Forming or changing dietary habits tends to be a long-term process that entails joint efforts of stakeholders and experts in policy, business and scientific communities.

Despite anecdotal evidence of increasing global or local popularity of sushi and other seaweed-based food products (e.g. snacks, salads and desserts), there is a general lack of detailed information and knowledge of algae-based food market potential (particularly market price and volume), which is essential to informed decision-making in policy and planning for the development of seaweed cultivation. In-depth, comprehensive assessments of algae markets and value chains at the global, regional, national and subnational levels are needed to fill the gap.

5.3 Innovation as game changer

Science and innovations have been the main driving forces behind breakthroughs in seaweed or microalgae development. A few examples of notable innovations that have resulted in a rapid expansion of seaweed cultivation include: (i) innovations in seedling production, mentioned in section 4.5; (ii) development of longline cultivating systems for kelp farming; (iii) technology of extracting good quality agar from *Gracilaria*; and (iv) food-grade semi-refined carrageenan (McHugh, 2003).

Based upon scientific publication metrics, bioprospecting efforts between 1965 and 2012 resulted in a total of 3 129 marine natural products or bioactive molecules from seaweeds (53 percent from red seaweeds; 39 percent from brown seaweeds; and 8 percent from green seaweeds). However, the steps from discovery to development have been slow to materialize (Leal *et al*., 2013; Leal *et al*., 2020).

Persistent and painstaking efforts in innovation and fostering close collaborations between the algae industry and the cross-disciplinary research community are needed to transform the extensive potential of seaweeds and microalgae into acceptable, available and affordable food or non-food products.

The public sector can facilitate the process by providing support for basic research on important topics, such as nutrition, genetic resources and diseases. There is a significant need for more research in controlled scientific studies with properly designed human trials, which will help determine the bioavailability of the many nutritional assets known to be present in seaweeds and their long-term effects on human health (Xi and Dragsted, 2019).

Limited knowledge of genetic diversity and inadequate integration of genetic analysis in seaweed breeding undermines the sustainability of seaweed production and their conservation. Improving knowledge of seaweed genetic diversity and taxonomy would assist in building a baseline for assessing the extinction risk of seaweed species given that only a minority of them are included in the IUCN Red List, and most of them have been classified as “Data Deficient”.

Ice-ice disease and epiphyte infestation have been an enduring factor that hindered farmers in Zanzibar from cultivating more lucrative *Kappaphycus alvarezii* (Largo, Msuya and Menezes, 2020). With a general trend of deteriorating farming environments and declined seedling quality, global seaweed cultivation is subject to increasing risks of disease outbreaks (Hurtado, Montano and Martinez-Goss, 2013; Kim *et al*., 2014). The pressing needs are to (i) better understand the causes of pathogenic and physiological disease; (ii) improve methodologies for the characterization of pathogens; (iii) develop rapid and robust diagnostic techniques; and (iv) establish effective national and international biosecurity policies (Campbell *et al*., 2019b; Ward *et al*., 2020).

Public support (including financial incentives) is also needed to support the development and commercialization of innovations that tend to have significant technical, economic, environmental and/or social benefits. Examples of such innovations include, among others, (i) tube-net technique suitable for growing warm-water red seaweeds in areas with strong currents (Mantri, Shah and

Thiruppathi, 2020); (ii) land-based tank culture systems that provide better-controlled environment conditions to optimize the quality, safety and traceability of seaweed products (Gadberry *et al*., 2019); (iii) species diversification and crop rotation that tend to help reduce the risk of disease, deter grazing by herbivores and improve crop yield (Grebe *et al.*, 2019); (iv) technologies to prevent the contamination of non-target species in large-scale open systems of microalgae cultivation; (v) technologies that reduce the high cost of harvesting microalgae in large-scale cultivation, which has been a major constraint deterring investments in large-scale microalgae cultivation; (vi) resource-efficient biorefinery technologies that convert algae biomass into different products (Lange *et al*., 2020); (vii) product improvement, such as the removal of undesirable tastes, better texture, more appealing appearance and longer shelf-life; and (viii) integration of seaweeds in local cuisine and innovative recipes.

