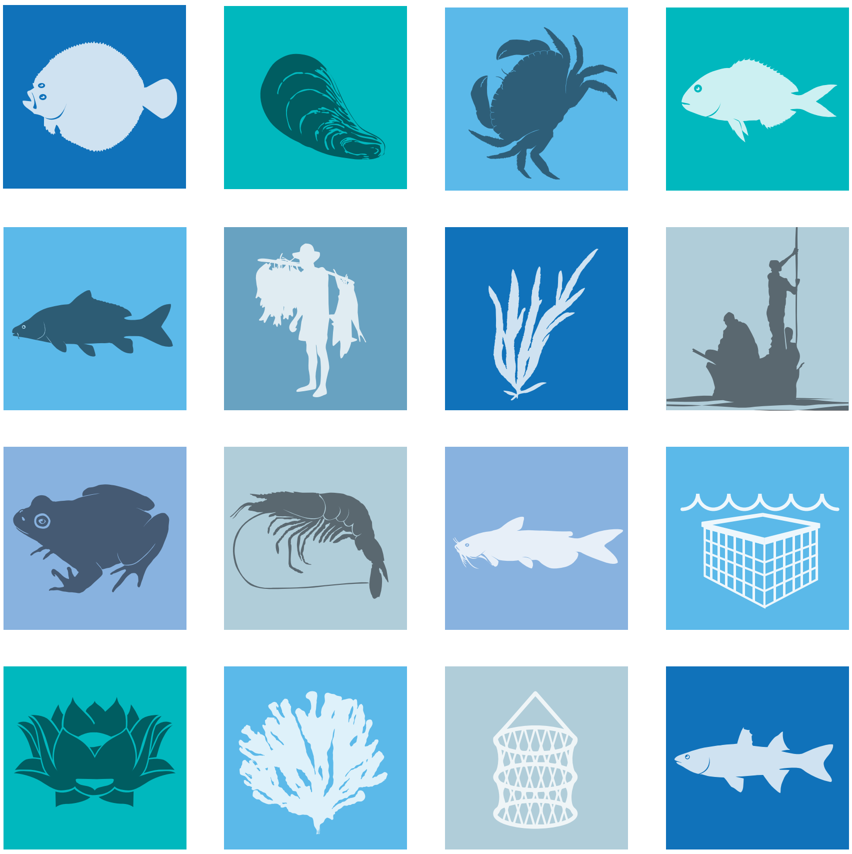
Food and Agriculture
Organization of the
United Nations

THEMATIC BACKGROUND STUDY

Genetic resources for farmed seaweeds



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Genetic resources for farmed seaweeds

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Food and Agriculture Organization of the United Nations
Rome, 2022

Required citation:
Hurtado, A.Q. 2022. *Genetic resources for farmed seaweeds – Thematic background study*. Rome. FAO. https://doi.org/10.4060/cb7903en

ISBN 978-92-5-135424-7

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Acknowledgements

The author is thankful to the following colleagues: Prof Yusho Aruga of Japan for providing data on seaweed production; Dr E.K. Hwang of the National Fisheries Research and Development Institute, Republic of Korea, for the latest seaweed production and photos of farmed seaweeds; and Dr Tong Pang of the Chinese Academy of Sciences Institute of Oceanology and Prof Show-Mei Lin for the information provided about the Chinese Phycological Society and the Taiwanese Phycological Society, respectively.

Abbreviations and acronyms

AmCFP	humanized cyan fluorescent protein AMPEP
AMT	aminomethyltransferase
AmCFP	humanized cyan fluorescent protein AMPEP
ASP12-NTA	synthetic medium with added vitamins
BA	6-benzyladenine
BAL	Bio Architecture Lab
BAP	6-benzylaminopurine
BAPs	Best Aquaculture Practices
CaMV 35S	cauliflower mosaic virus 35S promoter CAT
CIMTAN	Canadian Integrated Multi-Trophic Aquaculture Network
CaMV 35S	cauliflower mosaic virus 35S promoter CAT
CIMTAN	Canadian Integrated Multi-Trophic Aquaculture Network
CO2	carbon dioxide
DIN	dissolved inorganic nutrients
EFA	epiphytic filamentous algae
EGFP	enhanced green fluorenscent protein
ESS	Erd-Schreiber's Seawater
ESS/2	Erd-Schreiber's Seawater (half strength)
F_1	First generation
F_2	Second generation
FAO	Food and Agriculture Organization of the United Nations
FCP	fucoxanthin chlorophyll a/c- binding protein
GUS	glucuronidase
HBsAg	human hepatitis B surface antigen
IAA	indole-3-acetic acid
lacZ	bacterial beta-galactosidase
IBA	indole-3-butyric acid
IFREMER	L'Institut Français de Recherche Pour l'Exploitation de la Mer
IMTA	integrated multi-trophic aquaculture
ISAV	infectious salmon anaemia virus
mESCs	mouse embryonic stem cells
N	nitrogen
NAA	1-naphthaleneacetic acid

(NH4)2HPO4	diammonium phosphate
$(NH4)NO_3$	ammonium nitrate
NSE	natural seaweed extract
NTNU	Norwegian University of Science and Technology
OA	ocean acidification
P	phosphorous
PAA	phenylacetic Acid
PES	Provasoli's enriched seawater
PGRs	plant growth regulators
PI	protoplast isolation
POM	particulate organic matter
PR	plant regeneration
PtHSP70	*Porphyra tenera* promoter
PyAct1	*P. yezoensis* actin 1 (promoter)
PyGAPDH	*P. yezoensis* glyceraldehyde-3-phosphate dehydrogenase
PyGUS	*P. yezoensis* glucuronidase
Rt-PA	recombinant human tissue plasminogen activator
S65T	Mutated threonine
SABs	Seaweed Aquaculture Beds
SEA	Southeast Asia
SES	Seaweed Energy Solutions AS
sGFP	superfolder green fluorescent protein
SINTEF	Stiftelsen for industriell og teknisk forskning ved Norges tekniske høgskole
SSW	sterile seawater
SV40	a promoter
SWM3	seawater enrichment
UBI	ubiquitin (as gene promoter)
UprbcS	*Ulva pertusa* ribulose-1,5-bisphosphate carboxylase/oxygenase (gene promoter)
VS 50	von Stosch's (half strength)
ZsGFP	humanized green fluorescent protein
ZsYFP	humanized yellow fluorescent protein

Introduction

The increasing global population needs to source food from the ocean, which is a much greater area than the land. The ocean is rich with diversified flora and fauna, and both are sources of proteins, vitamins, minerals, phytohormones and bioactive compounds. Thousands of species of macroalgae (seaweed) dominate the vegetation of the sea floor from the intertidal to the subtidal zone.

The domestication of several economically important seaweed such as *Saccharina, Undaria* and *Pyropia* in China, Japan and the Republic of Korea, and *Kappaphycus* and *Eucheuma* in Indonesia, Malaysia, the Philippines and the United Republic of Tanzania led to intensive commercial cultivation of these seaweeds. Except for the United Republic of Tanzania, the commercial farming of seaweed, both temperate and tropical species, is centred in Asia. Despite the presence of several economically important seaweeds outside Asia, commercial farming is practised only in a few of non-Asian countries. These include Chile for *Gracilaria* and *Macrocystis* (Buschmann *et al*., 2001); France for *Palmaria palmata, Porphyra umbilicalis* and *Undaria pinnatifida* (Netalgae); and Canada for *Saccharina latissima* in integrated multi-trophic aquaculture (IMTA) (Chopin *et al*., 2013) and *Chondrus crispus*. Trial cultivation of *Saccharina* spp. and *P. palmata* is now taking place in Western Europe.

Seaweeds are farmed mainly for food as sea vegetables and food ingredients (Bixler and Porse, 2011), as well as feed (Wilke *et al*., 2015; Norambuena *et al*., 2015). However, there is increasing interest for their use for biorefinery products that require a vast amount of biomass which must be farmed.

The world is experiencing climate change, and several reports have shown that seaweeds are an efficient CO_2 sink. Seaweed aquaculture beds (SABs) provide ecosystem services similar to those seaweed beds existing in the wild. The use of SABs for potential CO2 mitigation has been established, with commercial seaweed production in China, India, Indonesia, Japan, Malaysia, the Philippines, the Republic of Korea, Thailand and Viet Nam, and it is also in the developmental stage in Australia and New Zealand (Chung and Lee, 2014). Seaweed farming is no doubt an aquaculture endeavour that can be socially and economically sustainable (= equitable); socially and environmentally sustainable (= bearable); and economically and environmentally sustainable (= viable) (Circular Ecology, 2016). Every stakeholder has an important role along the value chain to make it sustainable.

1. PRODUCTION, CULTIVATION TECHNIQUES AND UTILIZATION

For more than 100 years, China and other countries in Asia have grown seaweeds (also known as macroalgae) at a large industrial scale for the production of food, animal feed, pharmaceutical remedies and for cosmetic purposes. Commercial cultivation of seaweeds has a long history in Asia; in fact, the major source of cultivated seaweeds comes from this region. Despite being described as a low technology endeavour, it is highly successful and efficient. However, there is a newly emerging sector based on investment from petrochemical companies and governments for projects in Asia, Europe and the Americas aimed at extracting sugars from seaweed for ethanol, bio-based diesel, advanced biofuels, drop in fuels, biobutanol, biochemical and biopolymers.

Low technology cultivation can become highly advanced and mechanized, requiring on-land cultivation systems for seeding some life stages before grow-out at open-sea aquaculture sites. Cultivation and seedstock improvement techniques have been refined over the centuries, mostly in Asia, and can now be highly sophisticated. Advanced technologies and on-land cultivation systems have been developed in a few cases, mostly in the western world, wherein commercial viability can usually be reached only when high value-added products are obtained, their markets secured (not necessarily in response to a local demand, but often for export to Asia), and labour costs reduced to balance the significant technological investments and operational costs.

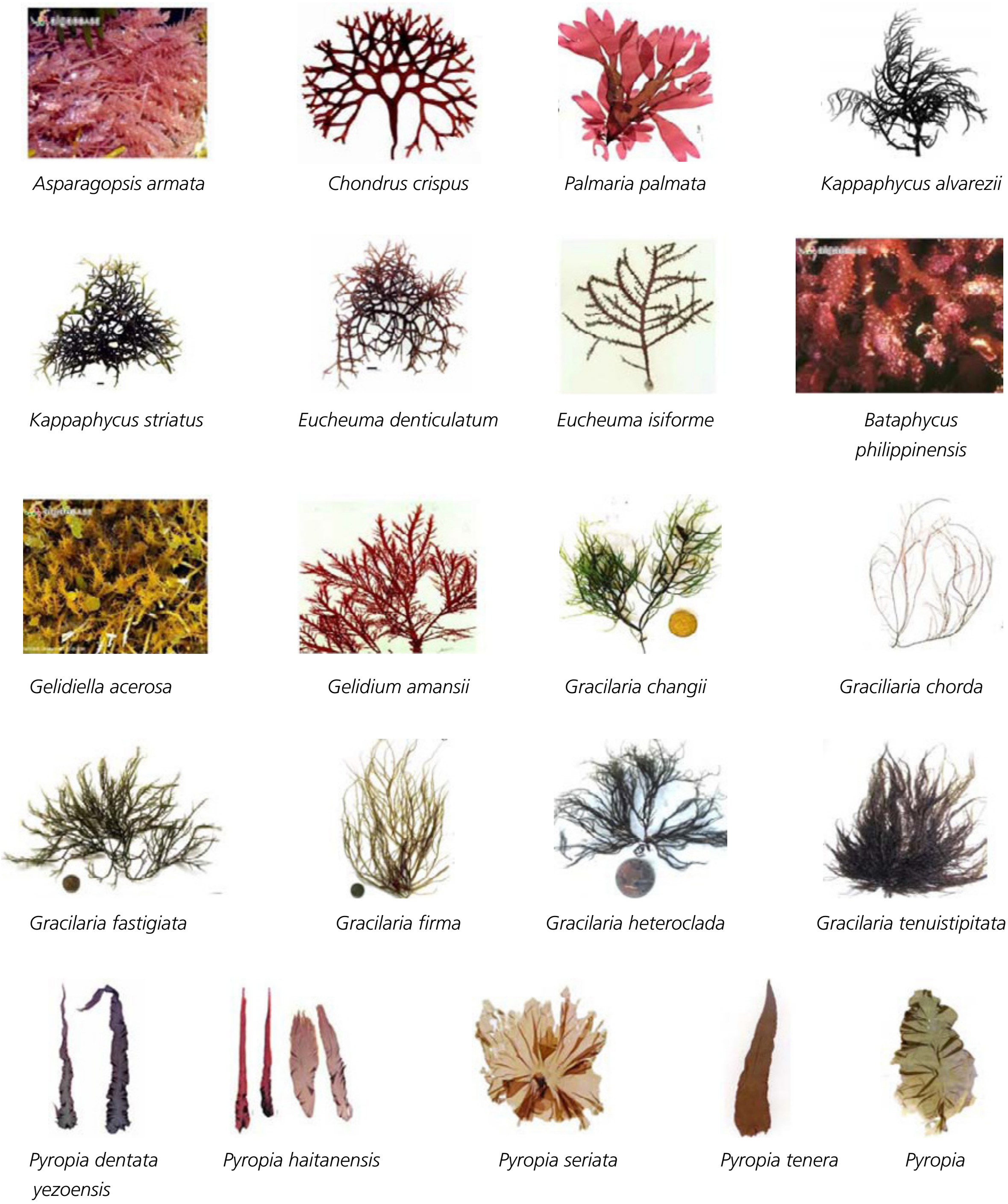
1.1 Species and varieties

Among the farmed seaweeds, *Chondrus crispus, Eucheuma denticulatum, Kappaphycus alvarezii* and *K. striatus* have different colour morphotypes, which range from brown, green, red, yellow and purple. Table 1 shows the different genera and species commercially farmed, which is composed of: 11 genera and over 25 species of red seaweeds with two varieties; 7 genera and 12 species of brown seaweeds; and 5 genera and 10 species of green seaweeds with one variety. Among the red seaweeds, *Gracilaria* has 11 species, followed by *Pyropia* with 5 species. In the brown seaweeds, *Sargassum* has 4 species while the green seaweeds are dominated by the genus *Ulva*, with 6 species (Figures 1–3). Figures 1, 2 and 3 provides pictures of some of the most important commercial species for the red, brown and green seaweeds respecitively.

TABLE 1.
Summary of seaweeds currently farmed

Red seaweeds		Brown seaweeds		Green seaweeds	
Genus	**Species**	**Genus**	**Species**	**Genus**	**Species**
Asparagopsis	*armata*	*Alaria*	*esculenta*	*Capsosiphon*	*fulvescens*
Betaphycus	*philippinensis*	*Cladosiphon*	*okamuranus*	*Caulerpa*	*lentillifera*
Chondrus	*crispus*	*Hizikia*	*fusiformis*	*Caulerpa*	*racemosa* var. *macrophysa*
Eucheuma	*denticulatum*	*Macrocystis*	*pyrifera*	*Codium*	*fragile*
Eucheuma	*denticulatum* var. *milyon milyon*	*Saccharina*	*digitata*	*Monostroma*	*nitidum*
Eucheuma	*isiforme*	*Saccharina*	*japonica*	*Ulva*	*compressa*
Gracilaria	*asiatica*	*Saccharina*	*latissima*	*Ulva*	*fasciata*
Gracilaria	*changii*	*Sargassum*	*fulvellum*	*Ulva*	*intestinalis*
Gracilaria	*chilensis*	*Sargassum*	*horneri*	*Ulva*	*linza*
Gracilaria	*fastigiata*	*Sargassum*	*muticum*	*Ulva*	*pertusa*
Gracilaria	*firma*	*Sargassum*	*thunbergii*	*Ulva*	*prolifera*
Gracilaria	*fisheri*	*Undaria*	*pinnatifida*		
Gracilaria	*heteroclada*				
Gracilaria	*lemaneiformis*				
Gracilaria	*manilaensis*				
Gracilaria	*tenuistipitata*				
Gracilaria	*tenuistipitata* var. *lui vermiculophylla*				
Gracilaria	*vermiculophylla*				
Gelidiella	*acerosa*				
Gelidium	*amansii*				
Hydropuntia	*edulis*				
Kappaphycus	*alvarezii*				
Kappaphycus	*malesianus*				
Kappaphycus	*striatus*				
Palmaria	*palmata*				
Pyropia	*dentata*				
Pyropia	*haitanensis*				
Pyropia	*pseudolinearis*				
Pyropia	*seriata*				
Pyropia	*tenera*				
Porphyra	*umbilicalis*				

FIGURE 1.
Photos of commercially farmed red seaweeds.



