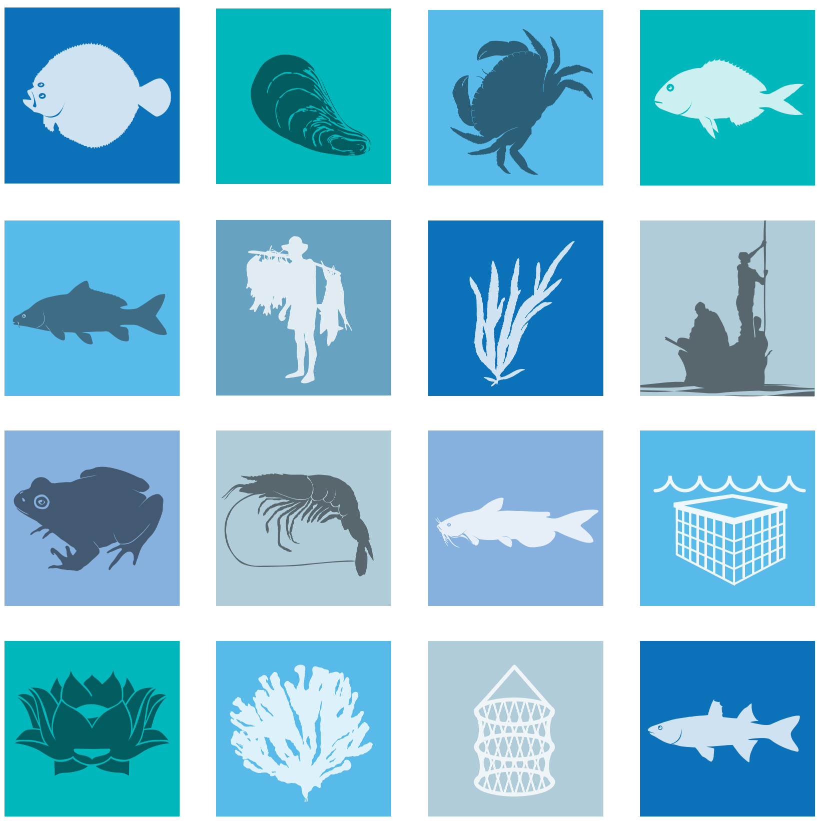
Food and Agriculture Organization of the United Nations

COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE

THEMATIC BACKGROUND STUDY

Genetic Resources for Farmed Seaweeds



Citationa: FAO. forthcoming. *Genetic resources for farmed seaweeds*. Rome.

Contents

List of tables

List of figures

Acronyms and abbreviations

CO_2	carbon dioxide
dwt	dry weight
F1	first generation
F2	second generation
FAO	Food and Agriculture Organization of the United Nations
GUS	glucuronidase
lacZ	bacterial beta-galactosidase
IFREMER	Institut Français de Recherche Pour l'exploitation de la Mer
IMTA	integrated multi-trophic aquaculture
OA	ocean acidification
PGRs	plant growth regulators
Ph.D.	Doctor of Philosophy
PyAct1	*P. yezoensis* actin1 promoter
PyGUS	*P. yezoensis* glucuronidase
RM	Malaysian ringgit
SEA	Southeast Asia
SES	Seaweed Energy Solutions
SINTEF	Stiftelsen for Industriell og Teknisk Forskning ved NTH
SV40	a promoter

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.

Abstract

The genetic resources of farmed seaweeds are often omitted from the State of the World Report despite the significance of these seaweeds as a source of human food; a source of natural colloids as food ingredients for cosmetics, pharmaceutical and nutraceuticals purposes; and a source of feed in aquaculture. Hence, this review has been done to provide significant data and information on the farmed red, brown and green seaweeds based on the following major areas: (i) cultivation – species/varieties, techniques, volume and value of production; (ii) genetic technologies; (iii) major problems of farming seaweeds; (iv) drivers or motivations to pursue farming; (v) conservation and sustainability strategies; (vi) enhancement programmes; (vii) regional and international collaborations; (viii) sources of databases; and (ix) exchange programmes.

Global seaweed farming occurs predominantly in Asia, both for the brown (*Saccharina* and *Undaria*) and the red seaweeds (*Eucheuma, Gelidium, Gracilaria, Kappaphycus* and *Pyropia*), compared with Europe, which is still small in scale and can be found in countries such as Denmark, France, Ireland, Norway, Portugal and Spain. Since the beginning, brown seaweeds (*Saccharina* and *Undaria*) dominated the farming of seaweed globally until it was overtaken by red seaweeds in 2010, which come mainly from the *Kappaphycus* and Eucheuma species. The brown seaweeds are normally farmed in subtemperate to temperate countries, such as China PR, Japan and the Republic of Korea, while *Kappaphycus* and *Eucheuma* are farmed in subtropical to tropical countries, dominated by Indonesia, the Philippines, Tanzania and Malaysia. At present, 29 species of red seaweeds dominate commercial cultivation, followed by 13 species of brown and 11 species of green seaweeds.

There are other red seaweeds that are currently farmed in open seas or brackish-water ponds, or in land- based tanks. These are *Asparagopsis, Chondrus crispus, Gelidium, Gracilaria, Hydropuntia, Palmaria palmata* and *Pyropia*. Among the green seaweeds, *Caulerpa codium, Monostroma* and *Ulva* are farmed for commercial purposes.

Phyco-mitigation (the treatment of wastes by seaweeds), through the development of integrated multi-trophic aquaculture (IMTA) systems, has existed for centuries, especially in Asian countries, as a result of trial and error and experimentation. At present, IMTA is a form of balanced ecosystem management, which prevents potential environmental impacts from fed aquaculture (finfish) and organic (shellfish) and inorganic (seaweed). It is gradually gaining momentum in western Europe and Israel. IMTA is mainly aimed towards higher production of seaweed biomass not only for food and feed purposes, but also as a source of fuel. It also provides exciting new opportunities for valuable crops of seaweeds.