5.4 Public support as enabling environment

The private sector, particularly in countries with little seaweed production and consumption, may lack incentives to devote substantial, long-term efforts to the development of seaweed markets with uncertain prospects. Thus, public support is needed to increase the public recognition and appreciation of seaweeds as nutritious human foods and help establish dietary habits in seaweed consumption.

For example, with the safety and nutritional value of seaweeds ensured, public programmes, such as nutrition education and seaweeds on the menu of hospitals, schools and other public institutions, can be implemented to promote seaweed consumption, which will not only increase seaweed demand immediately but also help foster future seaweed consumers. Seaweeds are good for the health and wellness of those who are clinically unwell, and their nutritious characteristics and health benefits (e.g. fibre, texture, robust nutritional profile, essential nutrients and antioxidants) make them an ideal food for the elderly.

The public sector should create an enabling environment to facilitate the development of algae cultivation. For example, governments can recognize seaweed and/or microalgae cultivation as a development priority and use licensing, financial support and other mechanisms to help reward the sector for its environmental benefits and ecosystem services.

Governments, civil societies, international organizations and other public sector partners can help improve the algae sector performance by (i) raising public awareness of the sector's environmental and socio-economic contributions; (ii) generating and compiling information and knowledge on algae supply chains needed for informed decisions in public and private sectors; (iii) establishing effective mechanisms to facilitate innovations, capacity-building, technology transfer and knowledge-sharing; and (iv) fostering collaboration and partnership among policy, scientific and business communities.

Considering the significant regional imbalance in seaweed production and consumption, it may be worthwhile to establish a global programme on seaweeds, be it a general one for strengthening seaweed cultivation and the value chain or a specific one focused on addressing key issues (e.g. promoting seaweed consumption).

Seaweed and microalgae cultivation may be jump-started by different impetuses, yet it needs strong value chains to become sustainable. This is particularly important for project-driven seaweed or microalgae development. Healthy, strong and sustainable value chains need to be characterized by low transaction costs, less asymmetric information and effective risk-sharing mechanisms and ought to be inclusive. One key lesson learned in public support to promoting seaweed cultivation is that ignoring the socio-economic aspects of seaweed farming can lead to a lack of sustainability. Many seaweed development projects have "ended in failure" because of overlooking the "human factor" that concerns not only seaweed farmers but also other stakeholders (Ask, 2001).

5.5 FAO's roles

FAO has conducted various projects that were either focused on seaweeds or that included seaweed development as a component; FAO has also generated and disseminated a number of information and knowledge products on algae; see Table 10 and Table 11 for some recent examples.

FAO's work on the Progressive Management Pathway for Improving Aquaculture Biosecurity (PMP/AB) (FAO, 2020b, 2020c, 2020d) can help establish a progressive, risk-based and collaborative management framework for seaweed farming biosecurity at the enterprise, national and international levels. A forthcoming FAO publication on diseases of aquatic organisms will include a section on seaweed.

FAO is developing a background document that identifies food safety hazards (chemicals, pathogens and toxins) linked to the consumption of seaweeds. The document would lay a foundation for further work in this area. FAO considers that there might be value in developing relevant Codex guidance on this subject and presented this issue for consideration in May 2021 during the 14th Session of the Codex Committee on Contaminants in Foods (JECFA Secretariats, 2021). The issue will be followed up by the Codex Alimentarius Commission.

As part of its work on aquatic genetic resources (FAO, 2019), FAO is developing an information system on the farmed types of aquatic genetic resources, including algae, which can help address the paucity of information of the genetic basis of seaweed cultivation.

FAO databases on global fisheries and aquaculture production have been a unique source of data and statistics on global wild and cultivated production of seaweeds and microalgae (under "aquatic plants"), which have been used extensively in the preparation of this document. More detailed information can be found in the factsheet on *Global seaweeds and microalgae production, 1950–2019* (FAO, 2021d).