Photos courtesy of EK Hwang, AQ Hurtado

FIGURE 2.
Photos of commercially farmed brown seaweeds.

FIGURE 3.
Photos of commercially farmed green seaweeds. Photos courtesy of EK Hwang, AQ Hurtado

Photos courtesy of EK Hwang, AQ Hurtado

English and local names of some farmed seaweeds are reported in Table 2.

TABLE 2.
English and local names of farmed seaweeds

Scientific name	English	Chinese	Japanese	Korean	SEA region
Red seaweeds					
Chondrus crispus	Irish moss				
Eucheuma denticulatum					Spinosum
Gracilaria			Ogonori		Agar-agar
Kappaphycus alvarezii					Tambalang, besar
Kappaphycus striatus	Elkhorn				Flower, sacol
Palmaria palmata	Dulse				
Pyropia sp.	Purple laver	Zicai	Nori	Gim	Gamet
Brown seaweeds					
Alaria esculenta	Winged kelp				
Hizikia fusiformis			Hijiki	Tot hiziki	
Saccharina digitata	Horsetail kelp				
Saccharina japonica	Royal kombu, Japanese kelp	Hai dai, Hai tai, Kunpu	Makombu, Shinori-kombu, Hababiro-kombu, Oki-kombu, Uchi kombu, Moto-kombu, Minmaya-kombu, Ebisume hirome, Umiyama-kombu, Hoiro-kombu, Kombu	Hae tae, Tasima	
Saccharina latissima	Sugar kelp, sweet kelp, sea belt, poor man's weather glass, Kombu kombu royale, sweet wrack, sugar tang, oarweed		Kombu, Kurafuto kombu		
Sargassum muticum	Wireweed				
Undaria pinnatifida	Japanese kelp, Asian kelp, apron-ribbon vegetable	Ito-wakame, Qundai-cai, Kizami-wakami	Wakame, Ito-wakame, Kizami-wakami, Nambu-wakame	Ito-wakame, Kizami-wakami, Miyok	
Green seaweeds					
Caulerpa lentillifera	Sea grapes, Green caviar				Lato
Codium fragile	Green sea fingers, felty fingers, dead man's fingers, stag seaweed, green sponge, green fleece, oyster thief, forked felt alga				
Monostroma nitidum		Jiao-mo Zi-cai	Hitoegusa, Hirano hitoegusa		
Ulva	Sea lettuce		Aonori, Aonoriko		
	green laver				

1.2 Farming systems

1.2.1 Sea based farming

Sea-based farming may be classified according to location: coastal; deep sea; and offshore. Coastal and deep-sea farming are common in Asia, and to a little extent in Latin America and in the Western Indian Ocean regions. The fixed off-bottom line, the hanging longline, single and multiple raft longlines and spider-web techniques of cultivating *Eucheuma* and *Kappaphycus* and sometimes *Gracilaria* in the coastal and deep-sea waters are well documented (Hayashi *et al*., 2014; Hurtado *et al*., 2014; Msuya *et al*., 2014). *Gracilaria* and *Macrocystis* are also commercially farmed in Chile (Buschmann *et al*., 2001; Gutierrez *et al*., 2006). On the other hand, offshore farming is confined to Western Europe (Watson, 2014) and Eastern Canada (Chopin and Sawhney, 2009), mainly the monoculture of *Saccharina* and *Undaria.* Seaweed cultivation is currently in its infancy in Europe. Commercial aquaculture of seaweed is found in France (Brittany, six farms) and Spain (Galicia, two farms), and on an experimental basis in Ireland, Asturias (Spain), Norway, and the United Kingdom of Great Britain and Northern Ireland. The main cultivated species are *Saccharina latissima* and *Undaria pinnatifida*. In Ireland, *Palmaria palmata* farming is being experimented with on the West coast, but the results seem limited. However, with the fast development of IMTA as a culture system in Europe, farming of *Alaria esculenta, P. palmata, S. latissima* and *Laminaria japonica* is gaining much attention in this region (Chopin *et al*., 2001; Ridler *et al*., 2007).

China is known as the superpower in seaweed production and has decades of experience in seaweed cultivation, innovation and production. IMTA started in China about 2 000 years ago with a different system, called spontaneous integrated culture. Most of the culture systems in the country, however, are still single species intensive culture. China is well known in the field of marine aquaculture. More than 30 important aquaculture species, including kelp, scallops, oysters, abalone and sea cucumbers, are grown using various culture methods, such as longlines, cages, bottom sowing and enhancement, pools in the intertidal zone, and tidal flat culture (Zhang et al., 2007).

The concept of IMTA was coined in 2004 and refers to the use of species from different trophic positions or nutritional levels in the same system (Chopin and Robinson, 2004). IMTA, however, has been successfully practiced in Sanggou Bay in North China since the late 1980s (Fang *et al*., 1996). There are several IMTA modes in the bay, with benefits at the ecosystem level. For instance, the co-culture of abalone and kelp provides combined benefits as a food source and for waste reduction: abalone feed on kelp, and the kelp take up nutrients released from the abalone (Tang *et al*., 2013). The co-culture of finfish, bivalves and kelp links organisms from different trophic levels so that the algae absorb nutrients released from finfish and bivalves and bivalves feed on suspended faecal particles from the fish. Since kelp and *Gracilaria lemaneiformis* are cultured from December to May and from June to November, respectively, nutrients are absorbed by the algae throughout the year. These examples of multi-trophic culture maximize the utilization of space by aquaculture as they combine culture techniques in the pelagic and benthic zones. Implementation of IMTA in Sanggou Bay has improved economic benefits, maintained environmental quality, created new jobs, and led to culture technique innovations (Fang and Zhang, 2015).

Table 3 presents a summary of the different culture techniques of the different farmed seaweeds per country, all of which are in the commercial stage, with the exception of the land based

IMTA in Portugal. Apparently, hanging longline is common both to red and brown seaweeds. Except for *Caulerpa*, *Eucheuma, Gracilaria* and *Kappaphycus,* the source of propagules for commercial farming comes from spores that are grown first in hatcheries and then planted out when reaching the juvenile stage during favourable sea temperatures. In contrast, the four genera above use vegetative cuttings as propagules for commercial farming.

TABLE 3.
Summary of the different culture techniques and species farmed by country

Country	Red	Brown	Green
Australia			Ulva pertusa*[1]
Brazil	Gracilaria birdiae*[6]		
	Gracilaria domingensis**[3]		
	Kappaphycus alvarezii**[4,6]		
	Kappaphycus striatus**[4,6]		
Cambodia	Kappaphycus alvarezii**[4,6]		
	Kappaphycus striatus**[4,6]		
Canada	Chodrus crispus**[1]	Alaria esculenta*[6]	
	Palmaria palmata*[2]	Macrocystis integrifolia*[6]	
		Saccharina latissima*[3]	
Caribbean Islands	Gracilaria spp.**[6]		
Chile	Gracilaria chilensis**[20,21]	Macrocystis pyrifera*[6]	
	Betaphycus philippinensis**[18]		
China	Eucheuma denticulatum**[4,6]	Hizikia fusiformis*[6]	
	Gracilaria lemaneiformis**[6]	Macrocystis pyrifera*[10]	
	Gracilaria tenuistipitata var.		
	liui**[13]	Saccharina japonica*[3]	
	Kappaphycus alvarezii**[6]	Sargassum fulvellum*[6]	
	Kappaphycus striatus**[4,6]	Sargassum horneri*[6]	
	Pyropia haitanensis*[5]	Sargassum muticum*[6]	
	Pyropia yezoensis*[5]	Sargassum thunbergii*[6]	
		Undaria pinnatifida*[3,6]	
Denmark		Saccharina latissima*[2,3]	Ulva intestinalis*[2]
France	Palmaria palmata*[1]	Undaria pinnatifida*[2,3]	Ulva pertusa*[2]
	Porphyra umbilicalis*[5]	Saccharina latissima*[2,3]	
Fiji Islands	Kappaphycus alvarezii**[6]		
	Kappaphycus striatus**[6]		
India	Eucheuma denticulatum**[4,6]		Ulva fasciata*[5]
	Gelidiella acerosa**[5]		
	Gracilaria sp.**[10]		
	Hydropuntia edulis**[1,6]		
	Kappaphycus alvarezii**[10]		
	Kappaphycus striatus**[10]		

(cont.)

Country	Red	Brown	Green
Indonesia	Eucheuma denticulatum**[4,6]		
	Gracilaria asiatica**[13]		
	Gracilaria heteroclada**[6,10,13]		
	Gelidium amansii**[6]		
	Kappaphycus alvarezii**[4,6]		
	Kappaphycus striatus**[4,6]		
Ireland	Asparagopsis armata**[6]	Alaria esculenta*[3]	
	Palmaria palmata*[6]	Saccharina latissima*[3]	
Israel	Gracilaria sp.**[2]		Ulva pertusa**[2]
Japan	Gelidium amansii*[6]	Cladosiphon okamuranus*[6]	Caulerpa lentillifera*[8]
	Pyropia pseudolinearis*[5]	Saccharina japonica*[6]	Monostroma nitidum*[5]
	Pyropia tenera*[5]	Undaria pinnatifida*[6]	Ulva sp.*16
	Pyropia yezoensis*[5]		
Republic of Korea	Gracilaria spp.*/**[6]	Hizikia fusiformis*[6]	Codium fragile*/**[6]
	Pyropia dentata*[5]	Saccharina japonica*[3]	Capsosiphon fulvescens*[17]
	Pyropia seriata*[5]	Saccharina latissima*[3]	Ulva compressa*[5]
	Pyropia tenera*[5]	Sargassum fulvellum*/**[6]	Ulva linza*[5]
	Pyropia yezoensis*[5]	Undaria pinnatifida*[3]	Ulva prolifera*[5]
Madagascar	Kappaphycus alvarezii**[6]		
Malaysia	Eucheuma denticulatum**[6]		
	Kappaphycus alvarezii**[6]		
	Kappaphycus malesianus**[6]		
	Kappaphycus striatus**[6]		
Myanmar	Kappaphycus alvarezii**[6]		
	Kappaphycus striatus**[6]		
Norway		Saccharina latissima*[3]	
Panama	Kappaphycus alvarezii**[6]		
Philippines	Eucheuma denticulatum**[6]		Caulerpa lentillifera**[14]
	Eucheuma denticulatum var. milyon milyon**[6]		Caulerpa racemosa var. macrophysa**[15]
	Gracilaria changii**[10,13]		
	Gracilaria firma**[10,13]		
	Gracilaria heteroclada**[10,13, 14]		
	Gracilaria manilaensis**[10,13]		
	Kappaphycus alvarezii**[6,7,11,12]		
	Kappaphycus malesianus**[6]		
	Kappaphycus malesianus**[6]		
	Kappaphycus striatus**[4,6,7,11,12]		

(cont.)

Country	Red	Brown	Green
Portugal	*Gracilaria vermiculophylla**[2]		*Codium tomentosum**[2]
	*Chondrus crispus**[2]		*Ulva armoricana**[2]
	*Palmaria palmata**[2]		*Ulva pertusa**[2]
	Pyropia sp.*[2]		
South Africa			*Ulva fasciata***[2]
			*Ulva pertusa***[2]
			*Ulva rigida***[2]
South Pacific Islands	*Eucheuma denticulatum***[4,6,10]		
	*Kappaphycus alvarezii***[4,6,10]		
Solomon Islands	*Kappaphycus alvarezii***[4]		
Spain	*Palmaria palmata***[7]	*Undaria pinnatifida**[3]	
Sri Lanka	*Kappaphycus alvarezii***[10]		
	*Kappaphycus striatus***[10]		
Tanzania	*Eucheuma denticulatum***[14]		
	*Kappaphycus alvarezii***[10]		
Taiwan	*Gracilaria confervoides***[19]		*Caulerpa lentillifera***[14]
	Pyropia sp.*[5]		*Monostroma* sp.
Thailand	*Gracilaria fisheri***[6,13,14]		*Caulerpa lentillifera***[2]
	*Gracilaria tenuistipitata***[6,13,14]		*Chaetomorpha* sp.**[19]
	*Hydropuntia edulis***[13]		*Ulva* sp.**[13]
Venezuela	*Kappaphycus alvarezii***[4,6]		
	*Kappaphycus striatus***[4,6]		
Viet Nam	*Eucheuma denticulatum***[6]		*Caulerpa lentillifera***[14]
	*Gracilaria asiatica***[13,14]		
	*Gracilaria firma***[13,14]		
	*Gracilaria heteroclada***[13,14]		
	*Gracilaria tenuistipitata***[13,14]		
	*Kappaphycus alvarezii***[6,9]		
	*Kappaphycus striatum***[6,9]		
United Kingdom of Great Britain and Northern Ireland (Scotland)		*Alaria esculenta**[3]	
		*Laminaria digitata**[3]	
		*Laminaria hyperborea**[3]	
		*Saccharina latissima**[3]	
United States of America	*Pyropia* sp.*[2]	*Saccharina latissima**[3]	

Note: *spore; **vegetative.[1]land-based raceways/tanks; [2]land-based IMTA; [3]sea-based longlines IMTA; [4]fixed off-bottom; [5]floating nets; [6]hanging longline (horizontal); [7]hanging longline (vertical); 8hanging longline (basket bag); [9]hanging longline (net bags); [10]single raft longline; 11multiple raft longline; [12]multiple longline (spider web); [13]pond broadcasting; [14]pond "rice-planting"; [15]intertidal "rice planting"; [1]6pole system; [17]bamboo-net; [18]stone tying; [19]co-culture with shrimps; [20]direct burial method; [21]plastic tube method.

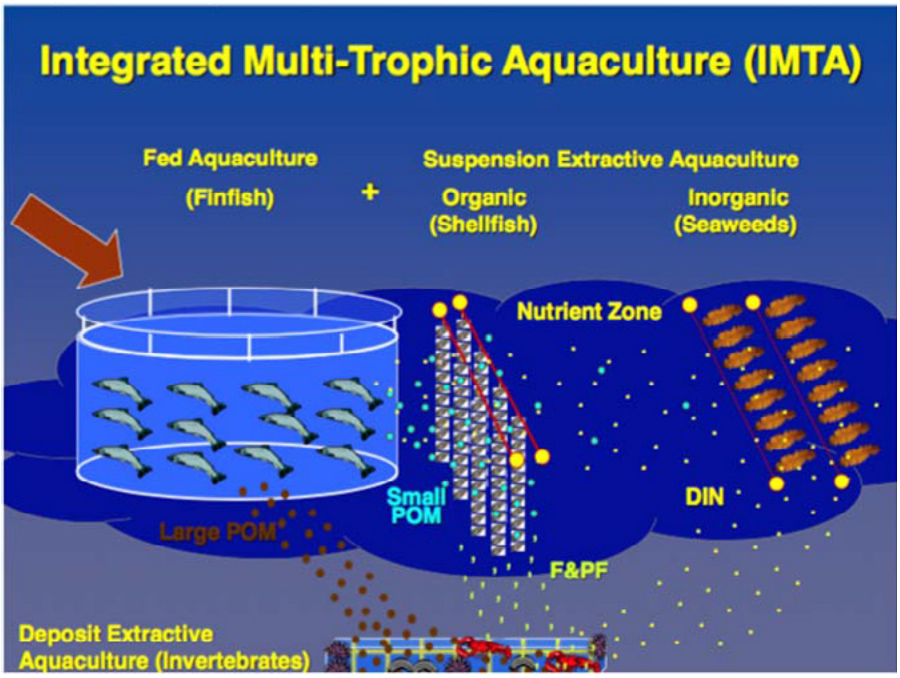
One of the most discussed types of aquaculture in Western Europe, Eastern Canada and the United States of America is IMTA, which is the farming, in proximity, of several species at different trophic levels (Figure 4). The species selected should be well adapted to these conditions and be appropriately chosen at multiple trophic levels, based on their complementary functions in the ecosystem as well as for their existing, or potential, economic value. Proximity should be understood as not necessarily considering absolute distances, but connectivity in terms of ecosystemic functionalities in which management at the sea-area level is paramount.