Traditional selection of strains based on growth performance and resistance to "disease" are 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. The development of plantlets from spores for outplanting purposes is still being practised today in some brown (*Saccharina* and *Undaria*), red (*Palmaria* and *Pyropia*) and green seaweeds (*Codium, Monostroma* and *Ulva*). Micropropagation through tissue and callus culture is becoming a popular method in generating new and improved strains in *Eucheuma* and *Kappaphycus*, though its commercial use for farming purposes has yet to be tested further. Vegetative propagation is still widely used, especially in the tropics.

Global climate change is adversely affecting the ecophysiology of farmed seaweeds, leading to decreased productivity and production, primarily in the tropics. "Diseases" and severe epiphytism are two major technical problems of farmed seaweeds.

The main driver for the continued interest in seaweed cultivation has been the potential for the production of large volumes of a renewable biomass, which is rich in carbohydrates and therefore attractive to third-generation biofuel production. Seaweed biomass has a wide range of applications, such as: (i) biobased and high-value compounds in edible food, food and feed ingredients, biopolymers, fine and bulk chemicals, agrichemicals, cosmetics, bioactives, pharmaceuticals, nutraceuticals and

botanicals; and (ii) lower-value commodity bioenergy compounds in biofuels, biodiesels, biogases, bioalcohols and biomaterials. Global consumption of sea vegetables is rising as consumers become more aware of the health and nutritional benefits of these plants. On the other hand, a biorefinery concept for cultivated seaweed biomass that approaches a complete exploitation of all the components in the raw material and that creates added value will likely succeed in the global market in the next few years.

The presence of regional and international networks is of prime importance in the exchange of databases/information, experts, young scientists and test plants in pursuit of an excellent level of competency and efficiency in the conduct of projects.

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 protein, vitamins, minerals, phytohormones and bioactive compounds. Thousands of species of macro-algae (seaweed) dominate the vegetation of the sea floor from the intertidal to the sub-tidal 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 in the Western countries, commercial farming is not yet practised there except in a few countries, such as Chile for *Gracilaria* and *Macrocystis* (Buschmann *et al*., 2001); France for *Palmaria palmata, Pyropia umbilicalis* and *Undaria pinnatifida (Netalgae);* and Canada for *Saccharina latissima* as integrated multi-trophic aquaculture (IMTA) (Chopin *et al*., 2013) and *Chondrus crispus*, to name a few. Trial farming of *Saccharina* and *P. palmata are* now being cultivated in western Europe, some of which are near the commercial stage.

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, Western countries are seriously looking into biorefinery products from seaweeds, which need a vast amount of biomass and which must be derived from farming. Sustainability of biomass must come from farming and not from the harvesting of the natural population.

The world is experiencing climate change, and several reports have shown that seaweeds are an efficient carbon dioxide (CO_2) sink. Seaweed aquaculture beds (SABs) provide ecosystem services similar to those services gained from seaweed beds in natural or wild habitats. The use of SABs for potential CO_2 mitigation efforts has been established, with commercial seaweed production in China PR, India, Indonesia, Japan, Malaysia, the Philippines, the Republic of Korea, Thailand and Viet Nam, and is in the developmental stage in Australia and New Zealand (Chung and Lee, 2014). Seaweed farming is no doubt an aquaculture endeavour that is 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 PR and other countries in Asia have grown seaweeds (also known as macro-algae) at a large industrial scale for the production of food, animal feed, pharmaceutical remedies and 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, it is highly successful and efficient coupled with intensive labour at low costs. On the other hand, an emerging rise in investment from petrochemical companies and governments for projects in Asia, Europe and the Americas aims at extracting sugars from seaweed for ethanol, bio-based diesel, advanced biofuels, drop-in fuels, biobutanol, biochemical and biopolymers.

Low technology cultivation practices can become highly advanced and mechanized, requiring on-land cultivation systems for seeding some phases of the life history 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. High technology, on-land cultivation systems have been developed in a few rare cases, mostly in the Western world, wherein commercial viability can only be reached 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, varieties and strains

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; and the green seaweeds are dominated by *Ulva* with 6 species (Figures 1–3). English and local names of some farmed seaweeds are shown in Table 2.

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*		*racemosa var. macrophysa*
Eucheuma	*denticulatum*	*Macrocystis*	*pyrifera*	*Codium*	*fragile*
Eucheuma	*var. milyon milyon*	*Saccharina*	*digitata*	*Monostroma*	*nitidum*
Eucheuma	*isiforme*			*Ulva*	*compressa*
		Saccharina	*japonica*		*fasciata*
		Saccharina	*latissima*		*intestinalis*
Gracilaria	*asiatica*	*Sargassum*	*fulvellum*		*linza*
Gracilaria	*changii*	*Sargassum*	*horneri*		*pertusa*
Gracilaria	*chilensis*	*Sargassum*	*muticum*		*prolifera*
Gracilaria	*fastigiata*	*Sargassum*	*thunbergii*		
Gracilaria	*firma*	*Undaria*	*pinnatifida*		
Gracilaria	*fisheri*				
Gracilaria	*heteroclada*				
Gracilaria	*lemaneiformis*				
Gracilaria	*manilaensis*				
Gracilaria	*tenuistipitata*				
Gracilaria	*tenuistipitata var. lui 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*				
Pyropia	*umbilicalis*				

FIGURE 1.
Photos of commercially farmed red seaweeds. Photos courtesy of EK Hwang, AQ Hurtado