There is much room for improvement in FAO statistics on the production of seaweeds and microalgae, in terms of accuracy and completeness (e.g. broader country coverage and more disaggregate species composition). Information and knowledge on other parts of seaweed or microalgae supply chains (e.g. processing and consumption) is also inadequate. Continuing support from FAO Members is needed for FAO to improve the quantity and quality of data and information on seaweeds and microalgae.

Other areas of FAO work on the development of algae (primarily seaweed) cultivation and value chain may include, among others, (i) developing practical manuals on seaweed cultivation; (ii) establishing technical platforms to facilitate capacity-building, technology transfer and knowledge-sharing in key areas (farming systems and technology, genetic improvement, disease control, among others); (iii) supporting market development for utilizing seaweeds as human foods; and (iv) facilitating collaboration and cooperation among Members in strengthening governance for sustainable algae sector development.

Table 10: Examples of recent FAO projects related to algae

Time frame	Beneficiaries	Project	Focused areas
Africa			
2016–2017	Zanzibar, United Republic of Tanzania	TCP/URT/3601/C1: Support to Seaweed Diseases and Die-off Understanding and Eradication in Zanzibar	Biosecurity and disease control
2015–2017	Kenya	TCP/KEN/3502 (14/XII/KEN/224): Support to the Implementation of Mariculture in Kenya Within an Ecosystem Approach	Capacity-building on policy and planning in public sector and business planning in the private sector
2014–2018	Kenya; United Republic of Tanzania	FMM/GLO/112/MUL: Baby 4 – Blue Growth Initiative in Support of Food Nutrition Security, Poverty Alleviation and Healthy Oceans	Food security and nutrition; poverty alleviation
2014–2015	Zanzibar, United Republic of Tanzania	TCP/URT/3401 (13/X/URT/220): Support to the Aquaculture Subsector of Zanzibar	Capacity-building; market development; investment planning
Asia			
2019–2021	Bangladesh	TCP/BGD/3704 (19/I/BGD/238): Support to Seaweed Cultivation, Processing and Marketing Through Assessment and Capacity Development	Sector development; capacity-building
2015–2017	Indonesia	TCP/INS/3502: (Indonesia) – Decent Work for Food Security and Sustainable Rural Development. (DW4FS&SRD): Support to Selected Coastal Communities along the Seaweed Value Chain	Strengthening socio-economic impacts
2001–2002	Indonesia	TFD-99/INS/003: Assistance for Fishermen’s Group in the Tidung Island to Establish a Small-scale Enterprise of Seaweed Production	Poverty alleviation; efficient resource management
1992–1994	Philippines	PHI/89/004/ /01/12: Seaweed Production Development	Production
1988–1989	Thailand	TCP/THA/8854 (8/III/THA/080): Seaweed Production and Processing	Production and processing
1988–1995	Viet Nam	VIE/86/010/ /01/12: Seaweed Culture and Processing	Production and processing
1987	China	TCP/CPR/6759 (6/X/CPR/086): Workshop on Seaweed Production	Production
Latin America			
2001–2004	Brazil	TCP/BRA/2907 and TCP/BRA/0065: Small-scale Seaweed Farming in Northeast Brazil – Phase II of TCP/BRA/0065	Feasibility analysis; market assessment; piloting
2017–2021	Chile	GCP/CHI/039/GFF: Strengthening the Adaptive Capacity to Climate Change in the Fisheries and Aquaculture Sector of Chile	Climate change adaptation