IMTA is an ecologically engineered ecosystem management approach, which, in fact, does nothing more than mimic a simplified natural trophic network. IMTA creates a balanced system for increased environmental sustainability (ecosystem services and green technologies for improved ecosystem health); economic stability (product diversification, risk reduction and job creation in coastal communities); and societal acceptability (better management practices, improved regulatory governance, and appreciation of differentiated and safe products). IMTA programmes, in different states of development and configuration, are taking place in at least 40 countries (Barrington *et al.,* 2009).

IMTA has gained recognition after 16 years of existence in the Western world and has slowly been developing in other regions. The most advanced IMTA systems, near commercial or at commercial scale, can be found in the temperate waters of Canada, Chile, China, Israel and South Africa, for example (Chopin *et al*., 2008; Barrington *et al*., 2009). Table 4 presents the genera selected based on their established husbandry practices, habitat appropriateness, biomitigation ability and economic life. Developments of IMTA projects have been started in France, Ireland, Japan, the Republic of Korea, Mexico, Norway, Portugal, Spain, Thailand, Turkey, the United Kingdom of Great Britain and Northern Ireland (mostly Scotland), and the United States of America (see Table 5 for sea-based practices and Table 6 for land-based practices) (Barrington *et al*., 2009). IMTA offers many advantages compared with the monoculture system (Barrington *et al*., 2009), such as:

i. **Effluent biomitigation:** the mitigation of effluents through the use of biofilters (e.g. seaweeds and invertebrates), which are suited to the ecological niche of the farm.
ii. **Disease control:** prevention or reduction of disease among farmed fish can be provided by certain seaweeds due to their antibacterial activity against fish pathogenic bacteria (Bansemir *et al*., 2006), or by shellfish that reduce the virulence of infectious salmon anaemia virus (Skar and Mortensen, 2007).
iii. **Increased profits through diversification:** increased overall economic value of an operation from the commercial by-products that are cultivated and sold.
iv. **Increased profits through obtaining premium prices:** potential for differentiation of the IMTA products through ecolabelling or organic certification programmes.
v. **Improving local economy:** economic growth through employment (both direct and indirect) and product processing and distribution.
vi. **Form of "natural" crop insurance:** product diversification may offer financial protection and decrease economic risks when price fluctuations occur, or if one of the crops is lost to disease or inclement weather.

FIGURE 4.
Conceptual diagram of an IMTA operation, including the combination of fed aquaculture (e.g. finfish) with organic extractive aquaculture (e.g. shellfish), taking advantage of the enrichment in particulate organic matter; and inorganic extractive aquaculture (e.g. seaweeds) taking advantage of the enrichment in dissolved inorganic nutrients (Chopin *et al.*, 2008).



Note: DIN = dissolved inorganic nutrients; POM = particulate organic matter.

TABLE 4.
Organisms suitable for IMTA in temperate waters

Fish	Crustaceans	Seaweeds	Molluscs	Echinoderms	Polychaetes
Anoplopoma	*Homarus*		*Argopecten*	*Apostichopus*	*Arenicola*
Dicentrarchus	*Penaeus*	*Alaria, Durvillaea,*	*Choromytilu*	*Athyonidium*	*Glycera*
Gadus		*Ecklonia, Lessonia,*	*Crassostrea*	*Cucumaria*	*Nereis*
		Laminaria,			
Hippoglossus		*Macrocystis,*	*Haliotis*	*Holothuria*	*Sabella*
		Saccharina,			
Melanogrammus		*Saccorhiza,*	*Mytilus*	*Loxechinus*	
Mugil		*Undaria*	*Pecten*	*Paracentrotus*	
Oncorhynchus			*Placopecten*	*Parastichopus*	
Paralichthys		*Asparagopsis*	*Tapes*	*Psammechinus*	
Pseudopleuronectes		*Callophyllis*		*Stichopus*	
		Chondracanthus		*Strongylocentrotus*	

(cont.)

Fish	Crustaceans	Seaweeds	Molluscs	Echinoderms	Polychaetes
Salmo					
Scophthalmus		*Chondrus*			
		Gigartina			
		Gracilaria			
		Gracilariopsis			
		Palmaria			
		Sarcothalia			
		Ulva			

Source: Barrington *et al*., 2009.

TABLE 5:
Sea-based IMTA practices in different countries

Country	Fish / shrimp	Molluscs / invertebrates	Seaweed	Status	Reference/ company
Australia	*Thunnus maccoyii Seriola lalandi*		*Solieria robusta Ecklonia radiata*	E	Wiltshire *et al*., 2015
Canada	*Salmo salar*	*Mytilus edulis*	*Saccharina latissima Alaria esculenta*	CSP P	Chopin & Robinson, 2004 Ridler *et al*., 2007
China	Shrimp, finfish	*Chlamys farreri Crassostrea gigas Haliotis discus hannai Patinopecten yessoensis Scapharca broughtonii Apostichopus japonicus*	*Saccharina japonica Gracilaria lemaneiformis*	C	Fang *et al*., 1996a &b; Fang *et al*., 2016
China	*Lateolabrax japonicus Pseudosciaena crocea*	*Ostrea plicatula*	*Laminaria/Gracilaria*	E	Jiang *et al*., 2009
Chile	*Salmo salar*		*Gracilaria chilensis Macrocystis pyrifera*	C	Troell *et al*., 1997
Denmark	*Oncorhynchus mykiss*		*Saccharina latissima*	C	Marinho *et al*., 2015
Denmark	*Oncorhynchus mykiss*		*Chondrus crispus*	E	Marinho *et al*., 2015
Indonesia	*Chanos chanos*	*Litopenaeus vannamei*		E	Putro *et al*., 2015
Indonesia	Grouper Pomfret fish Red carp	Abalone Lobster	*Kappaphycus alvarezii Eucheuma cottonii*	E	Sukiman *et al*., 2014
Ireland	*Salmo salar*	*Crassostrea gigas Mytilus edulis*	*Laminaria digitata Pyropia Asparagopsis armata*	E	Kraan, 2010
Japan	*Pagrus major*	*Apostichopus japonicus*	*Laminaria Undaria Ulva*	E	Yokoyama, 2013

(cont.)

Country	Fish / shrimp	Molluscs / invertebrates	Seaweed	Status	Reference/ company
Japan	*Pagrus major*		*Ulva*	E	Hirata *et al.*, 1994
Norway	*Salmo salar*	*Mytilus edulis*	*Laminaria*	E	Barrington *et al.*, 2009
Norway	*Salmo salar*	*Mytilus edulis*	*Gracilaria*	E	Handå, 2012
Philippines		*Haliotis asinina*	*Caulerpa lentillifera* *Eucheuma denticulatum* *Gracilaria heteroclada*	E	Largo *et al.*, 2016
Portugal	*Dicentrarchus labrax* *Scophthalmus maximus*		*Chondrus crispus* *Gracilaria bursa- pastoris* *Palmaria palmata*	E	Matos *et al.*, 2006
Spain	*Dicentrarchus labrax* *Scophthalmus maximus*		*Chondrus crispus* *Gracilaria bursa- pastoris* *Palmaria palmata*	E	Matos *et al.*, 2006
United Kingdom of Great Britain and Northern Ireland	*Salmo salar*	*Mytilus edulis* *Psammechinus miliaris* *Paracentrotus lividus*		E	Stirling & Okumuş, 1995
United Kingdom of Great Britain and Northern Ireland	*Salmo salar*	*Crassostrea gigas Pecten maximus Psammechinus miliaris Paracentrotus lividus*	*Palmaria palmata* *Laminaria digitata* *Laminaria hyperborea* *Saccharina latissima* *Sacchoriza polyschides*	E	SAMS-Loch Duart Limited/ West Minch Salmon
United States of America	Atlantic cod		*Pyropia* spp.	C	Carmona *et al.*, 2006

Note: CSPP - Commercial Scale Pilot Project; E - Experimental; C – Commercial

Seaweed is a growing category in Europe, although it is far behind Asia, where marine plants are part of a longstanding traditional culinary culture.

In France, the largest producer of seaweed is Algolesko, which began harvesting seaweed in May 2014. Interestingly, two of its partners are oyster growers, which, apart from their obvious expertise in aquaculture, also demonstrates the complementary nature of seaweed culture with other types of aquaculture. Future aquaculture production will see more IMTA practices, which optimizes interaction between species while reducing environmental impact, leading to sustainable production systems that will supply healthy sustainable seafood for future generations. The potential of seaweed for bioenergy production and a strong interest in developing IMTA have given a new dimension to seaweed aquaculture.

1.2.2 Land-based farming

There are only a few successful commercial land-based tanks/raceways of seaweed farming that have been reported. These are: *Chondrus crispus* (three different colour morphotypes) in Canada as sea vegetables (direct source of human food) grown in raceways; *Ulva pertusa*, in Israel, grown in raceways using deep seawater from the Mediterranean Sea and used in diversified food preparations such as pasta, salads, drinks, and abalone feed (SEAKURA); *Ulva pertusa* in South Africa, grown in raceways as the primary food of abalone (Bolton *et al*., 2006; Robertson-Anderson *et al*., 2008), and SeaOr Marine Enterprise in Israel using fish (*Sparus aurata*), seaweeds (*Ulva* and *Gracilaria*) and molluscs (*Haliotis discus hannai*).

TABLE 6.
Land-based IMTA practices in different countries

Country	Fish/shrimp	Molluscs/ invertebrates	Seaweed/micro-algae	Status	Reference/ company
Canada	*Hippoglossus hippoglossus*		*Palmaria palmata*	E	Corey *et al*., 2014
Chile	*Oncorhynchus kisutch* *O. mykiss*	*Crassostrea gigas*	*Gracilaria chilensis*	C	Buschmann *et al*., 1996
France	*Dicentrarchus labrax*		*Cladophora* *Ulva*	E	Metaxa *et al*., 2006
		C. gigas	*Ulva*	E	Lefebvre, Barillé & Clerc, 2000
Ireland	*O. mykiss*		*Pyropia dioica Ulva*		Hanniffy & Kraan, 2006; www.thefishsite.com
Israel	*Sparus aurata*	*Haliotis discus hannai*	*Gracilaria Ulva*		SeaOr Marine Farm, Israel
Portugal	*Scophthalmus maximus*		*Chondrus crispus* *Gracilaria bursa-pastoris* *Palmaria palmata,*	E	Matos *et al*., 2006
Republic of Korea	*Sebastes schlegeli*	*Stichopus japonicus*	*Sargassum fulvellum*	E	Kim *et al*., 2014
South Africa		*Haliotis midae*	*Gracilaria Ulva*	C	Bolton *et al*., 2006
Spain	*Dicentrarchus labrax*	*Tapes decussatus*	*Isochrysis galbana*	E/C	Borges *et al*., 2005
Spain	*S. maximus*		*Tetraselmis suecica* *Phaeodactylum tricornutum*		
United States of America	*Hippoglossus stenolepsis*		*Chondracanthus exasperatus*	C	Söliv International
United States of America	*Anoplopoma fimbria*	*H. discus hannai*	*Palmaria mollis*	C	Big Island Abalone Corporation

Note: CSPP = Commercial Scale Pilot Project; E = Experimental; C = Commercial

1.3 Major seaweed producing countries

Except for Chile, which farms *Gracilaria* and *Macrocystis*, and the United Republic of Tanzania, which cultivates *Eucheuma*, seaweed production is mainly concentrated in Asia (Table 7).

TABLE 7.
Major seaweed producing countries

Species	Major countries
Red seaweeds	
Chondrus crispus	Canada
Eucheuma denticulatum	Indonesia, Philippines, United Republic of Tanzania
Gracilaria spp.	China, Chile, Indonesia, South Africa, Viet Nam
Kappaphycus alvarezii, K. striatus	Indonesia, Malaysia, Philippines, United Republic of Tanzania
Pyropia spp.	China, Japan, Republic of Korea
Brown seaweeds	
Saccharina spp.	China, Japan, Republic of Korea
Hizikia fusiformis	Republic of Korea
Undaria	China, Japan, Republic of Korea
Green seaweeds	
Caulerpa lentillifera	Japan, Philippines, Viet Nam
Codium fragile	Republic of Korea
Monostroma nitidum	Japan
Ulva spp.	Japan, Republic of Korea

1.4 Volume and value of farmed seaweeds

As of 2016, recent production data on *Saccharina, Undaria* and *Pyropia* from China were not available. The author communicated with colleagues in academia and industry, but only Japan and the Republic of Korea responded to the request. Table 8 shows the volume of farmed seaweeds in Japan and the Republic of Korea.

Indonesia and the Philippines are the world's two major producing countries of *Kappaphycus alvarezii* (*cottonii*) but while Indonesia continues to increase its production, in the Philippines it has decreased since 2009. The sudden increase of production in Indonesia since 2008 is mainly due to the opening of new cultivation areas, considering the presence of thousands of islands in the country. However, the country's productivity is only 11 tonnes dry weight (dwt) ha^{-1} $year^{-1}$. Despite the geographic location of the Philippines, which every year is exposed to several cyclones that often destroy farming structures and propagules, the country's productivity is 18 tonnes dwt ha^{-1} $year^{-1}$ (Porse and Rudolph, 2017). Malaysia, though it is within the Coral Triangle and has vast areas suitable for farming, is still facing challenges to increase its production. In 2014 and 2015, 26 076 tonnes and 24 533 tonnes of *Kappaphycus*, respectively, were produced (Suhaimi, personal communication).

Production of *Kappaphycus* in other Southeast Asian countries, such as Cambodia, China, India, Myanmar, Viet Nam, and in Latin America are still small at present and data are not available.

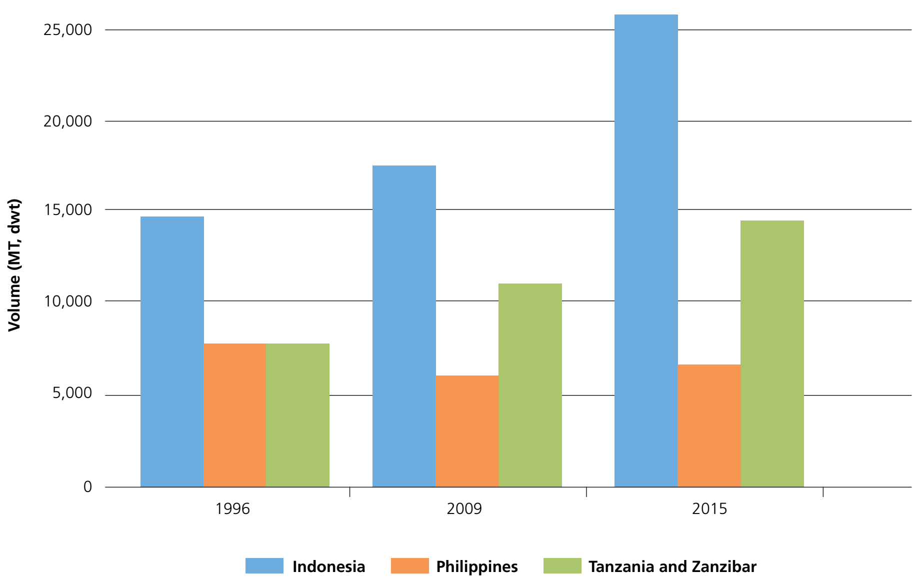
TABLE 8.
Major seaweeds farmed in Japan and the Republic of Korea

Genus	Japan (2014)	Republic of Korea (2015)	
	Volume (tonnes)	Volume (tonnes)	Value (USD 1 000)
Red			
Gracilaria		4	8
Pyropia	316 200	390 196	319 441
Brown			
Hizikia		28 157	15 227
Saccharina	32 800	442 771	78 409
Sargassum		86	256
Undaria	43 900	321 910	70 104
Green			
Capsosiphon		377	9 964
Codium		3 895	997
Cladosiphon	15 500		
Ulva		6 748	

Sources: Korea Ministry of Oceans and Fisheries, 2015; Japan Ministry of Agriculture, Forestry and Fisheries, 2014.

The shallow areas in the coastal zone of the United Republic of Tanzania and Zanzibar allow favourable cultivation of *Eucheuma denticulatum*; hence, these locations are major producing areas. Figure 5 shows the latest production of spinosum (common vernacular name of *E. denticulatum*) in the three major producing countries.