Asparagopsis armata


Chondrus crispus


Palmaria palmata

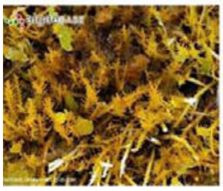

Kappaphycus alvarezii


Kappaphycus striatus


Eucheuma denticulatum


Eucheuma isiforme


Bataphycus philippinensis


Gelidiella acerosa


Gelidium amansii


Gracilaria changii


Graciliaria chorda


Gracilaria fastigiata


Gracilaria firma


Gracilaria heteroclada


Gracilaria tenuistipitata


Pyropia dentata


Pyropia haitanensis


Pyropia seriata


Pyropia tenera


Pyropia yezoensis

FIGURE 2.
Photos of commercially farmed brown seaweeds. Photos courtesy of EK Hwang, AQ Hurtado

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

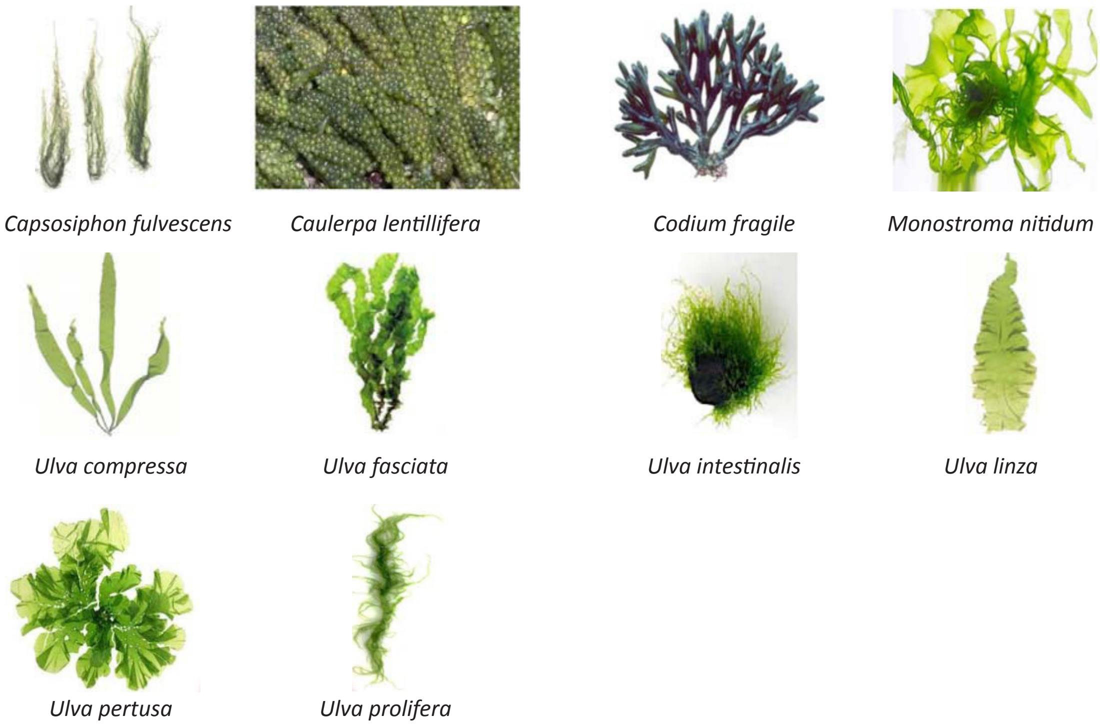


TABLE 2.
English and local names of farmed seaweeds

Scientific name	English	Chinese	Japanese	Korean	SEA region
Red					
Chondrus crispus	Irish moss				
Eucheuma					Spinosum
denticulatum					
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					
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 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-wakame	Wakame, Ito-wakame, Kizami-wakami, Nambu-wakame	Ito-wakame, Kizami-wakami, Miyok	
Green					
Caulerpa lentillifera	Sea grapes,green caviar				Lato
Codium fragile	Green sea fingers, felty fingers, dead man's fingers, stag seaweed, sponge seaweed, green sponge, green fleece, oyster thief, forked felt alga				
Monostroma nitidum		Jiao-mo Zi-cai	Hitoegusa, Hirano hitoegusa Aonori, Aonoriko		
Ulva	Sea lettuce, green laver				

1.2 Farming systems

1.2.1 Sea-based farming

Sea-based farming may be classified according to location: (i) coastal; (ii) deep sea; and (iii) 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* (Figure 4) 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 integrated multi-trophic aquaculture (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 an industry leader in seaweed production and has long 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 culturing 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 incorporation 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 of a food source and 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 fecal 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 outplanted when reaching the juvenile stage during favourable sea temperature. In contrast, these four genera 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]
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]		

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]
			Capsosiphon
	Pyropia dentata[*5]	Saccharina japonica[*3]	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] Eucheuma denticulatum var. milyon milyon[**6] 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 striatus[**4,6,7,11,12] Caulerpa racemosa var.		Caulerpa lentillifera[**14] Caulerpa racemosa var. macrophysa**
Portugal	Gracilaria vermiculophylla[*2] Chondrus crispus[*2] Palmaria palmata[*2] Codium tomentosum[*2] Palmaria palmata[*2] Pyropia sp.[*2]		Caulerpa lentillifera[**14] Ulva armoricana[*2] Ulva pertusa[*2]