Time frame	Beneficiaries	Project	Focused areas
Caribbean			
Forthcoming	Dominica; Grenada; Saint Kitts and Nevis; Trinidad and Tobago	AMEXCID-CARICOM-FAO: Capacity Training (in Production Practices, Post-production Practices and Accessing Credit), Policy Creation and Establishment or Upscaling of Farms	Capacity-building
2020–2023	Grenada and Saint Lucia	GCP/RLA/230/IFA: Farmers' Organizations for Africa, Caribbean and Pacific Countries Programme in the Caribbean Region	Food security and nutrition; poverty alleviation
2020–2021	Grenada and Saint Lucia	UNJP/SLC/021/UNO: Building Effective Resilience for Human Security in the Caribbean Countries – The Imperative of Gender Equality and Women Empowerment in a Strengthened Agriculture (and Related Agri/Fisheries Small Business) Sector Project	Gender balance
2020–2021	Saint Lucia	TCP/STL/3702: Technical Assistance to Support UK Market Penetration for Saint Lucian Agricultural Products	Market development; food safety
2019–2020	Saint Lucia	FMM/GLO/145/MUL: Empowering Women in Food Systems and Strengthening the Local Capacities and Resilience of Small Island Developing States (SIDS) in the Agrifood Sector	Gender balance
2017–2021	Antigua and Barbuda; Dominica; Grenada; Saint Lucia; Saint Vincent and the Grenadines; Saint Kitts and Nevis; Trinidad and Tobago	GCP/SLC/202/SCF: Climate Change for the Eastern Caribbean Fisheries Sector	Climate change adaptation
Pacific			
2020	Kiribati	UNJP/KIR/002/UNJ: Enhancing Food Security, Nutrition and Resilience to COVID-19 in Kiribati	Capacity-building on production and marketing
2017–2020	Federated States of Micronesia/Marshall Islands/ Nauru/Palau/Kiribati	TCP/SAP/3603: Aquaculture Business Investment Planning and Development to Increase Resilience and Improve Food Security. TCP/KIR/3602/C2: In-depth Aquaculture Risk Assessment and Business Investment Planning	Sector development; investment planning
2016–2017	Fiji	OSRO/FIJ/602/BEL: Emergency Support to Re-establish Agricultural, Fisheries and Aquatic Plant Production Post-Tropical Cyclone Winston (Fiji)	Post-disaster recovery
2004	Marshall Islands	TCP/MAS/2801 or TCP/MAS/2902: Seaweed Cultivation in the Marshall Islands	Capacity-building on production

Table 11: Examples of recent FAO publications on algae

Year of publication	Title	Notes
Forthcoming	Occurrence and regulation of food safety hazards in seaweed and aquatic plants: current status and future perspectives	Expected to be published in 2021.
Forthcoming	Genetic resources for farmed seaweeds	Draft report available at www.fao.org/3/CA3065EN/ca3065en.pdf
2021	Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development	FAO Fisheries and Aquaculture Circular No. 1229 (i.e. the current document).
2021	Global seaweeds and microalgae production, 1950–2019	World Aquaculture Performance Indicators (WAPI) factsheet. www.fao.org/3/cb4579en/cb4579en.pdf
2021	Seaweed revolution: where is the next milestone?	WAPI policy brief. www.fao.org/3/cb4850en/cb4850en.pdf#page=13
2020	*Sargassum* uses guide: a resource for Caribbean researchers, entrepreneurs and policy makers	CERMES Technical Report No. 97. www.cavehill.uwi.edu/cermes/projects/sargassum/docs/desrochers_et_al_2020_sargassum_uses_guide_advance.aspx
2020	Understanding diseases and control in seaweed farming in Zanzibar	FAO Fisheries and Aquaculture Technical Paper No. 662. www.fao.org/3/ca9004en/CA9004EN.pdf
2018	The global status of seaweed production, trade and utilization	FAO Globefish Research Programme, Vol. 124. www.fao.org/3/CA1121EN/ca1121en.pdf
2013	Social and economic dimensions of carrageenan seaweed farming	FAO Fisheries and Aquaculture Technical Paper No. 580. www.fao.org/3/a-i3344e.pdf
2013	Seaweed for a better life	RFLP Report. www.fao.org/3/a-ar486e.pdf
2012	Spirulina: a livelihood and a business venture	Report SF/2011/16. SmartFish. www.fao.org/3/az386e/az386e.pdf
2008	A review on culture, production and use of spirulina as food for humans and feeds for domestic animals and fish	FAO Fisheries and Aquaculture Circular No. 1034. www.fao.org/3/i0424e/i0424e00.pdf
2003	A guide to the seaweed industry	FAO Fisheries Technical Paper No. 441. www.fao.org/tempref/docrep/fao/006/y4765e/y4765e00.pdf

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