FIGURE 5:
Seaweed carrageenan (*Eucheuma spinosum*) production, 2015 (tonnes, dry weight)



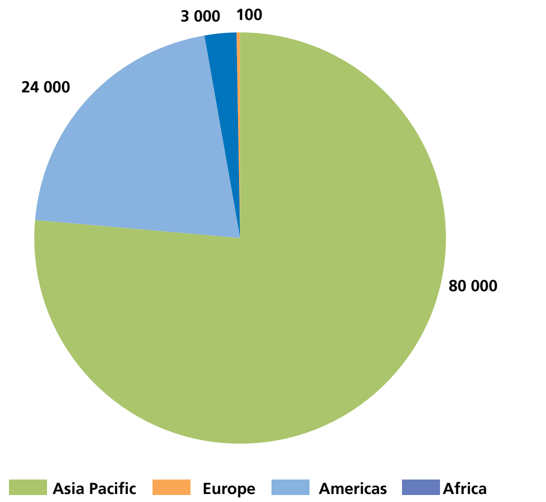
Source: Porse and Rudolph, 2017.

Gracilaria and *Gelidium* are two genera of seaweed suitable for the processing of agar, the former being more appropriate for food applications while the latter for bacteriological and biotechnological applications.

Gracilaria is a ubiquitous seaweed, which can be found both in tropic and temperate waters, while *Gelidium* is more confined to temperate waters. The capacity of *Gracilaria* to grow in euryhaline areas and to regenerate from fragments are characteristics that favour intensive cultivation from brackish-water to full seawater areas (Hurtado-Ponce *et al*., 1992; Hurtado-Ponce, 1993; Hurtado-Ponce *et al.,* 1997).

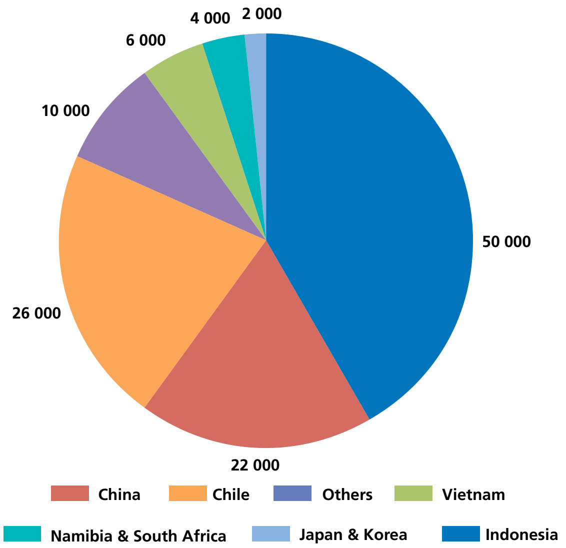
Asia-Pacific is the largest producing region of *Gracilaria,* followed by the Americas (mainly Chile), and Africa and Europe (Figure 6). A more detailed graph is presented in Figure 7, which shows the countries that produce *Gracilaria*, with Indonesia being the major producer. Africa is the leader for the production of *Gelidium* (Figure 8).

FIGURE 6.
***Gracilaria* production by region, 2015 (tonnes, dry weight)**



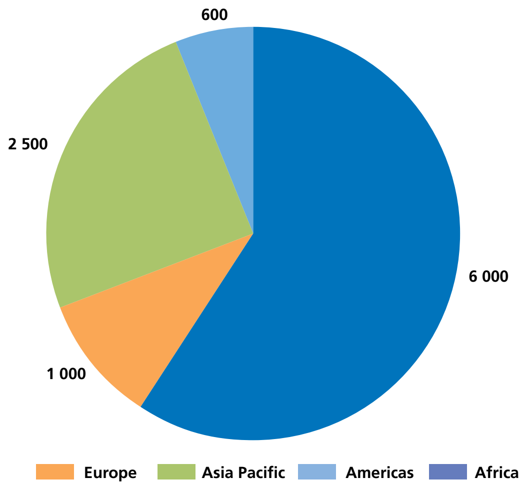
Source: Porse and Rudolph, 2017.

FIGURE 7.
***Gracilaria* production by country, 2014 (tonnes, dry weight)**



Source: Paravano, 2015.

FIGURE 8.
***Gelidium* production by region, 2015 (tonnes, dry weight)**



The production of *Gelidium* is led by Africa with 6 000 tonnes, followed by Asia-Pacific (2 500 tonnes), Europe (1 000 tonnes), and the Americas (600 tonnes)

Source: Porse and Rudolph, 2017.

1.5 Utilization

Farmed seaweeds have been mainly used as sources of direct food in Asia for many centuries; however, in the past two to three decades, western countries have started including seaweeds in their diet for health reasons. Several single species have various applications, as reflected in Table 9. A total of 59 species are currently farmed and dominated by red seaweed (54.3 percent), followed by brown seaweeds (23.7 percent), and finally green seaweeds (22 percent). Seaweeds are prime candidates for the integrated biorefinery approach, both for the production of high-value compounds (such as edible food, food and feed ingredients, biopolymers, fine and bulk chemicals, agrichemicals, cosmetics, bioactives, pharmaceuticals, nutraceuticals, botanicals) and low-value bioenergy compounds (e.g. biofuels, biodiesels, biogases, bioalcohols, biomaterials).

TABLE 9.
Summary of utilizations of farmed seaweeds

Species	Food				Feed	Fuel*
		Food ingredient				
	Sea vegetable	Agar	Carrageenan	Alginate		
Red seaweeds						
Asparagopsis armata	x					
Betaphycus philippinensis			x			
Chondrus crispus	x		x			
Eucheuma denticulatum	x		x			x
Eucheuma denticulatum var. *milyon milyon*	x		x			x
Gelidiella acerosa	x	x				
Gelidium amansii	x	x				
Gracilaria asiatica	x	x			x	

(cont.)

Species	Food				Feed	Fuel*
		Food ingredient				
	Sea vegetable	Agar	Carrageenan	Alginate		
Red seaweeds						
Gracilaria birdiae	x	x				
Gracilaria changii	x	x			x	
Gracilaria chilensis	x	x			x	
Gracilaria domingensis	x	x				
Gracilaria firma	x	x			x	
Gracilaria fisheri	x	x			x	
Gracilaria heteroclada	x	x			x	
Gracilaria lemaneiformis	x	x				
Gracilaria manilaensis	x	x			x	
Gracilaria tenuistipitata	x	x			x	
Gracilaria tenuistipitata var. *liui*	x	x			x	
Gracilaria vermiculophylla		x			x	
Gracilaria sp.		x				
Hydropuntia edulis	x	x				
Kappaphycus alvarezii	x		x			x
Kappaphycus malesianus	x		x			x
Kappaphycus striatus	x		x			x
Palmaria palmata	x				x	
Porphyra umbilicalis	x					
Pyropia dentata	x					
Pyropia haitanensis	x					
Pyropia pseudolinearis	x					
Pyropia seriata	x					
Pyropia tenera	x					
Pyropia yezoensis	x					
Pyropia sp.	x					
Brown seaweeds						
Alaria esculenta	x					
Cladosiphon okamuranus	x					
Hizikia fusiformis	x					
Macrocystis integrifolia					x	x
Macrocystis pyrifera					x	x
Saccharina digitata	x					x
Saccharina hyperborea	x					x
Saccharina japonica	x					x
Saccharina latissima	x					x
Sargassum fulvellum			x			x
Sargassum horneri			x			x
Sargassum muticum			x			x
Sargassum thunbergii			x			x
Undaria pinnatifida	x			x	x	x
Green seaweeds						
Capsosiphon fulvescens	x					
Caulerpa lentillifera	x					

(cont.)

Species	Food				Feed	Fuel*
		Food ingredient				
	Sea vegetable	Agar	Carrageenan	Alginate		
Green seaweeds						
Caulerpa racemosa var. *Macrophysa*	x					
Codium fragile	x					
Codium tomentosum	x					
Monostroma nitidum	x					
Ulva compressa	x			x		
Ulva fasciata	x			x		
Ulva intestinalis	x			x		
Ulva linza	x			x		
Ulva pertusa	x			x		
Ulva prolifera	x			x		
Ulva sp.	x			x		

*Experimental stage.

1.6 Impact of climate change

Seaweeds are a key source of carbon in the reef ecosystem, and they are involved in other important processes, including the construction of reef frameworks, coral settlements and creation of habitats. They are a direct food source for herbivorous fish, crabs and sea urchins. The carbon they fix in photosynthesis enters the food chain via microbes.

Seaweeds are subject to both regional and global environmental changes in coastal waters, where environmental factors fluctuate dramatically because of high biological production and land runoff. Ocean warming and ocean acidification (OA) caused by climate changes can influence coastal environments and consequently affect the physiology, life cycles and community structures of seaweeds. According to Ji *et al*. (2016), some species showed enhanced growth and/or photosynthesis under elevated CO_2 levels or ocean acidification conditions, possibly due to increased availability of CO_2 in seawater with neglected influence of pH drop. Nevertheless, OA can harm some macroalgae because of their high sensitivity to the acidic perturbation to intracellular acid-base stability. Mild cean warming has been shown to benefit most macroalgae examined. OA may positively affect gametogenesis because of increased availability of CO_2 and may neutrally influence germination due to the counteractive effects of decreased pH (Roleda *et al*., 2012). OA can impact photosynthesis and respiration differently in some macroalgae. While it is important to look into responses of macroalgae to fluctuating pH under OA (common in coastal waters) (Cornwall *et al*., 2012), the impact of OA can affect productivity of sea-farmed macroalgae that experience dramatic diel pH variations. Altered chemistry under OA may reduce growth, photosynthesis and even lead to death of some macroalgal species (Israel and Hophy, 2002; Martin and Gattuso, 2009). Ultraviolet B, which penetrates only several metres in coastal waters, is harmful for macroalgae throughout their life cycles.

Sea level rise may create more available habitat space for macroalgae to grow as more land area will be inundated with water. In general, the macroalgae are not particularly vulnerable to the impact of sea level rise, even if in some cases the increase in sea level could negatively impact some species that live in shallow waters by reducing their exposure to sunlight (increased depth will mean more distance for sunlight to travel to reach the macroalgae).

The predicted increase in the frequency of severe weather events such as cyclones, storms and floods will bring an influx of nutrients into the reef ecosystem, which will increase macroalgae growth and reproduction. Cyclones and storms can also destroy coral reef structures, increasing habitat areas for macroalgae to grow.

The most notable impact of rising temperature and concomitant elevated salinity has been reported on farmed *Kappaphycus.* The high incidence of "ice-ice", a disease affecting *Kappaphycus* and *Eucheuma* production, as well as epiphytic filamentous algae, were reported in Southeast Asia by Critchley *et al*. (2004), Hurtado and Critchley (2006), Vairappan (2006), Vairappan *et al*. (2008), Tisera and Naguit (2009), Borlongan *et al*. (2011); in China by Pang *et al*. (2011, 2012, 2015); and in Madagascar by Ateweberhan *et al.* (2015) and Tsiresy *et al*. (2016).

Low productivity and production and the unavailability of propagules for the next growing cycles were the major problems for seaweed farmers as a result of rising temperatures. Sometimes the seaweed farmers stopped cultivating *Kappaphycus* and, consequently, their economic life was severely affected. While there are possible positive effects of ocean warming for some warm seawater-grown species, the rise of temperature may still represent a threat for the cold seawater-grown species by reducing their living space and ecological niche.

1.7 Future prospects

Farmed seaweeds in the tropics and subtropics will continue to grow and expand, not only because of their economic significance among coastal fishers, but also because of the development of more product applications in food industries as well as in pharmaceuticals, nutraceuticals, cosmetics and personal care. The combination of increasing production, innovative products and consumer demand for natural and organic products will no doubt lead to bright days for seaweed in Europe and other parts of the globe.

In Western Europe, Northeastern Canada and the United States of America, the brown seaweed *Alaria, Laminaria* and *Saccharina* will experience a tremendous expansion in terms of sea cultivation, both as monocultures and as part of the IMTA, mainly for biorefineries. Further, sea vegetables like *Chondrus crispus, Palmaria palmata, Pyropia yezoensis* and *Ulva pertusa* will be cultivated extensively in land-based systems both as a monoculture and in IMTA.

IMTA will find its way in countries where intensive fish cage and pond shrimp farming are practised, as in Southeast Asia, India and South America. IMTA is considered more sustainable than the common monoculture systems, a system of aquaculture where only one species is cultured, in that fed monocultures tend to have an impact on their local environments due to their dependence of supplementation with an exogenous source of food and energy without mitigation (Chopin *et al*., 2001). For some twenty years now, many authors have shown that this exogenous source of energy (e.g. fish feed) can have a substantial impact on organic matter and nutrient loading in marine coastal areas (Gowen and Bradbury, 1987; Folke and Kautsky, 1989; Chopin *et al.*, 1999; Cromey *et al.,* 2002), affecting the sediments beneath the culture sites and producing variations in the nutrient composition of the water column (Chopin *et al.,* 2001).

2. GENETIC TECHNOLOGIES

The global seaweed industry produced 23–24 million tonnes of wet seaweed from aquaculture in 2012 (FAO, 2014), as the demand for seaweed based-products exceeds the supply of seaweed raw material from natural stocks. Aquaculture of seaweed offers advantages over the harvest of natural stocks for the following reasons: stable supply and reliable access of raw material; uniformity of quality of the raw material; and selection of germplasm with desired traits. Seaweed cultivation must be technically feasible, environmentally friendly, economically equitable, and socially acceptable in order to be sustainable.

Traditional selection of varieties based on growth performance and resistance to "disease" is still used in propagating farmed species. The breakthrough in the hybridization of *Laminaria japonica* in China paved the way to massive cultivation of this species globally. *In vitro* cell culture techniques have also been employed, as these facilitate development and propagation of genotypes of commercial importance. There are more than 85 species of seaweeds for which tissue culture aspects have been reported.

Initially, the aim of these techniques focused mostly on genetic improvement and clonal propagation of seaweeds for mariculture; however, recently, the scope has been extended for use in bioprocess technology for the production of high-value chemicals of great importance in pharmaceuticals and nutraceuticals, and more recently, in biorefinery.

2.1 Sporulation (tetraspores and carpospores)

All brown seaweeds commercially cultivated *(Hizikia, Macrocystis, Saccharina* and *Undaria*) use strings for the attachment of zoospores in hatcheries during summertime until they reach 1 mm long, and then they are out planted into the sea in autumn. When these stocks attain a size of more than 1 m long, they are ready to be harvested. The growth stage from the land-based hatchery to grow-out is nine to ten months.

A number of reports have been conducted on the trial use of spores from *Gracilaria* for possible commercial cultivation, but as of 2016 no one has adopted the use of spores for commercial propagation. Likewise, the use of carposporelings from *Kappaphycus alvarezii* as possible propagules for field cultivation (Azanza and Aliaza, 1999; Azanza-Corrales, Aliaza and Montano, 1996; Azanza and Ask, 2003) did not gain much success compared with the carposporelings from *K. striatus,* which were field cultivated in Guimaras Island, the Philippines (Luhan and Sollesta, 2010). Further, the use of tetrasporelings from *K. alvarezii* (de Paula, 1999; Bulboa *et al.,* 2007*)* also did not gain much attention among the seaweed farmers for use in commercial cultivation compared with other species, such as *Laminaria digitata, Palmaria palmata, Pyropia yezoensis, Saccharina latissima* and *Undaria pinnatifida*. This is probably due to the low germination rate under laboratory/hatchery conditions for mass field cultivation. Hatchery production of the conchocelis and/or spores for out planting purposes is already well developed in China, Japan and the Republic of Korea and is still practised today.

2.2 Clonal propagation and varietal selection

Clonal propagation is the most common and simplest approach to select superior varieties from wild populations to improve the performance of cultivated crops (Santelices, 1992), as done for *Chondrus* (Cheney *et al.,* 1981), *Gigartina* (Sylvester and Waaland, 1983), *Gracilaria* (Patwary and van der Meer, 1982, 1983), and *Kappaphycus* (Doty and Alvarez, 1973), all cases where it was exploited the organogenetic potential of seaweeds in isolating superior clones for cultivation. Clonal propagation of *Chondrus crispus* in raceways in Canada is the only known successful cultivation of this red seaweed. Its commercial cultivation has been perfected after more than ten years of trial cultivation.

2.3 Somatic embryogenesis

Somatic embryogenesis is an asexual form of plant propagation that mimics many of the events of sexual reproduction. This process may be reproduced artificially by the manipulation of tissues and cells *in vitro*. Some of the most important factors for a successful plant regeneration are the culture medium and the environmental incubation conditions. *In vitro* somatic embryogenesis is an important prerequisite for the use of many biotechnological tools for genetic improvement as well as for mass propagation.