Country	Red	Brown	Green
South Africa			_Ulva fasciata_[**2] _Ulva pertusa_[**2] _Ulva rigida_[**2]
South Pacific Island	_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 striatum_[**10]		
Tanzania	_Eucheuma denticulatum_[**4] _Kappaphycus alvarezii_[**10]		
Taiwan	_Gracilaria confervoides_[**19] _Pyropia sp._[*5]		_Caulerpa lentillifera_[**14] _Monostroma sp._
Thailand	_Gracilaria fisheri_[**6,13,14] _Gracilaria tenuistipitata_[**6,13, 14] _Hydropuntia edulis_[**13]		_Caulerpa lentillifera_[**2] _Chaetomorpha sp._[**19] _Ulva sp._[**13]
Venezuela	_Kappaphycus alvarezii_[**4,6] _Kappaphycus striatus_[**4,6]		
Viet Nam	_Eucheuma denticulatum_[**6] _Gracilaria asiatica_[**13,14] _Gracilaria firma_[**13,14] _Gracilaria heteroclada_[**13,14] _Gracilaria tenuistipitata_[**13,14] _Kappaphycus alvarezii_[**6,9] _Kappaphycus striatum_[**6,9]		_Caulerpa lentillifera_[**14]
United Kingdom (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; 6hanging longline (horizontal); 7hanging longline (vertical); [8]hanging longline (basket bag); [9]hanging longline (net bags); [10]single raft longline; [11]multiple raft longline; [12]multiple longline (spider web); [13]pond broadcasting; [14]pond "rice-planting"; [15]intertidal "rice planting"; [16]pole system; [17]bamboo-net; [18]stone tying; [19]co-culture with shrimps; [20]direct burial method; [21]plastic tube method.

FIGURE 4 (A-T).
Examples of sea-based commercial farming

(a, b) *Saccharina japonica* on ropes in north west China (photo courtesy of Dr XL Wang)

(c) *Saccharina digitata* on lines in Ireland (Watson *et al.*, 2012)

(d) *Saccharina latissima* on lines in France (photo courtesy www.c-weed-culture.com)

(e,f) *Undaria* cultivation in Korea (Kim *et al*., 2017)

(g,h) *Hizikia fusiformis* cultivation on ropes in Korea (Photos courtesy of EK Hwang)

(i, j) *Pyropia* net culture (photo courtesy of Yang)

(k) Raft cultivation of *Gracilaria* in Indonesia (photo courtesy of S Kusnowirjono)

(i) *Palmaria palmata* on lines in Ireland (Watson *et al.*, 2012)

(m) *Kappaphycus alvarezii* on long lines in Vietnam (photo courtesy AQ Hurtado)

(n) *Kappaphycus alvarezii* on rafts in Sri Lanka (photo courtesy of S Bondada)

(o, p) *Codium fragile* cultivation in Korea using long lines (Hwang *et al.,* 2009)

(q) *Capsosiphon* net cultivation in Korea

(r) *Ulva* net cultivation in Korea

(s, t) *Monostroma nitidum* net cultivation in Japan

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 5). 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 West 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).

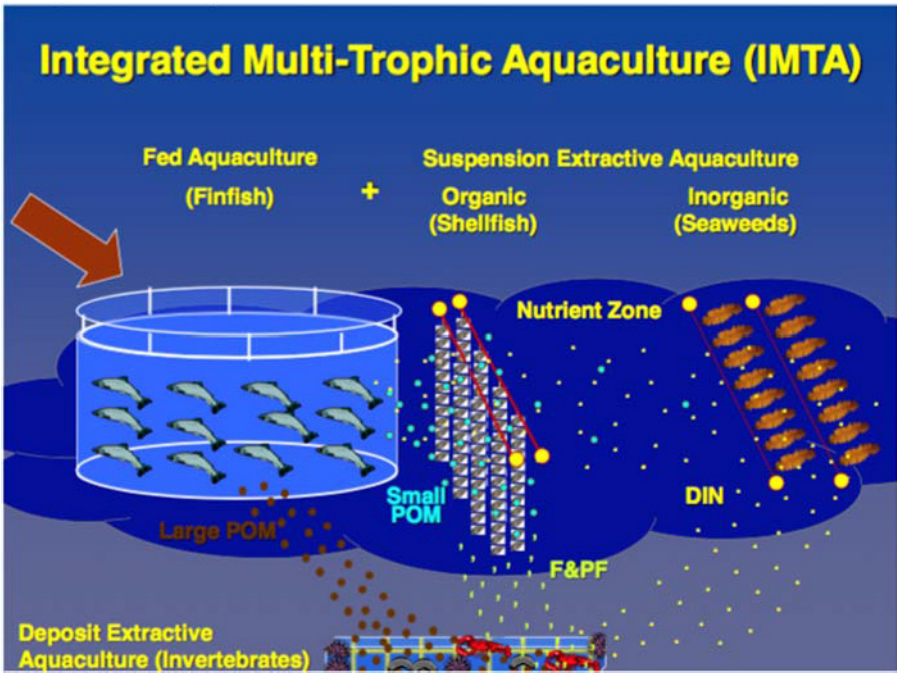
(iii) **Increased profits through diversification:** increased overall economic value of an operation from the commercial by-products that are cultivated and sold.

(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 5.
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*	**Brown:**	*Argopecteen*	*Apostichopus*	*Arenicola*
Dicentrarchus	*Penaeus*	*Alaria, Durvillaea,*	*Choromytilu*	*Athyonidium*	*Glycera*
Gadus		*Ecklonia, Lessonia,*	*Crassostrea*	*Cucumaria*	*Nereis*
Hippoglossus		*Laminaria,*	*Haliotis*	*Holothuria*	*Sabella*
Melanogrammus		*Macrocystis,*	*Mytilus*	*Loxechinus*	
Mugil		*Saccharina,*	*Pecten*	*Paracentrotus*	
Oncorhynchus		*Sacchoriza,*	*Placopecten*	*Parastichopus*	
Paralichthys		*Undaria*	*Tapes*	*Psammechinus*	

Fish	Crustaceans	Seaweeds	Molluscs	Echinoderms	Polychaetes
Pseudopleuronectes		**Red:**		*Stichopus*	
Salmo		*Asparagopsis*			
Scophthalmus		*Callophylis*			
		Chondracanthus			
		Chondrus		*Strongylocentrotus*	
		Gigartina			
		Gracilaria			
		Gracilariopsis			
		Palmaria			
		Sarcothalia			
		Green:			
		Ulva			

Source: Barrington *et al*., 2009.

TABLE 5.
Selection of 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

Country	Fish / shrimp	Molluscs / invertebrates	Seaweed	Status	Reference/ company
Ireland	*Salmo salar*	*Crassostrea gigas Mytilus edulis*	*Laminaria digitata Pyropia* sp. *Asparagopsis armata*	E	Kraan, 2010
Japan	*Pagrus major*	*Apostichopus japonicus*	*Laminaria* *Undaria* *Ulva*	E	Yokoyama, 2013
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	*Salmo salar*	*Mytilus edulis* *Psammechinus miliaris* *Paracentrotus lividus*		E	Stirling & Okumuş, 1995
United Kingdom	*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
USA	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: (i) *Chondrus crispus* (three different colour morphotypes) in Canada as sea vegetables (direct source of human food) grown in raceways (Figure 6); (ii) *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) (Figure 7); and (iii) *Ulva pertusa* in South Africa (Figure 8a) grown in raceways basically 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*) and seaweeds (*Ulva* and *Gracilaria*) and mollusc (*Haliotis discus hannai*) (Figure 8b).

FIGURE 6.
Raceway cultivation of Chondrus crispus at Acadian Seaplants Limited, Canada. Photo curtesy Acadian Seaplants Limited (www.acadianseaplants.com)

FIGURE 7:
Ulva grown in tanks/raceways using deep seawater from the Mediterranean Sea (Israel)

FIGURE 8A-B.
(a) Ulva fasciata, U. lactuca and U. rigida – Haliotis midae grown in raceways in South Africa (photo by R.J. Anderson). (b) Fish (Sparus aurata) and seaweeds (Ulva and Gracilaria) and mollusc (Haliotis discus hannai) in Israel at SeaOr Marine Enterprise

TABLE 6.
Selection of land-based IMTA practices in different countries

Country	Fish/shrimp	Molluscs/ invertebrates	Seaweed/micro-algae	Stat us	Reference/ company
Canada	*Hippoglossus hippoglossus*	-	*Palmaria palmata*	E	Corey *et al.*, 2014
Chile	*Oncorhynchus kisutch* *Oncorhynchus mykiss*	*Crassostrea gigas*	*Gracilaria chilensis*	C	Buschmann *et al.*, 1996
France	*Dicentrarchus labrax*	-	*Cladophora. Ulva*	E	Metaxa *et al.*, 2006
France	-	*Crassostrea gigas*	*Ulva* sp.	E	Lefebvre *et al.*, 2000
Ireland	*Oncorhynchus mykiss*	-	*Pyropia dioica Ulva* sp.	-	Hanniffy & Kraan, 2006; www.thefishsite.com
Israel	*Sparus aurata*	*Haliotis discus hannai*	*Gracilaria Ulva*	-	SeaOr Marine Farm, Israel
Portugal	*turbot*	-	*Chondrus crispus Gracilaria bursa-pastoris Palmaria palmata,*	E	Matos *et al.*, 2006
Republic of Korea	*Sebastes shlegeli*	*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	*Scophthalmus maximus*	-	*Tetraselmis suecica Phaeodactylum tricornutum*	-	
USA	*Hippoglossus stenolepsis*	-	*Chondracanthus exasperatus*	C	Söliv International
USA	*Anoplopoma fimbria*	*Haliotis 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*, world farming of seaweed mainly comes from Asia (Table 7).

TABLE 7.
Major seaweed producing countries

Species	Major countries
Red	
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	
Saccharina	China, Japan, Republic of Korea
Hizikia fusiformis	Republic of Korea
Undaria	China, Japan, Republic of Korea
Green	
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.

Because Indonesia and the Philippines are the two main producing countries of *Kappaphycus* (*cottonii*) in the world, it can be gleaned from Figure 9 that Indonesia continues to increase its production, while the Philippines has decreased its production 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-1year-1. Despite the geographic location of the Philippines, which is prone to several cyclones every year that 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 struggling to increase its production. In 2014 and 2015, 26 076 tonnes and 24 533 tonnes of *Kappaphycus*, respectively, were produced (Suhaimi, personal communication).

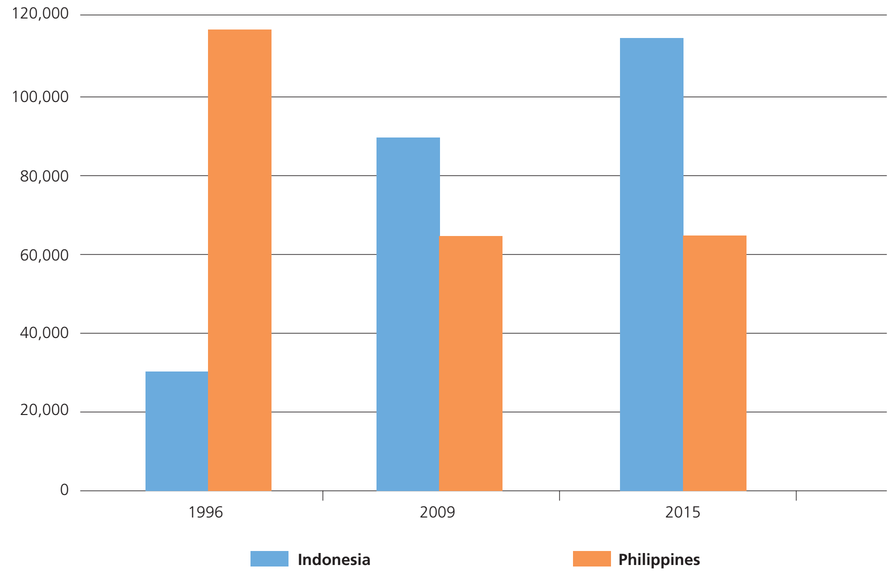
Production of *Kappaphycus* in other southeast Asian countries, such as Cambodia, China, India, Myanmar and Viet Nam, and in Latin America are still small at present and data are not available.