Whole plants are regenerated from culture via two different processes: somatic embryogenesis, in which cells and tissues develop into a bipolar structure containing both root and shoot axes with a closed vascular system (essentially, the type of embryogenesis that occurs in a seed); and organogenesis, in which cells and tissues develop into a unipolar structure, namely a shoot or a root with the vascular system of this structure often connected to parent tissues.

2.4 Micropropagation

2.4.1 Tissue and callus culture

Tissue culture is the science of maintaining cells and/or tissues *in vitro* in a sterile environment that regulates specific growth and development patterns. Culture conditions requiring control include: physical conditions (controlled with an environmental chamber or walk-in culture room), light, temperature, photoperiod and aeration; and chemical conditions (controlled by the culture media), all essential nutrients, minerals, pH and quality of water. Culture media is either solid (agar) or liquid. Plant growth regulators (PGRs) are essential to induce developmental changes in cells to create specific tissues. There are five classes of PGR, namely: auxins, promoting both cell division and cell growth; cytokinins, promoting cell division; gibberellins, for cell division; abscisic acid, inhibiting cell division; and ethylene, controling fruit ripening.

Plants can be regenerated in tissue culture either from tissue explants or from isolated cells. When plant cells and tissues are cultured *in vitro,* in most cases they exhibit a very wide range of plasticity. Regeneration of the whole plant from any single cell depends on the concept that each cell, if given the appropriate stimuli, has the genetic potential to divide and differentiate into all types of tissues. This genetic potential by plant cells is referred to as totipotency. Several species of red, brown and green macroalgae have been reported to regenerate from callus, as shown in Table 10. Although several successful studies were reported on the regeneration of plantlets of *Kappaphycus* and *Eucheuma* from callus through micropropagation using different culture media, their economic viability in the field has yet to be tested further, though initial trials have been started.

TABLE 10.
Earlier reports on the regeneration of plants from callus

Species	Status of success	Major media and PGR used	Reference
Red			
Chondrus crispus	Plant development	SWM3	Chen & Taylor, 1978
Eucheuma sp.	Callus formation	PES	Polne-Fuller & Gibor, 1987
E. denticulatum	Plant development	ESS + IBA and kinetin	Dawes & Koch, 1991
	Plant development	ESS + IBA and kinetin	Dawes et al., 1993
	Plant development	ESS/2 + PAA and kinetin	Hurtado & Cheney, 2003
Gelidium sp.	Plant development	SSW + NH_4NO_3 + $(NH_4)_2HPO_4$	Titlyanov *et al*., 2006a
Gracilaria changii	Plant development	mESCs; PES	Yeong, Khalid and Phang, 2008
G. tenuistipitata	Plant development	PGRs	Yokoya *et al.,* 2004
Kappaphycus alvarezii	Plant development	ESS + IBA and kinetin	Dawes & Koch, 1991
	Plant development	ESS + IBA and kinetin	Dawes *et al.,* 1993
	Plant development	PES + NAA, BA, spermine	Munoz *et al*., 2006
	Plant development	ESS/2 + PAA and kinetin	Hurtado & Biter, 2007
	Plant development	AMPEP + PAA and kinetin	Hurtado *et al.,* 2009; Yunque *et al*., 2011
	Plant development	VS 50, f/2 50, ASP12-NTA + IAA, 2-4-D, BA and colchicine	Hayashi *et al*., 2008
	Plant development	PES, VS 50, F/2 + IAA and BAP	Yong *et al*., 2014
	Plant development	VS 50 + IAA, kinetin, spermine, colchicine or oryzalin	Neves *et al*., 2015
	Callus formation	VS 50, f/2 50, ASP_{12}-NTA	Zitta *et al*., 2013
	Callus formation	PES + IBA + 6-BA	Li, *et al*., 2015
	Callus and filament formation	PES and Conway + BA + IAA; BA + NAA	Sulistiani *et al*., 2012
	Plant development	PES + BAP, NAA, NSE	Yong *et al*., 2014
Palmaria palmata	Plant regeneration	KTH f/2	Titlyanov *et al*., 2006b; Sanderson, 2015
Brown seaweeds			
Laminaria japonica	Plant regeneration	MS + Vit. B2 + C-751	Yan, 1984
Undaria pinnatifida	Plant regeneration	MS + Vit. B2 + C-751	Zhang, 1982; Yan, 1984; Kawashima & Tokuda, 1993
Green seaweeds			
Ulva intestinalis	Callus induction	PES	Polne-Fuller & Gibor, 1987

2.4.2 Protoplast isolation and fusion

Protoplasts are living plant cells without cell walls that offer a unique uniform single cell system that facilitates several aspects of modern biotechnology, including genetic transformation and metabolic engineering. Protoplasts isolation from macrophytic benthic marine algae was reported as early as 1970 using mechanical methods (Tatewaki and Nagata, 1970; Enomoto and Hirose, 1972; Kobayashi, 1975). However, the success in producing a large number of viable protoplasts became possible only after the development of an enzymatic method by Millner *et al.* (1979) for *Enteromorpha intestinalis* (Linnaeus) Nees. Plantlet regeneration from the same species was reported by Rusing and Cosson (2001).

Only a few species among the farmed seaweeds were tested for protoplast isolation and its possible regeneration to plantlets. Among the brown seaweeds, only *Laminaria japonica* (Saga and Sakai, 1984; Tokuda and Kawashima, 1988; Sawabe *et al.,* 1993; Sawabe and Ezura, 1996; Inoue *et al.,* 2008); *L. saccharina* and *L. digitata* (Butler *et al*., 1989); *Macrocystis pyrifera* (Kloareg *et al.,* 1989); and *Undaria pinnatifida* (Tokuda and Kawashima, 1988) were reported. Only the works of Kloareg *et al.* (1989) on *Macrocystis pyrifera* and Matsumura *et al.* (2000) on *L. japonica* were successful in the regeneration of plantlets from protoplasts.

Early protoplast isolations from *Kappaphycus alvarezii* were made with the purpose of improving the genetic characteristics of this species as a source of propagules for possible commercial cultivation (Zablackis, *et al.,* 1993). Digestions with cellulase and kappa-carrageenase produced only a few cortical cell protoplasts, while digestions with cellulase and iota-carrageenase only produced epidermal cell protoplasts. When both carrageenases were used in the digestion media with cellulase, protoplasts were released from all cell types and yields ranged from 1.0 to 1.2 × 10^7 cells g^{-1} with sizes from 5 to 200 mm diameter. Protoplasts were subsequently cultured to study cell wall regeneration; however, no regeneration of plantlets was observed.

Attempts to isolate protoplast from tissue fragments (<1 m_{m2}) of three Philippine cultivars of *Kappaphycus alvarezii,* namely the giant cultivar, the cultivar L and the Bohol wild type, by enzymatic dissolution of cell walls was reported by Salvador and Serrano (2005). The yields of viable protoplasts from young and old thalli (apical, middle, basal segments) were compared at various temperatures, duration of treatment and pH using eight combinations of commercial enzymes (abalone acetone powder and cellulase), and prepared extracts from fresh viscera of abalone (*Haliotis asinina*) and a terrestrial garden snail. Though viable protoplasts formed radially expanded discs and filaments arising from the disc, no regeneration to a plantlet was reported. Table 11 shows a summary of earlier reports on protoplast isolation and regeneration. As of 2016, protoplast isolation and regeneration are not being used commercially and all applications remain in the research and development phase.

TABLE 11.
Summary of protoplast isolation and regeneration of farmed seaweeds

Species	Status	Reference
Red seaweeds		
Gelidium robustum	PI	Coury *et al*., 1993
Gracilaria asiatica	PI	Yan & Wang, 1993
G. changii	PI	Yeong *et al*., 2008
G. chilensis	PR	Cheney, 1990
G. gracilis	PI	Huddy *et al*., 2013
G. tenuistipitata	PI	Chou & Lu, 1989; Bjork *et al*., 1990
Kappaphycus alvarezii	PI	Zablackis *et al*., 1993; Salvador & Serrano, 2005
Palmaria palmata	PI	Liu *et al*., 1992; Nikolaeva *et al*., 1999
Pyropia tenera	PI	Song & Chung, 1988; Fujita & Saito, 1990
P. yezoensis	PI	Fujita & Saito, 1990
P. yezoensis	PR	Yamazaki, *et al*., 1998; Hafting, 1999
Brown seaweeds		
Cladosiphon okamuranus	PR	Uchida & Arima, 1992
Laminaria digitata	CW	Butler *et al*., 1989
L. digita	PR	Benet *et al*., 1997
L. japonica	PI	Saga & Sakai 1984; Sawabe & Ezura, 1996; Sawabe *et al*., 1997; Matsumura *et al*., 2000
L. saccharina	CW	Butler & Evans, 1990
L. saccharina	PI	Benet *et al*., 1994
L. saccharina	PR	Benet *et al*., 1997
Macrocystis pyrifera	CW	Saga *et al*., 1986; Kloareg *et al*., 1989; Polne-Fuller *et al*., 1990
Undaria pinnatifida	PR	Matsumura *et al*., 2000
Green seaweeds		
Monostroma nitidum	PI	Yamaguchi *et al*., 1989
M. nitidum	PR	Fujita & Migita, 1985; Uppalapati & Fujita, 2002
Ulva fasciata	PR	Chen & Shih, 2000
U. flexuosa	PR	Reddy *et al*., 2006
U. intestinalis	PR	Rusing & Cosson, 2001; Millner *et al.* 1979
U. pertusa	PI	Saga, 1984; Yamaguchi *et al*., 1989
U. pertusa (wild)	PI	Reddy *et al*., 2006; Yamaguchi *et al*., 1989
U. pertusa (wild)	PR	Chou & Lu, 1989; Reddy *et al*., 2006
U. pertusa (mutant)	PR	Zhang, 1983; Fujimura *et al*., 1989; Reddy *et al*., 1989; Uchida *et al*., 1992; Uppalapati & Fujita, 2002

Note: CW = cell wall formation; PI = protoplast isolation; PR = plant regeneration.

2.5 Hybridization and crossbreeding

Among the commercial farmed seaweeds, only a few brown and red seaweed species were subjected to hybridization and crossbreeding.

For example, *S. japonica* in China was bred by crossing gametophytes and self-crossing the best individuals and selecting the best self-crossing line (Li *et al*., 2016). Its sporophytes were reconstructed each year from representative gametophyte clones, from which seedlings were raised for farming. As stated by the Authors, *"such strategy ensured Dongfang No. 7 against a variety of contamination due to cross-fertilization, and occasional mixing and inbred depletion due to self-crossing number-limited sporophytes matured year after year"*. Dongfang No. 7 is derived from a crossbreeding of different lines of *S. japonica* through four rounds of self-crossing and selection and retains a certain degree of genetic heterozygosity, and thus it is relatively immune to inbreeding depression caused by the reduction of genetic variability. The farming of Dongfang No. 7 increased the air-dry yield by 43.2 percent over two widely farmed controls on average. This value was however less than the value obtained with the interspecific hybrids or the varieties derived from them.

The successful work of Hwang *et al*. (2014) on the hybridization of female *U. pinnatifida* and male *U. peterseniana* led to the extended period of availability of *Undaria* for abalone feed and cultivation in the Republic of Korea. Using free-living gametophyte seeding and standard on-growing techniques, the second generation (F_2) hybrids were found to have longer pinnate blades and narrower midribs than the first generation (F_1) hybrid and formed only sporophylls. The growth and morphology of F_2 hybrids originating from the sporophyll or sorus of the F_1 hybrids were not morphologically different from each other. Both of the F_2 hybrids exhibited late maturation, with the early stages of sporophylls appearing in April.

An attempt to hybridize *Kappaphycus alvarezii* and *Eucheuma denticulatum* was successful, as reported by Wang (1993), using a somatic cell-fusion method to produce hybrids of non-filamentous or anatomically complex algae as evidenced by isoenzyme electrophoresis. However, this was not pursued further for its mass production for possible commercial cultivation (Table 12).

TABLE 12.
Summary of seaweeds that were hybridized

Fusion species	Status	Reference
Red		
Gracilaria chilensis × *G. tikvahiae*	Plant development	Cheney, 1990
Porphyra yezoensis (red) × *P. yezoensis* (green)	Plant development	Fujita & Migita, 1987
P. yezoensis × *P. pseudolinearis*	Plant development	Fujita & Saito, 1990
P. yezoensis × *P. haitanensis*	Callus development	Dai *et al.*, 1993
P. yezoensis × *P. tenera* (green)	Callus development	Araki & Morishita, 1990
P. yezoensis (green) × *P. suborbiculata*	Callus development	Mizukami *et al*., 1995
P. yezoensis × *P. vietnamensis*	Callus development	Matsumoto *et al.*, 1995
P. tenera × *P. suborbiculata*	Callus development	Matsumoto *et al.*, 1995
P. yezoensis × *Bangia atropurpurea*	Callus development	Fujita, 1993
P. yezoensis × *Monostroma nitidum*	Plant development	Kito *et al*., 1998
Green		
Ulva pertusa × *U. conglobata*	Plant development	Reddy & Fujita, 1989
U. pertusa × *U. prolifera*	Plant development	Reddy *et al.*,1992
Ulva sp. × *Pyropia yezoensis*	Protoplast fusion	Saga, *et al.*, 1986
U. linza × *U. pertusa*	Protoplast fusion	Jie, 1987
Brown		
Undaria pinnatifida (female gametophyte, from parthenosporophytes, × male gametophyte)	Sporeling production	Shan *et al.*, 2013

2.6 Genetic transformation

Genetic transformation occurs at the cellular level and can be used to introduce trait altering genes into the host genome. Cells must be regenerated into plants to recover the transgenic plant. Genetic transformation is a powerful tool not only for elucidating the functions and regulatory mechanisms of genes involved in various physiological events, but also for establishing organisms that efficiently produce biofuels and medically functional materials, or that carry stress tolerance under uncertain environmental conditions (Torney *et al*., 2007; Bhatnagar-Mathur *et al.,* 2008). As of 2016 no genetically transformed seaweeds are being sold or used commercially for food, biofuel or any other applications; this technology is only used for research and development purposes.

Donald P. Cheney is the pioneer in researching red algal transformation. He and his colleague performed transient transformation of the red alga *Kappaphycus alvarezii* using particle bombardment, which was the first report about the transient transformation of seaweeds (Kurtzman and Cheney, 1991). Since then, there have been recent developments in macroalgal transformation. The report of Wang *et al*. (2010a) showed a viable way of producing stable transformants to eliminate chimeric expression, and to achieve transgenic breeding in *K. alvarezii* using SV40 promoter-driving lacZ gene into cells of *K. alvarezii* through particle bombardment of epidermal and medullary cells at 650 psi (pounds per square inch) at a distance of 6 cm. In another report, a transgenic *K. alvarezii* was successfully produced when a binary vector pMSH1-Lys carrying a chicken lysozyme (Lys) gene was transformed into *Agrobacterium tumefaciens* LBA4404 by triparental mating (Handayani *et al*., 2014). The percentage of pMSH1-Lys transformation on *K. alvarezii* was 23.5 percent, while the efficiency of regeneration was 11.3 percent. PCR analysis showed that three of the regenerated thalli contained the lysozyme gene, which has the ability to break down the bacterial cell wall, a significant result in the prevention of "ice-ice" disease in *K. alvarezii.*

Among the red industrially important macroalgae such as *Chondrus, Gelidium, Kappaphycus* and *Pyropia,* the transient gene expression system has not yet been developed in these red macroalgae other than *P. yezoensis*. Optimization of codon usage in coding regions of the reporter gene and recruitment of endogenous strong promoters (pPyAct1-PyGUS and pPyAct1-GUS plasmids) are important factors in the transient gene expression system. Furthermore, the use of particle bombardment is the proven method of gene transfer into red algal cells (Mikami *et al*., 2011) (Table 13).

TABLE 13.
Summary of farmed seaweeds that were genetically transformed

Species	Status of expression	Method of gene transfer	Promoter	Marker or reporter	Reference
Red					
Gracilaria changii	Stable	Particle bombardment	SV40	lacZ	Gan *et al*., 2004
G. changii	Transient	Particle bombardment	SV40	lacZ	Gan *et al*., 2003
Kappaphycus alvarezii	Transient	Biolistic particle	CaMV 35S	GUS	Kurtzman & Cheney, 1991
K. alvarezii	Stable	Particle bombardment	SV40	lacZ	Wang *et al*., 2010a
Pyropia haitanensis	Stable	Glass bead agitation	SV40	lacZ; EGFP	Wang *et al*., 2010b

(cont.)