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

Genus	Japan (2014)	Republic of Korea (2015)	
	Volume (tonnes)	Volume (tonnes)	Value (US$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.

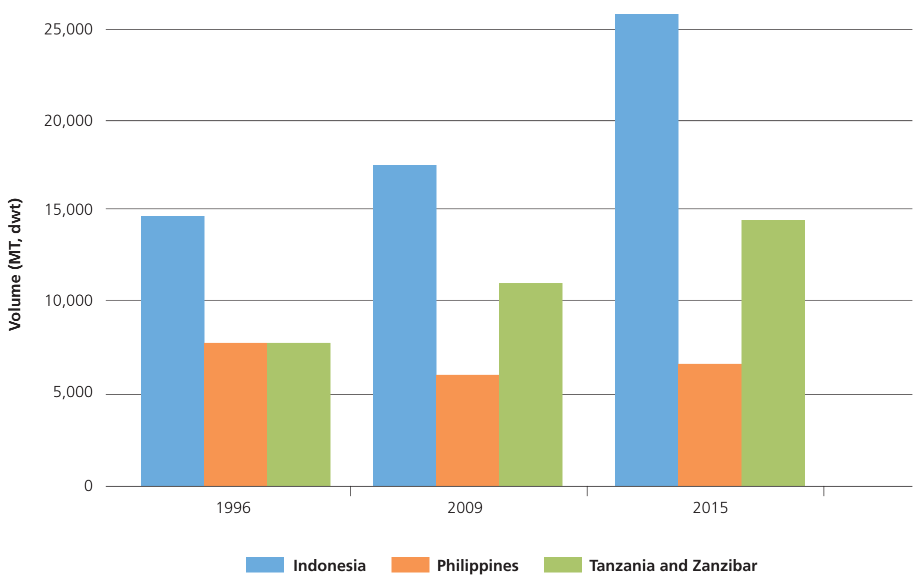
FIGURE 9.
Seaweed carrageenan (*cottonii*) production, 2015 (tonnes, dry weight)



Source: Porse and Rudolph, 2017

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 10 shows the latest production of spinosum (common vernacular name of *E. denticulatum*) in the three major producing countries.

FIGURE 10.
Seaweed carrageenan (*spinosum*) production, 2015 (tonnes, dry weight) Source: Porse and Rudolph, 2017.



Gracilaria and *Gelidium* are two genus 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 an ubiquitous seaweed, which can be found both in tropic and temperate waters, while *Gelidium* is more confined to temperate waters. Hence, one would expect that the sourcing of *Gracilaria* for agar processing purposes is much easier than *Gelidium*. 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 in Chile), and Africa and Europe (Figure 11). A more detailed graph is presented in Figure 12, which shows the countries that produce *Gracilaria*. Just like *Kappaphycus* production, which is led by Indonesia, the same is recorded for *Gracilaria.*

FIGURE 11.
***Gracilaria* production by region, 2015 (tonnes, dry weight) Source: Porse and Rudolph, 2017.**

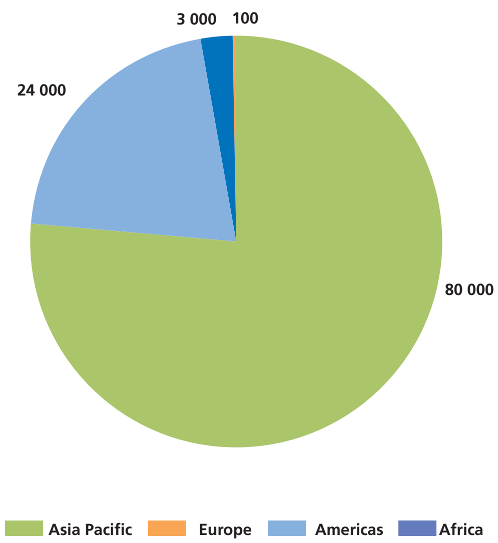
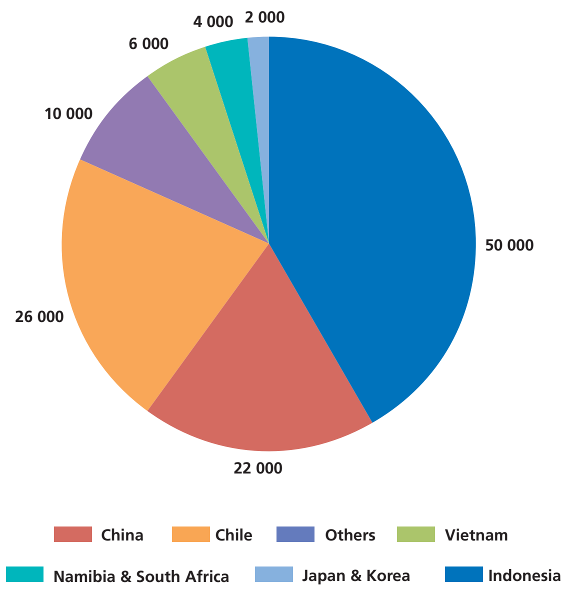
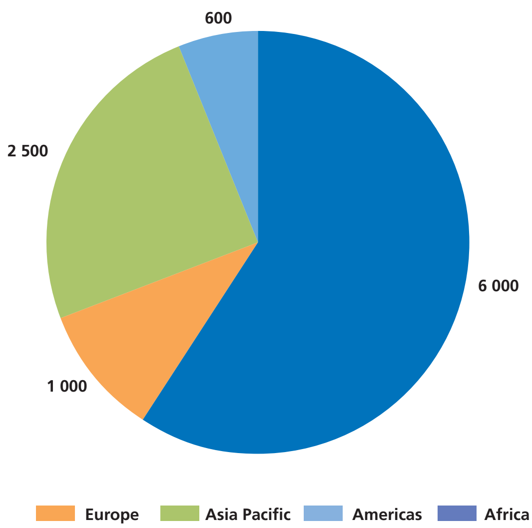


FIGURE 12.
Gracilaria production by country, 2014 (tonnes, dry weight) Source: Paravano, 2015.



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) Figure 13.

FIGURE 13.
***Gelidium* production by region, 2015 (tonnes, dry weight) 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 (23.7 percent), and finally green (22.0 percent). Seaweeds are prime candidates for the integrated biorefinery approach – on the one hand, there is a wide range of bio-based, high-value compounds (such as edible food, food and feed ingredients, biopolymers, fine and bulk chemicals, agrichemicals, cosmetics, bioactives, pharmaceuticals,nutraceuticals, botanicals), and on the other hand, lower-value commodity bioenergy compounds (including 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						
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	
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

Species	Food				Feed	Fuel*
		Food ingredient				
	Sea vegetable	Agar	Carrageenan	Alginate		
Kappaphycus malesianus	x		x			x
Kappaphycus striatus	x		x			x
Palmaria palmata	x				x	
Pyropia dentata	x					
Pyropia haitanensis	x					
Pyropia pseudolinearis	x					
Pyropia seriata	x					
Pyropia tenera	x					
Pyropia umbilicalis	x					
Pyropia yezoensis	x					
Pyropia sp.	x					
Brown						
Alaria esculenta	x					
Clad siphon 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						
Capsosiphon fulvescens	x					
Caulerpa lentillifera	x					
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 produce in photosynthesis enters the food chain via the 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. Because global ocean changes can influence coastal environments, global warming-induced ocean warming and ocean acidification (OA) caused by atmospheric CO_2 rise and increasing ultraviolet B irradiance at the earth's surface thus affect the physiology, life cycles and community structures of seaweeds. According to Ji *et al*., (2016), some species tested 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 macro-algae because of their high sensitivity to the acidic perturbation to intracellular acid-base stability. Mild ocean warming has been shown to benefit most macro-algae 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 macro-algae. While it is important to look into responses of macro-algae to diel fluctuating pH (common in coastal waters) under OA (Cornwall *et al*., 2012), the impacts of OA would affect productivity of sea-farmed macro-algae that experience dramatic diel pH variations.

Increased availability of carbon and increased acidity in seawater with atmospheric CO_2 rise may have counteractive effects on the physiological activities and growth of macro-algae, and 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 macro-algae either in their adult stages or throughout their life cycles.

Sea level rise may create more available habitat space for macro-algae to grow, as more land area will be inundated with water. While the increase could impact some species that live in shallow habitats by reducing their exposure to sunlight (the more water will mean more distance for sunlight to travel to reach the macro-algae), as a group macro-algae is not vulnerable to negative impacts of sea level rise. 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 macro-algae growth and reproduction. Cyclones and storms can also destroy coral reef structures, increasing habitat areas for macro-algae to grow.

Rising sea temperatures will increase the production of some species of macro-algae. Changes in temperatures could also lead to changes in these species' life cycles, growth and production. Climate change is more notably felt in the tropics than in the temperate countries. The most notable impact of rising temperature and a concomitant elevated salinity have 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 of 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, for the cold seawater-grown species, the rise of temperature may reduce their living space and narrow their available 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 opening and discovery 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 the temperate countries, especially in western Europe, northeastern Canada and the United States of America, the brown seaweed *Alaria, Laminaria* and *Saccharina* will be expanded tremendously in terms of sea cultivation, both as a monocrop 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 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: (i) stable supply and reliable access of raw material; (ii) uniformity of quality of the raw material; and (iii) facilitates the 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 strains based on growth performance and resistance to "disease" are 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 of these techniques 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 outplanted into the sea in autumn. When these individuals attain a size of more than 1 m long, they are ready to harvest. 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 *et al.,* 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 to use in commercial cultivation compared with other species, such as *Laminaria digitata, Palmaria palmata, Pyropia yezoensis, Saccharina latissima* and *Undaria pinnatifida*. This is probably because of the low germination rate under laboratory/hatchery conditions for mass field cultivation. Hatchery production of the *conchocelis* and/or spores for outplanting purposes is already well developed in China, Japan and the Republic of Korea and is still practised today.

2.2 Clonal propagation and strain selection

Clonal propagation is the most common and simplest approach to select superior strains from wild populations to improve the performance of cultivated crops (Santelices, 1992), such as *Chondrus* (Cheney *et al.,* 1981), *Gigartina* (Sylvester and Waaland, 1983), *Gracilaria* (Patwary and van der Meer, 1982, 1983), and *Kappaphycus* (Doty and Alvarez, 1973). These studies 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. Also, 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: (i) 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 (ii) 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: (i) physical conditions (controlled with an environmental chamber or walk-in culture room), light, temperature, photoperiod and aeration; and (ii) 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: (i) auxins – promote both cell division and cell growth; (ii) cytokinins – promote cell division; (iii) gibberellins – for cell division; (iv) abscisic acid – inhibits cell division; and (v) ethylene – controls 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 macro-algae 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 *Euchuema* 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	mES; PES	Yeong *et al*., 2008
G. tenuistipitata	Palnt development	PGRs	Yokoya *et al*., 2004

Species	Status of success	Major media and PGR used	Reference
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, ASP_{12}-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			
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			
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 pinatifida* (Tokuda and Kawashima, 1988) were reported. Only the works of Kloareg *et al.,* (1989) on *M. 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 mm^2) 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 is 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		
Gelidium robustum	PI	Coury *et al*., 1993
Gracilaria asiatica	PI	Yan & Wang, 1993
Gracilaria 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		
Cladosiphon okamurans	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

Species	Status	Reference
Green		
Monostroma nitidum	PI	Yamaguchi *et al*., 1989
Monostroma 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

Among the commercial farmed seaweeds, only a few brown and red species have been subjected to hybridization attempts. The first seaweed that was successfully hybridized was *Saccharina* (= *Laminaria*) done by Chinese scientists during the late 1950s and early 1960s. China pioneered the method of hybridization, considering that *Saccharina japonica* was an introduced species from Hokkaido, Japan. This hybrid *Saccharina* created a few highly productive strains that were partially responsible for the increasing annual production in China.