Species	Status of expression	Method of gene transfer	Promoter	Marker or reporter	Reference
Red					
P. tenera	Transient	Particle bombardment	PtHSP70; PyGAPDH	PyGUS	Son *et al*., 2012
P. yezoensis	Transient	Electroporation; particle bombardment	CaMV 35S	GUS	Kuang *et al*., 1998
P. yezoensis	Transient	Electroporation	rbcS	GUS	Hado *et al*., 2003
P. yezoensis	Transient	Electroporation	CaMV 35S	GUS	Liu *et al*., 2003
P. yezoensis	Transient	Electroporation	CaMV 35S; B-tubulin	GUS	Gong *et al*., 2005
P. yezoensis	Transient	Electroporation	CaMV 35S	CAT, GUS	He *et al*., 2001
P. yezoensis	Transient	Electroporation	Rubusico	GUS, sGFP; (S65T)	Mizukami *et al*., 2004
P. yezoensis	Transient	Particle bombardment	CaMV 35S; PyGAPDH	PyGUS	Hado *et al*., 2003
P. yezoensis	Transient	Particle bombardment	PyAct1	PyGUS	Takahashi *et al*., 2010
P. yezoensis	Transient	Particle bombardment	PyAct1	AmCFP; ZsGFP	Mikami *et al*., 2009
P. yezoensis	Transient	Particle bombardment	PyAct1	ZsYFP, sGFP (S65T)	Uji *et al*., 2010
P. yezoensis	Transient	Particle bombardment	PtHSP70; PyGAPDH	PyGUS	Son *et al*., 2012
P. yezoensis	Stable	Agrobacterium-mediated gene transfer	Unknown	Unknown	Bernasconi *et al*., 2004
P. yezoensis	Stable	Agrobacterium-mediated gene transfer	CaMV 35S	GUS	Cheney *et al*., 2001
Brown					
Laminaria japonica	Transient	Particle bombardment	CaMV 35S	GUS	Qin *et al*., 1998
L. japonica	Stable	Particle bombardment	SV40	GUS	Jiang *et al*., 2003
L. japonica	Transient	Particle bombardment	CaMV 35S, UBI, AMT	GUS	Li *et al*., 2009
L. japonica	Stable	Particle bombardment	FCP	GUS	Li *et al*., 2009
L. japonica	Stable	Particle bombardment	SV40	HBsAg	Jiang *et al*., 2002
L. japonica	Stable	Particle bombardment	SV40	Rt-PA	Zhang *et al*., 2008
L. japonica	Stable	Particle bombardment	SV40	bar	Zhang *et al*., 2008
Undaria pinnatifida	Transient	Particle bombardment	CaMV 35S	GUS	Qin *et al*., 1998
U. pinnatifida	Transient	Particle bombardment	SV40	GUS	Yu *et al*., 2002
Green					
Ulva pertusa	Transient	Electroporation	CaMV 35S,	GUS	Huang *et al*., 1996
U. pertusa	Transient	Particle bombardment	UprbcS	EGFP	Kakinuma *et al*., 2009

Note: AmCFP = humanized cyan fluorescent protein; AMT = aminomethyltransferase; CaMV 35S = cauliflower mosaic virus 35S promoter; CAT = chloramphenicol acetyltransferase; EGFP = enhanced green fluorescent protein; FCP = fucoxanthin chlorophyll a/c- binding protein; GUS = glucuronidase; HBsAg = human hepatitis B surface antigen; lacZ = bacterial beta-galactosidase; PtHSP70= *Porphyra tenera* promoter; PyAct1 = *P. yezoensis* actin 1 promoter; PyGAPDH = *P. yezoensis* glyceraldehyde-3-phosphate dehydrogenase; PyGUS = *P. yezoensis* glucuronidase; Rt-PA = recombinant tissue plasminogen activator; sGFP = superfolder green fluorescent protein; S65T = mutated threonine; SV40 = a promoter; UBI = ubiquitin (as gene promoter); UprbcS = *Ulva pertusa* ribulose-1,5-bisphosphate carboxylase/oxygenase (gene promoter); ZsGFP = humanized green fluorescent protein; ZsYFP = humanized yellow fluorescent protein.

According to Mikami (2013), genetic transformation is reported in red and brown seaweeds using the SV40 promoter; however, isolation of transgenic clone lines produced from distinct single transformed cells, which is the final goal of the genetic transformation of seaweeds as a tool, has not been reported, and seaweed genetic transformation is thus not fully developed. Due to the problems with efficient genetic transformation systems, the molecular biological studies of seaweeds are currently progressing more slowly than are the studies of land green plants. Since a genetic transformation system allows the performance of genetic analysis of gene function via inactivation and knock-down of gene expression by RNAi and antisense RNA suppression, its establishment will enhance both biological understanding and genetical engineering for the sustainable production of seaweeds and also for the use of seaweeds as bioreactors.

Though *in vitro* culture techniques as described above are currently being developed for seaweeds, which can create new genetic variants or promote clonal propagation in photobioreactors for high-end applications, most commercial seaweed cultivation, especially in the subtropical to tropical waters, is currently based on simple vegetative propagation because of economic and farming advantages.

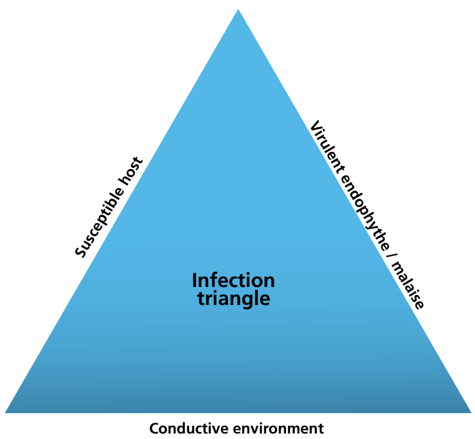
3. MAJOR PROBLEMS OF FARMING SEAWEEDS

3.1 Disease and epiphytism

When a seaweed is suffering, we call it diseased. A seaweed is diseased when it is continuously disturbed by some causal agents that results in an abnormal physiological process that it disrupts its normal structure, growth, function or other activities. The concepts of disease are the following (Singh, 2007): the normal physiological functions of seaweed are disturbed when they are affected by pathogenic living organisms and/or by some environmental factors; initially, seaweed reacts to the disease causing agents, particularly in the site of infection; later, the reaction becomes more widespread and histological changes take place; such changes are expressed as different types of symptoms of the disease which can be visualized macroscopically; and as a result of the disease, seaweed growth is reduced, deformed or even dies.

Disease occurrence is generally driven by the interactions of three factors (Agrios, 2005; Garret *et al*., 2009): a susceptible host population; the presence of a competent endophyte/malaise; and a conducive (biotic and abiotic) environment (Figure 9).

FIGURE 9.
Infection triangle



Despite the advances in seaweed farming, disease occurs, especially in areas where stocking is intensive. Table 14 shows a summary of seaweed diseases caused by bacteria, fungi and epiphytes.

TABLE 14.
Summary of seaweed diseases and epiphytism

Species	Disease name	Causative organism(s)	Symptoms/effects	References
Red seaweeds				
Chondrus crispus	Fungal parasite	Fungal parasite (*Petersenia pollagaster*)	Cavities and holes in fronds	Craigie & Correa, 1996
C. crispus	Green spot or green rot	Pathogen *Lautitia danica*	Infecting both cystocarpic and tetrasporangial region	Wilson & Knoyle, 1961; Schatz, 1984; Stanley, 1992
C. crispus		Endophyte *Acrochaete heteroclada* and *A. operculata*	Disrupts the cortica tissue of the host, slowing growth and decreasing the capacity for regeneration	Correa & McLachlan, 1991, 1992, 1994; Bouarab *et al.*,1999, 2001; Potin *et al.*, 1999, 2002; Brown *et al.*, 2003; Weinberger *et al.*, 2005
Gracilaria chilensis		Endophytic amoeba	Whitening, thallus decay and fragmentation	Correa & Flores, 1995; Buschmann *et al.*, 2001
G. tenuistipitata	White canopy disease or colourless disease	Unknown, though probably similar to "ice-ice" in *K. alvarezii*		Phap & Thuan, 2002
G. heteroclada	Red spots	Agar-digesting bacteria; *Vibrio* sp.	White to pinkish discolouration and gradual disintegration of the thallus	Lavilla-Pitogo, 1992
Kappaphycus alvarezii; *K. striatus*	Ice-ice	*Pseudomonas, Flavobacterium* and Actinobacteria	Slow growth and greening of tissue	Uyenco, Saniel & Gomez, 1977; Largo *et al.*, 1995a, 1995b, 1999
Eucheuma denticulatum	Ice-ice	Marine-derived fungi (complex)	Whitening of thallus; softening of the branches or parts of branches; development of white spots of dead tissue; and thallus fragmentation	Solis, Draeger & dela Cruz, 2010
E. denticulatum		*Penicillium waksmanii*		Dewey, Donnelly & Foster, 1983
E. denticulatum		*Scopulariopsis brevicaulis*		Dewey, Hunter-Blair & Banbury, 1984
K. alvarezii; *K. striatus*	Endophytic filamentous algae (EFA)	*Neosiphonia* savatieri; red filamentous algae	Black goosebumps; presence of fine filamentous red algae; thallus fragmentation	Critchley *et al.*, 2004; Hurtado & Critchley, 2006; Hurtado *et al.*, 2006; Vairappan, 2006; Vairappan *et al.*, 2008; Liu *et al.*, 2009; Pang *et al.*, 2011, 2012, 2015; Ateweberhan, Rougier & Rakotmahzo, 2015
K. alvarezii; *K. striatus*	Endophyte	*Colaconema infestans*	Red endophytic filaments; alters the morphology and cellular organization breakdown of cell wall	Araujo *et al.*, 2014
K. alvarezii; *K. striatus*		*Polysiphonia* sp.		Tsiresy *et al.*, 2016

(cont.)

Species	Disease name	Causative organism(s)	Symptoms/effects	References
Red seaweeds				
Palmaria palmata		Copepods (*Thalestris rhodymeniae*)	Galls or pinholes	Apt, 1988; Park *et al*., 1990
Pyropia yezoensis	Green-spot disease	*Flavobacterium* sp., *Pseudoalteromonas* sp., *Vibrio* sp., Gram-negative bacteria	Lesions with wide green borders; slimy rots and holes in the blade	Nakao *et al*., 1972
P. yezoensis	Olpidiopsis disease	*Olpidiopsis pyropiae*; Oomycete	Bleached portions on the blades; appearance of greenish lesions; formation of numerous holes, followed by disintegration of the entire blade	Klochkova *et al*., 2016
P. yezoensis	Diatom felt	*Flagellaria* sp., *Licmophora fabellata, Melosira* sp., *Navicula* sp./Bacillariophyceae	Dirty surface of blade; bleaching of blade	
P. yezoensis	Red-rot disease	*Pythium porphyrae*/Oomycete	Red patches on the blade; blade's colour changes from natural brown, red to violet-red formation of numerous holes, followed by disintegration of the blade	Ding & Ma, 2005
P. yezoensis	Cyanobacteria felt	Filamentous and coccoid blue-green algae, cyanobacteria	Dirty surface of blade; lesions and holes in the blade	
P. yezoensis	White spot disease	*Phoma* sp., Coelomycetes.	Bleaching of oyster shell with shell- boring conchocelis	Tsukidate, 1971; 1977
P. yezoensis	Suminori disease	*Flavobacterium* sp.		
Green seaweeds				
Ulva lactuca	Pigmented marine bacteria	*Pseudoalteromonas* sp.	Surface covered by the bacteria, preventing the colonization of other seaweeds and invertebrate larvae	Egan *et al*., 2001
Brown seaweeds				
Alaria esculenta	Hollowing of stipes; stipe blotch disease	Amphipod *Amphitholina cuniculus*; ascomycete *Phycomelaina laminariae*	Boring of stipes and production of hollow	Myers, 1974; Chess, 1993
Macrocystis pyrifera	Black rot; hollowing of stipes	Unidentified parasitic micro-organism; amphipod *Peramphithoe humeralis*	Boring of stipes and production of hollow	Rheinheimer, 1992; Chess, 1993
Saccharina digitata	Stipe blotch disease	Ascomycete *Phycomelaina laminariae*	Hyphae of *P. laminariae* penetrate the surface, leading to necrotic tissue and reduced overall performance	
S. digitata		*Ascomycete Ophiobolus laminariae*	Blackened patches of stipes	Sutherland, 1915

(cont.)

Species	Disease name	Causative organism(s)	Symptoms/effects	References
Brown seaweeds				
S. digitata		Ascomycete *Petersenia sp.*	Damaged stipes	Kohlmeyer, 1968
S. digitata		Unknown hyphomycete	Contortion of the blade and blackening of the stipe	Kohlmeyer, 1968
S. digitata		Endophyte *Entocladia viridis*		Nielsen, 1979
S. digitata		Endophyte *Laminariocolax tomentosoides*		Pedersen, 1976; Burkhardt & Peters, 1998
S. digitata		Endophyte *Laminariocolax tomentosoides* spp. deformans	Galls and stipe coiling	Peters, 2003
S. digitata		Endophyte *Laminariocolax aecidioides*	Host thalli becoming thicker and stiffer, lowering their market value	Peters, 2003
S. japonica	Red spots	Bacterial flora (*Flavobacterium*; *Cytophaga*)	Lytic action on the viable cells	Ezura *et al*., 1988
S. japonica		Marine bacterium (*Pseudoalteromonas bacteriolytica*)	Unique bacteriolytic activity and that induces damages	Yumoto *et al.,* 1989a; Yumoto *et al*., 1989b
S. japonica		Proteobacteria like *Alteromonas*, *Vibrio*	Detachment of gametophytes and young sporophytes from the ropes	Ezura *et al*., 1988, Yamada *et al*., 1990
S. japonica	Green rot	*Pseudoalteromonas* and *Pseudomonas*	Marginal portions of the diseased fronds turned greenish, become soft, decay and disintegrate	Tang *et al*., 2001; Liu *et al*., 2002
S. japonica	White rot		Development in green rot, only the fronds turn white due to strong sunlight, high water temperature and lack of nutrients	Andrews, 1976
S. japonica	Malformation disease	Sulfate-reducing bacteria (*Micrococcus*)	Plasmolyzed oogonial and abnormal, malformed sporelings, which subsequently die and drop off the cultivation lines	Wu *et al.,*1983
S. japonica	Falling-off disease	Alginic decomposing bacteria (*Pseudomonas*)	Sporelings falling off from the seeding ropes, especially during summer	Chen *et al.,* 1979
S. japonica	Frond-twist disease	Polymorphic mycoplasma-like organism, (coccoid, ovoid dumbbell, amoeboid shape)	Subnormally twisted fronds with great swollen stipes and very shortened rhizoidal holdfast	Wang *et al*., 1983; Wu et *al*., 983; Tsukidate, 1991
S. japonica	Hollowing of stipes	Amphipod *Ceinina japonica*	Boring of stipes and production of hollows	Akaike *et al*., 2002
S. latissima	Stipe blotch disease	Ascomycete *Phycomelaina laminariae*	Hyphae of *P. laminariae* penetrate the surface, leading to necrotic tissue and reduced overall performance	
S. latissima		Endophyte *Entocladia viridis*		Nielsen, 1979

(cont.)

Species	Disease name	Causative organism(s)	Symptoms/effects	References
Brown seaweeds				
S. latissima		Endophyte *Laminariocolax tomentosoides*		Lund, 1959
S. latissima		Endophyte *Laminariocolax aecidioides*	Host thalli becoming thicker and stiffer, lowering market value	Peters & Ellertsdottir, 1996; Heesch & Peters, 1999; Peters, 2003
Undaria pinnatifida	Spot rotting	*Aeromonas, Flavobacterium, Moraxella, Pseudomonas* and *Vibrio*		Kimura, *et al*., 1976
U. pinnatifida	Shot-hole disease	*Vibrio*	Brown spots appearing on the thallus blade near the midrib, which subsequently fuse together and spread onto the pinnate part of the blade	Tsukidate, 1991
U. pinnatifida	Green spot disease/rot	Unspecified bacteria	Small holes with green margins	Ishikawa & Saga, 1989; Vairappan *et al*., 2001; Kang, 1982
U. pinnatifida	Green decay disease	*Aliivibrio logei*		Jiang *et al*., 1997
U. pinnatifida	Yellow hole disease	Unspecified bacteria	Small holes with yellow margins	Ishikawa & Saga, 1989; Vairappan *et al*., 2001; Vairappan *et al*., 2001
U. pinnatifida	Spot rotting	Unspecified bacteria		Kito, Akiyama & Sakasi, 1976
U. pinnatifida	Spot decay	Bacterium *Halomonas venusta*		Ma *et al*., 1997a, 1997b, 1998
U. pinnatifida	Pin hole	Frond-mining nauplii of harpacticoid copepod *(Amenophia orientalis, Parathalestris infestus*, *Scutellidium* sp. and *Thalestris* sp.)		Tsukidate, 1991; Ho & Hong, 1988; Rho *et al*.., 1993
U. pinnatifida	Tunnel	Gammaridae amphipod*, Ceinina japonica*	Invades the midrib of *U. pinnatifida* through the holdfast and bores a tunnel, which may cause the longitudinal separation of the entire frond through the midrib	Kang, 1982
U. pinnatifida	Chytrid blight	Oomycete, *Olpidiopsis*	The fungus affects sporophytes, where it grows inside host cells, killing them slowly	Tsukidate, 1991
U. pinnatifida	Endophytic brown alga	*Laminariocolax aecidioides*	Host thalli becoming thicker and stiffer, lowering their market value	Akiyama, 1977; Yoshida & Akiyama, 1978

3.2 Social and financial

Issues on social problems pertinent to seaweed farming stem from the unacceptability by the community to the introduction of a novel farming system. This is brought on mainly if such farming system affects the immediate environment.

One of the biggest problems of seaweed carrageenan farming is the accessibility to financial assistance, especially in areas where cyclones or typhoons occur, such as the Philippines. Normally, farming structures and propagules are destroyed when the typhoon signal is No. 2 or higher. The capacity to rehabilitate is a major problem. The need to have crop insurance in seaweed aquaculture activity is important so that in times of calamities seaweed farmers can claim a certain amount of the lost crop and structures to restart farming.

4. IMPACT OF SEAWEED FARMING

4.1 Socio-economic impact

The comprehensive report of Valderamma *et al*. (2013), which includes six case studies of carrageenan seaweed farming in six different countries (India, Indonesia, Mexico, the Philippines, Solomon Islands and the United Republic of Tanzania), attests to the economic benefits of *Kappaphycus* farming in the tropics and subtropics. In the temperate countries, reports include an economic analysis of *Laminaria digitata* farming in Ireland by Edwards and Watson (2011); a cost analysis for ethanol produced from farmed seaweeds by Philippsen *et al.* (2014); a new bioeconomy for Norway by SINTEF (2014); and economic feasibility of offshore seaweed production in the North Sea by Van den Burg *et al*. (2013). All these reports clearly show that seaweed farming is economically beneficial to farmers in particular and the local and national economy in general.

4.2 Ecological and environmental impact

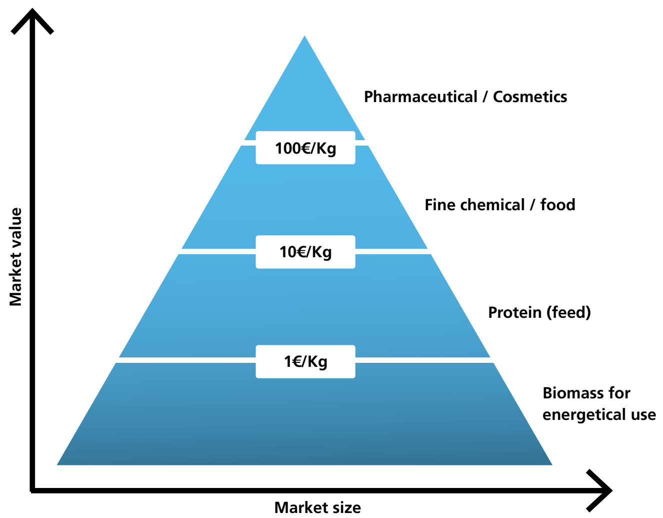
Seaweed farming is an extractive aquaculture whose process of production of valuable biomass renders various ecosystem services with ecological and economic values (Chopin *et al*., 2008, 2010; Neori *et al*., 2007; Radulovich *et al*., 2015). Seaweed farming adds oxygen during photosynthesis and cleans seawater from excess nutrients (nitrogen, phosphorus and others). Nutrient extraction, or uptake, cleans water effectively and thoroughly through a process known as bioremediation (Forster, 2008). Seaweed farming enhances biodiversity and fisheries (Radulovich *et al*., 2015). Seaweeds are carbon sinks that can reduce ocean acidification through uptake of CO_2 from water.

Among the red seaweeds being farmed, *Kappaphycus* is drawing much attention in places where it is being introduced. The literature shows that this seaweed is endemic in the tropics such as Indonesia, Malaysia and the Philippines; its first successful commercial farming was reported in the Philippines in the early 1970s (Doty, 1973; Parker, 1974; Doty and Alvarez, 1981). Since then, it has been introduced in almost 30 countries worldwide. Such introduction without prior scientific and quarantine protocols and proper management led to some negative impacts in Hawaii, United States of America (Rodgers and Cox, 1999; Smith *et al*., 2002; Conklin & Smith, 2005), and in India (Chandrasekaran *et al*., 2008), where the plant became invasive.

5. DRIVERS OR MOTIVATIONS TO PURSUE OR EXPAND FARMING

The expansion or increase in seaweed farming in terms of production is mainly due to increasing demand for food, feed (animal) and, recently, fuel. The global demand for seaweed biomass is rising. Large companies using algae in their products require a regular and reliable supply of the material, both in quantity and quality. Western Europe, for example, will continue to improve farming techniques to increase production, mainly because of the high market value of the different products derived from seaweeds (Holdt, 2011). Figure 10 shows the pyramid of the seaweed product markets.

FIGURE 10.
Pyramid schematic of seaweed product markets



5.1 Food

Asian countries will continue to consume seaweeds as part of their daily diet. There is a rising awareness of health and nutritional benefits from seaweeds in western countries. Likewise, there is a growing use by food processors in new applications that include seaweed pasta, mustard, rillettes and pâtés. Also, there is a high demand from the catering and food service sector that requires seaweed recipes. Hence, cultivation of economically important seaweed will expand as the population grows.

5.2 Feed (aquaculture)

The commercialization of land- and sea-based IMTA in Western Europe will open more opportunities to an immense use of seaweed as part of the diet of fish such as salmon, rainbow trout, cod, sea bass and other high-value fish. This is simply because several earlier studies have demonstrated the positive effects not only in terms of the increased growth rate, but more importantly, on the prevention of diseases (Wan *et al*., 2016; Walker *et al*., 2009; Valente *et al*., 2006). Likewise, hogs fed with seaweed resulted in higher milk production, decreased mortality by 50 percent, reduction in the use of antibiotics by 50 percent, generally improved health, reduced feed intake (gut health), earlier maturation, improved taste (industrial taste panel), and doubled omega-3 content (Kraan, 2015). The high demand of seaweed-fed abalone will continue, as the growing population prefers traceable marine food. The newly emerged application of seaweed in the shrimp diet will be developed and refined further. For these reasons, responsible and sustainable farming of seaweed will increase in the next few years.

5.3 Fuel

Traditionally, seaweeds have not been considered as feedstock for bioenergy production, but have been used in food, in medicine or as fertilizer, and in the processing of phycolloids and chemicals (Bixler and Porse, 2011). The cultivation of algal biomass for the production of third-generation biofuels has received increasing attention in recent years, as seaweeds can be produced in the marine environment and on non-arable lands. Production yields of algae per unit area are significantly higher than those for terrestrial biomass (Wei, Quarterman and Jin, 2013; Schenk *et al*., 2008). The chemical composition of algae makes it suitable for conversion into biofuels, especially the subtidal large brown kelps of the order Laminariales (Hughes *et al*., 2013) and *Ulva* (Bruton *et al*., 2009).

Seaweeds are already farmed on a large scale in Asia and to a lesser extent in Europe, primarily in France, and on a research scale in Scotland (Kelly and Dworjanyn, 2008). Western Europe, Ireland in particular, is becoming aggressive in research and development for a marine bioenergy and biofuel industry (Roberts and Upham, 2012). Biofuel production from macro-algae is in its infancy. There is a strong collaboration in the private sector, such as Statoil ASA, which entered into a partnership with Seaweed Energy Solutions AS (SES) and Bio Architecture Lab (BAL) to develop a macroalgae-to- ethanol system in Norway. The aim of the partnership is to develop a 10 000 ha seaweed farm off the coast of Norway, which will produce 200 000 tonnes of ethanol (equivalent to 2 percent of the European Union's ethanol market) (Ystanes and Fougner, 2012). SES is developing the technology for large-scale cultivation and harvesting technology, while BAL is responsible for developing the technology and the process to convert the macro-algae into ethanol (Murphy *et al*., 2013).

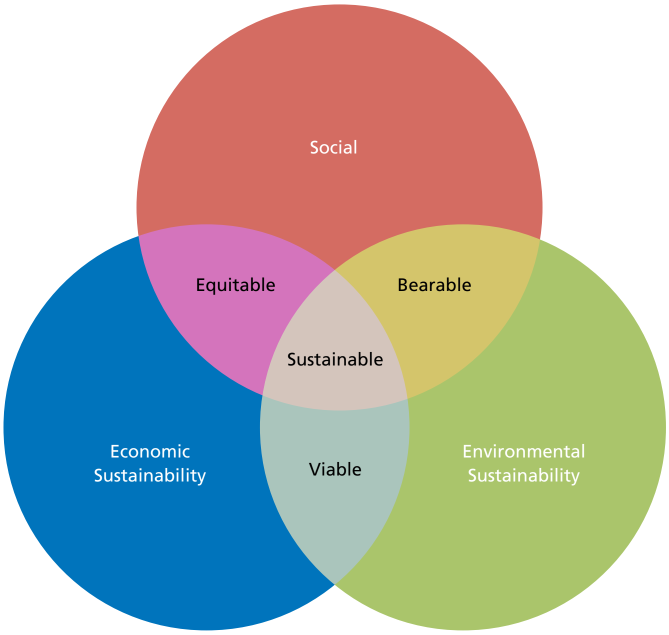
Though several preliminary investigations have been conducted to assess the technical feasibility, environmental viability and economic profitability of seaweed farming for fuel (Watson, 2014; Valderamma *et al*., 2013; Watson *et al*., 2012), numerous parameters (such as method of cultivation, species of seaweed, yields of seaweed per hectare, time of harvest, method of harvesting, suitability of seaweed to ensiling the gross and net energy yields in biogas, carbon balance, cost of the harvested seaweed, and cost of the produced biofuel) have to be developed economically to obtain viable algae biofuel production.

6. CONSERVATION AND SUSTAINABLE USE STRATEGIES

Conservation is a careful preservation and protection of resources that includes a well-planned management of the natural resources to prevent exploitation, destruction or neglect. There is biodiversity of seaweeds within species, between species, and ecosystems, with each species having its own peculiar characteristics to adapt in a certain habitat. Seaweeds, both harvested and farmed, are important sources of livelihood to humans. Conserving and sustaining these resources for the benefit of mankind are imperative.

A sustainable livelihood is one that can be carried out over the foreseeable future without depleting the resources it depends upon and without depriving others of a livelihood. In order for a livelihood to be sustainable, there should be: economic development; social equity; and environmental protection. Sustainable development can be achieved if decisions are made to be economically profitable, biologically appropriate and socially acceptable (Figure 11) (Eigner-Thiel *et al*., 2013) (Circular Ecology, 2016).

FIGURE 11:
Sustainability paradigm (http://www.circularecology.com)



Currently, intensive fed aquaculture (finfish and shrimp) throughout the world is rapidly increasing, making environmental impact the main concern. This concern pertains to the direct discharge of significant nutrient loads into coastal waters from open waters and with the effluents from land-based systems. The only way to mitigate this environmental concern is to adopt an aquaculture system that is sustainable and balanced, a system known as integrated multi-trophic aquaculture (IMTA) (Chopin *et al*., 2001). Aquaculture is the world's fastest growing food production sector, and is associated with environmental, economic and societal issues. IMTA offers an innovative solution for environmental sustainability, economic stability, and societal acceptability of aquaculture by taking an ecosystem-based management approach. IMTA is the farming, in proximity, of aquaculture species from different trophic levels and with complementary ecosystem functions, so that one species' excess nutrients are recaptured by the other crops and synergistic interactions among species occur (Chopin *et al*., 2013). By integrating fed aquaculture (finfish, shrimp) with inorganic and organic extractive aquaculture (seaweed and shellfish), the wastes of one resource user becomes a resource (fertilizer or food) for the others. Such a balanced ecosystem approach provides nutrient bioremediation capability, mutual benefits to the co-cultured organisms, economic diversification by producing other value-added marine crops, and increased profitability per cultivation unit for the aquaculture industry.

In order for seaweed farming to be sustainable, the following actions are to be implemented: expansion of farming areas, wherever possible and profitable, and subject to the needs of other sectors and environmental health; improvements in productivity through the development and wide adoption of better aquaculture practices, to include improved quality of seed supply, establishment of land-sea based nurseries, including innovative approaches such as IMTA; increased investment in research, development and extension (RD&E) to meet expected challenges, including disease risks, climate change and introductions of non-indigenous species; and strong collaboration among government agencies, academia and the private sector. Table 15 presents the conservation and sustainability strategies for farmed seaweeds.

TABLE 15.
Conservation and sustainable strategies for farmed seaweeds

Conservation and sustainable strategies	Action plans
Capacity enhancement of human resources	• Active enhancement of public promotion and environmental education through regular training/workshops/seminars • Cross-country/area visits to successful seaweed areas/farmers • National and international collaboration and networking • Improve scientific knowledge and strong cooperation with local and international societies and stakeholders working on the conservation of marine resources
Diversified livelihood	• Introduction of invertebrate aquaculture and sea-ranching, such as sea urchins, sea cucumbers and sea abalone and other high-value animals, instead of fisheries/capture in areas where there is natural population • Cultivation of other economically important seaweeds with bioactive, biofuel, pharmaceutical, cosmetic and nutraceutical potential
Ecosystem- based management	• Adaption of better aquaculture practices > Sufficient buffer space between lines and farms to allow free water movement > Reduction of the number of farms in dense cultivation areas to include maximum carrying capacity > Use of appropriate cultivation method suitable to the environmental conditions of a given area > Use of biodegradable planting materials • Proper zoning of aquaculture activities • Adaption of a no-no policy of placing seaweed farms near or on top of coral reefs or in marine protected areas • Prevention of marine pollution coming from inland domestic and industrial effluents and sea-oil pollution

(cont.)

Conservation and sustainable strategies	Action plans

Secured sustainability	• Large-scale production
	  > Production on a large scale in order to secure profitability, stable operation of the production facilities, and build up a buyer’s market
	  > Maximizing the potential of macro-algae using the biorefinery approach
	• Products
	  > Development of other product applications of agarophytes, carrageenophytes, alginophytes and some green macro-algae
	  > Development of biorefinery processes, which make possible parallel utilization of several components (pharmaceuticals and cosmetics, food and feed, bioplastic and polymers, bulk chemicals and fuel, and heat and energy)
	  > Development and testing of animal feed based on seaweed biomass
	  > Securing marketing channels and maturing of the market for seaweed and products based on seaweed
	  > Strong cooperation between industry, academia/research centres and government authorities

7. CAPACITY BUILDING

7.1 Education

Development of human resources through scholarships and fellowships is encouraged, especially in developing countries, to pursue professional and personal advancement in the different fields of specialization in seaweeds for graduate and post-graduate programmes. Such education will prepare students to embark in tougher responsibilities needed in the community and the industry. A number of scholarships are being offered by developed countries, such as Australia, European countries, Japan, United Kingdom of Great Britain and Northern Ireland, and the United States of America, and are highly competitive.

7.2 Research and training

Skills training is designed both to improve student effectiveness as researchers and to equip them with the skills they will need in a career after graduating, whether to choose to follow an academic or a non-academic career path. The structure and design of PhD programmes should incorporate generic skills and be formulated with direct engagement with employers and enterprises where appropriate.

Worldwide, state universities and colleges as well as research centres have good programmes for seaweed research and training. Students and trainees are given the opportunity to conduct research according to the needs of the industry under the supervision of a professor or a scientist. They are trained to: conceptualize and write a proposal; conduct the study with little supervision; collect, analyse and interpret the data; make conclusions; write a manuscript for publication; and share the results with the scientific community through attendance at symposia and congresses.

It is in the stage of research and training that individuals will establish a strong working relationship with their mentor, peers, the private sector and the scientific community.

8. ROLE OF INTERNATIONAL AND REGIONAL ASSOCIATIONS IN THE DEVELOPMENT AND MANAGEMENT OF FARMED SEAWEEDS

There are several international and regional associations that are involved in the development and management of farmed seaweeds, as shown in Table 16. These associations have different mandates to fulfil for the betterment of the community and industry.

TABLE 16.
International, regional and local associations, organizations and societies engaged in seaweed research and other related activities

Location	Name of organization/ society	Objectives
Asia-Pacific	Asian Pacific Phycological Association	• Develops phycology in the Asia-Pacific region, to serve as a venue for the exchange of information related to phycology and to promote international cooperation among phycologists and phycological societies in the Asia-Pacific region • Holds meetings at least once every three years
Asia-Pacific	Asia-Pacific Society for Applied Phycology	• Cooperates with national and international phycological organizations.
Australia	Australasian Society for Phycology and Aquatic Botany	• Promotes, develops and assists the study of, or an interest, in phycology and aquatic botany within Australasia and elsewhere • Establishes and maintains communication with people interested in phycology and botany
China	China Algae Industry Association	• Promotes the rationalization of alga, producing and processing product mix, management system and business organization • Contributes to the alliance of industry, agriculture and business • Coordinates the relation of production, supplement and marketing
China	Chinese Phycological Society	• Builds China's largest professional information service platform, science and technology innovation platform, and brand promotion platform for the algae industry
Europe	British Phycological Society	• Advances education by the encouragement and pursuit of all aspects of the study of algae and publishes the results of the research in a journal as well as other publications. • Publishes the British Journal of Phycology and the newsletter, The Phycologist
Europe	Federation of European Phycological Societies	• Provides a forum for all European phycological societies and individuals with an interest in phycology; enables, promotes and enhances algal (including cyanobacterial) research, education and other activities; increases public awareness of the importance of algae and cyanobacteria; and contributes to public debate and policy issues involving these organisms throughout Europe
Europe	Hellenic Phycological Society	• Promotes basic and applied phycological research, organizes congresses, and develops international relationships
Indonesia	Asosiasi Rumput Laut Indonesia	• Develops downstream seaweed industries to create more added value from this marine commodity and to create job opportunities

(cont.)

Location	Name of organization/ society	Objectives
Japan	Japanese Society of Phycology	• Promotes research that is related to algae and phycology and serves as a central hub of people who are interested in phycology
Republic of Korea	Korean Society of Phycology	• Promotes publications of algae, which deal with phylogenetics, taxonomy ecology and population biology, physiology and biochemistry, cell and molecular biology, and biotechnology and applied phycology • Publishes the journal Algae
Philippines	Philippine Phycological Society, Inc.	• Promotes the science of phycology in the Philippines
Philippines	Seaweed Industry Association of the Philippines	• Develops better technology for growing and processing better quality colloids in alliance with academic institutions and international associations
South America	Brazilian Society of Phycology	• Gathers together people and institutions interested in the development of phycology • Promotes and stimulates teaching and research on algae and other photosynthetic aquatic organisms
South America	Chilean Phycological Society	• Promotes phycological research, and the development, scientific knowledge and protection of the phycological flora in Chile
Southeast Asia	ASEAN Seaweed Industry Club	• Promotes strong cooperation and networking among the ASEAN countries
Spain	Spain Phycological Society (Sociedad Española de Ficologia)	• A forum of national and foreign professionals interested in the world of algae • Establishes partnerships between phycologists, public and private research organizations, and companies interested in the study and applications of algae
United States of America	International Phycological Society	• Develops phycology; distributes phycological information; cooperates among international phycologists and phycological organizations; and convenes the International Phycological Congress every four years
United States of America	International Seaweed Association	• Convenes the International Seaweed Symposium every three years, the leading global forum for researchers, industrial companies and regulators involved in the seaweed sector
United States of America	International Society for Applied Phycology	• Promotes research, preservation of algal genotypes and the dissemination of knowledge concerning the utilization of algae
United States of America	Marinalg International	• Promotes the image and uses of seaweed-derived hydrocolloids in food, pharmaceuticals and cosmetics
United States of America	Phycological Society of America	• Promotes research and teaching in all fields of phycology; publishing the Journal of Phycology

9. SOURCES OF INFORMATION

9.1 Regional and international centres

Only a few countries and regions have their own seaweed centres that cater to the needs of the industry and community. The western countries have centres dedicated mainly for basic and applied research on algae that may be absent in the developing countries. However, a small research laboratory is normally present in the university or in fisheries institutions. Table 17 lists international centres that have strong collaboration with other institutions/academia or industry in and out of the region with their respective mandates.

TABLE 17.
Some international algae centres

Name and website	University/private sector	Mandate
AlgeCenter Danmark (www.algecenterdanmark.dk)	Aarhus University; Kattegatcentret; Danish Technological Institute	Research in the areas of: biorefinery; algae growing; and energy production dedicated to the study and enhancement of algae (macro and micro) marine plants and marine biotechnology
Centre d'Etude et de Valorisation des Algues (CEVA) (www.ceva.fr)	Pleubian, France	
MACRO – the Centre for Macroalgal Resources & Biotechnology (https://research.jcu.edu.au/macro)	James Cook University, Australia	Develops and commercializes marine and freshwater macroalgae for fuel, feed and fertilizer applications
Norwegian Seaweed Technology Center (www.sintef.no)	SINTEF Fisheries and Aquaculture; SINTEF Materials and Chemistry; Norwegian University of Science and Technology (NTNU); Department of Biology; Department of Biotechnology	Develops technology within industrial cultivation, harvesting, processing and application of seaweed in Norway
Seaweed Energy Solutions AS (www.seaweedenergysolutions.com)	Norway, Portugal and Denmark	Focuses on large-scale cultivation of seaweed primarily for energy purposes

The biggest storage of seaweed information in terms of taxonomy, description and distribution is found in www.algaebase.org. All universities and research institutions that have seaweed programmes have a herbarium of their local species, as well as algae journals and books in their libraries.

9.2 Dissemination, networking and linkages

Scientific knowledge coming from research can be disseminated through the following ways: publication in peer-reviewed journals, symposium proceedings and books; presentation of results in different symposia and congresses; and writing in popularized magazines, newsletters, brochures and flyers for the industry.

Networking is important in the seaweed community. There is a need to work together to develop sea agriculture, or sea farming, in order to cater to the needs of the industry. Vertically integrated supply chains request a lot of energy from small companies. There is a need to improve the value chain for better efficiency and maximize shared benefits among the seaweed community. There are mutual benefits and assistance derived from linkages and networking activities with both local and international organizations. Linkages and networking are different in the degree of commitment by the partners. In linkages, the relationship between partner organizations is quite loose. It intends to serve the members of both sides according to their respective needs, interests and objectives. It creates bonds together to solicit support and assistance for purposeful activities. Networking, on the other hand, is much stronger, usually because the groups and agencies have common objectives and beneficiaries. Networking is basically about extending the outreach of the resources in different ways so as to increase the effectiveness of the programme. The areas of operation can also be increased through networking. A network is composed of several institutions, universities or research centres that bind together for a common goal. They work together to attain common objectives, undertake innovative practices, and update members regarding breakthroughs in different disciplines. Table 18 lists some of the active networks in different regions.

TABLE 18.
Various networks involved in seaweed farming and allied activities

Network	Objectives
Asian Network for Using Algae as CO_2 Sink	Encourages collaboration among member countries in conducting research in sustainable CO_2 removal by marine-life mechanisms
Canadian Integrated Multi-Trophic Aquaculture Network	Provides interdisciplinary research and development and highly qualified personnel training in the following linked areas: ecological design, ecosystem interactions and bio mitigative efficiency; system innovation and engineering; economic viability and societal acceptance; and regulatory science
Danish Seaweed Network	Promotes the production, application, communication and knowledge of seaweed, and also to strengthen the national collaboration.
Global Seaweed Network	Develops a programme, which over the next 5–10 years will enhance and develop the global seaweed community into an internationally recognized and respected scientific body that can innovate, provide knowledge and tools for scientific research, aquaculture, conservation and society, influence policymakers, and enable economic progress
Nordic Algae Network (Denmark, Iceland, Norway, Sweden).	Analyses the results that will establish a best practice model and suggests policies for the successful sustainable commercial utilization of marine macro-algae resources Helps the partners to a leading position in the algae field for commercial utilization of high-value products and energy from algae

(cont.)

Network	Objectives
Norwegian Latin American Seaweed Network. Norwegian Seaweeds Network.	Increases the synergy and facilitates collaboration between partners Encourages cooperation among the seaweed stakeholders across Latin America and Europe in order to support the development of the seaweed sector
REBENT (France – national network coordinated by IFREMER)	Strengthens interest and knowledge of benthic algal taxonomy, systematics and species identification, and promotes collaboration and exchange of information Collects and organizes data concerning marine habitats and benthic biological communities in the coastal zone to provide relevant and coherent data to allow scientist administrators and the public to better determine the existing conditions and detect spatiotemporal evolution

10. EXCHANGE PROGRAMMES

10.1 Information

Science and technology provide critical tools that help address national and global needs. Freedom of scientific exchange and stronger scientific collaboration to benefit humankind is of paramount importance. Open exchange of information and ideas is critical to scientific progress. To achieve this end, there should be: promotion of a strong, non-governmental, scientific publishing enterprise that ensures access to information and exchange of scientific ideas and information among all parties with legitimate uses while appropriately protecting copyright and security-related information; assurance of the quality of science and technological advancement through open, rigorous and inclusive peer review scientific publishing; and open interactions among scientists, engineers and students from across the globe.

Developments in computer technology have opened many opportunities to gain access to multiple systems to gather data or exchange information. Open access and exchange of information is one of the core values of academics. Open access is part of the open science movement and covers various initiatives and projects across the globe to make academic studies and results available to a wider readership. As open access publications are available free of charge throughout the world, even people in poorer countries who usually lack the financial means can access and use them.

Regular members of the International Seaweed Association have free access to the *Journal of Applied Phycology*, a journal that publishes articles on microalgae and macroalgae (seaweeds) with four issues each year.

10.2 Scientists and experts

Scientists and experts play crucial roles in the exploitation, management, conservation and sustainability of seaweed resources. Results of their scientific studies are used to formulate policies for the government to adapt for implementation.

According to Dr Houde of the Chesapeake Biological Station, United States of America, scientists have the difficult task of walking the fine line between traditional "science-worthy" science or making the news. Traditional science takes time, as the peer review process is typically a slow one, even though it helps to minimize errors. Often, it moves too slowly for policy, which has now begun to turn to "post normal" science, which pools the collective advice of experts.

Seaweed farming is centred on the management of the environment and sustainability of the commodities. It takes several years for scientists and experts to transfer the science-based technology to the industry. Trials of farming *Kappaphycus* and *Eucheuma* in the Philippines started in 1965 and it was only in 1971 that the first harvest of seaweed for export purposes was attained (Doty and Alvarez, 1981). Also, the introduction of IMTA in Canadian waters started as early as 2000 and became commercial several years after. Though biological and economic results were positive, social acceptability was a critical component in aquaculture sustainability (Barrington, Chopin and Robinson, 2009). Scientists and experts, together with the different stakeholders, met several times to discuss the importance and significance of IMTA. All agreed that IMTA has the potential to reduce the environmental impacts of salmon farming, benefit community economies, and improve industry competitiveness and sustainability. This successful aquaculture system is currently being replicated either on an experimental or near commercial stage in Western Europe (Holdt and Edwards, 2014; Lamprianidou, Telfer and Ross, 2015; Freitas, Morrondo and Ugarte, 2016).

Scientific and technological development is impossible without efficient communication between scientists or technologists and the community. Such that, a higher level of scientific research can be achieved through collaboration.

10.3 Test plants

Only test plants preserved in silica gels and dried samples previously soaked in 10 percent formaldehyde and later drained are allowed to be sent by courier to other universities or institutions outside from its point of origin for collaborative work. This is especially true in developing countries, which lack the facilities to analyse the samples for a specific test. The test plants serve as the share of the collaborative study, and ultimately, part of the authorship when the results are written and submitted to a peer-reviewed journal for possible publication. No fresh test plants are allowed by courier for scientific studies. However, live test plants can be brought by a scientist personally after proper documents from point of origin to final destination are in order. If no prior agreement is made with the provider of test plants for research and scientific purposes, a due recognition through acknowledgement at the end of the report or paper is appropriate.

11. CONCLUSIONS

The farming of economically important seaweeds for food has been predominantly in Asia for the past several decades and will continue to increase as population increases. On the other hand, the farming of seaweed for feed and fuel purposes will be centred in the western countries. Also, people in western countries are increasing their seaweed consumption as part of their diet for health reasons.

China, Japan and the Republic of Korea are the leading producing countries of brown seaweeds (*Saccharina* and *Laminaria*) and red seaweed (*Pyropia*), while Indonesia and the Philippines are the top leading producers of *Kappaphycus* and *Eucheuma*. It is surprising to learn that Indonesia has surpassed China and Chile in the production of *Gracilaria* since 2013. Indonesia is presently the world's number one producer of farmed red seaweeds, notably *Eucheuma, Gracilaria* and *Kappaphycus.*

Innovations in farming systems are being done because of disease and epiphytism problems brought on by climate change. Seaweed farmers with the technical assistance of scientists and experts will continue to work together for the improvement of crop management, productivity and production. One example of a culture farming modification is the traditional farming of *Kappaphycus*, which has now shifted from shallow waters to deeper waters to avoid elevated surface water temperature that adversely affects productivity and production.

The use of plantlets from spores remains to be used in the laboratory for out planting purposes with improvements in nutrition-temperature-light requirements. Although several successful studies were reported on the regeneration of plantlets of *Kappaphycus* and *Eucheuma* from callus through micropropagation using different culture media, their economic viability in the field needs additional testing, though initial trials have been started. Likewise, the use of seaweed extract as a biostimulant in the micropropagation of *Kappaphycus* has proven successful and field trials are in progress. At present, vegetative propagation still dominates the commercial farming of *Kappaphycus* and *Eucheuma*. The successful crossbreeding of *Saccharina japonica* using gametophytes and sporophytes (Dongfang No. 7) may provide a model for domestication to be used with other brown seaweeds (kelp).

Currently, seaweed genetic transformation is not fully developed despite several studies reported. Because a genetic transformation system would allow to perform genetic analysis of gene function via inactivation and knock-down of gene expression by RNAi and antisense RNA suppression, its establishment will enhance both our biological understanding and genetical engineering for the sustainable production of seaweeds and also for the use of seaweeds as bioreactors.

IMTA as a holistic aquaculture system has been tested to be technically feasible, environmentally friendly, economically viable and socially acceptable in the western countries and China. Its replication in other countries, especially in countries engaged in intensive shrimp and finfish aquaculture, has yet to be introduced or developed.

Conservation and sustainability of farmed seaweeds are the ultimate goals to ensure that the biomass needed for its final product is maintained commercially.

Seaweed international centres, societies, organizations and associations, and networking among scientists and experts will continue to play important and significant roles in the further development and ultimate sustainability of farmed seaweeds, which are good for food, feed and fuel.

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The genetic resources of farmed seaweeds are often omitted from regular aquaculture production reporting by countries despite their significance as a source of: human food; natural colloids for food ingredients, cosmetics, pharmaceutical and nutraceuticals purposes; and feed in aquaculture. This study provides significant data and information on the farmed red, brown and green seaweeds, with a specific focus on the following issues: (i) cultivation – species/varieties, techniques, volume and value of production; (ii) genetic technologies; (iii) major problems of farming seaweeds; (iv) drivers of seaweed farming; (v) conservation and sustainability strategies; (vi) enhancement programs; (vii) regional and international collaborations; (viii) sources of databases; and (ix) exchange programmes.

ISBN 978-92-5-135424-7

CB7903EN/1/01.22