One successful farming of seaweed recorded as a result of hybridization is *S. japonica* in China. This seaweed 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. 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 an intraspecific hybrid through four rounds of self-crossing and selection and retains a certain degree of genetic heterozygosity, and thus is immune to inbred depletion because of diversity reduction. Most importantly, farming Dongfang No. 7 was compatible when used in the farming system. It increased the air dry yield by 43.2 percent over two widely farmed controls on average, close to the increased intraspecific hybrid, but less than that of interspecific hybrids or the varieties derived from them. Such strategy was feasible at least for genetically improving the brown algae with a similar life cycle, e.g. *Undaria pinnatifida* and *Macrocystis pyrifera*.

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. tivahiae	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 × 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 thallus 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 macro-algae such as *Chondrus, Gelidium, Kappaphycus* and *Pyropia,* the transient gene expression system has not yet been developed in these red macro-algae 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
Gracilaria changii	Transient	Particle bombardment	SV40	lacZ	Gan *et al*., 2003
Kappaphycus alvarezii	Transient	Biolistic particle	CaMV 35S	GUS	Kurtzman & Cheney, 1991
Kappaphycus alvarezii	Stable	Particle bombardment	SV40	lacZ	Wang *et al*., 2010a
Pyropia haitanensis	Stable	Glass bead agitation	SV40	lacZ; EGFP	Wang *et al*., 2010b
P. tenera	Transient	Electroporation	CaMV 35S	GUS	Okauchi & Mizukami, 1999
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

Species	Status of expression	Method of gene transfer	Promoter	Marker or reporter	Reference
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
Brown					
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 = Amino methyl transferase; 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 pertus*a 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.

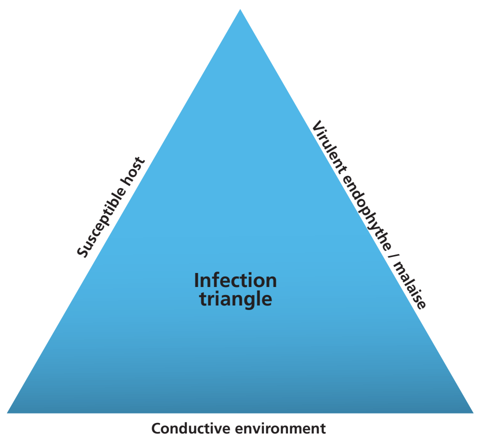
3. MAJOR PROBLEMS OF FARMING SEAWEEDS

3.1 Disease and epiphytism

When a seaweed is suffering, we call it diseased, i.e. it is “dis-ease”. 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): (i) the normal physiological functions of seaweed are disturbed when they are affected by pathogenic living organisms and/or by some environmental factors; (ii) initially, seaweed reacts to the “disease” causing agents, particularly in the site of infection; (iii) later, the reaction becomes more widespread and histological changes take place; (iv) such changes are expressed as different types of symptoms of the disease which can be visualized macroscopically; and (v) 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): (i) a susceptible host population; (ii) presence of a competent endophyte/malaise; and (iii) a conducive (biotic and abiotic) environment (Figure 14).

FIGURE 14.
Infection triangle



Despite a developed technology of farming a seaweed, disease occurs, especially in areas where stocking is intensive. Table 14 shows a summary of diseases caused by bacteria, fungi and epiphytes among farmed seaweeds.

TABLE 14.
Summary of seaweed diseases and epiphytism

Species	Disease name	Causative organism(s)	Symptoms/effects	References
Red				
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 ., 1999, 2002; Brown ., 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
Kappapphycus alvarezii/ K. striatum	Ice-ice	Pseudomonas, Flavobacterium and Actinobacterium	Slow growth and greening of tissue	Uyenco *et al.*, 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 *et al.*, 2010
E.denticulatum		Penicillium waksmanii		Dewey *et al.*,1983
E.denticulatum		Scopulariopsis brevicaulis		Dewey *et al.*, 1984
Kappapphycus alvarezii/ K. striatus	Endophytic filamentous algae (EFA)	Neosiphonia saavatierii/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 et al., 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
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	Fragellaria sp., Licmophora abellata, 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./Coelomycete	Bleaching of oyster shell with shell- boringconchocelis	Tsukidate, 1971; 1977
P. yezoensis	Suminori disease	Flavobacterium sp.		
Green				
Ulva lactuca	Pigmented marine bacteria	Pseudoalteromonas	Populate the surface, preventing the colonization of other seaweeds and invertebrate larvae	Egan *et al.*, 2001
Brown				
Alaria esculenta	Hollowing of stipes; stipe blotch disease	Amphipod Amphitholina cuniculus; ascomycete Phycomelaina laminariae	Boring of stipes and produces hollow	Myers, 1974; Chess, 1993
Macrocystis pyrifera	Black rot; hollowing of stipes	Unidentified parasitic micro-organism; amphipod P. humeralis	Boring of stipes and produces 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
S. digitata		Ascomycete Petersenia sp.	Damages the stipes	Kohlmeyer, 1968

S. digitata		Unknown hyphomycete	Causes 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		Same course of development in green rot, only the fronds turn white due to strong sunlight, high water temperature and lack of nutrients	Andrews, 1976
S. japonica	Malformatio n 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 produces hollow	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
S. latissima		Endophyte Laminariocolax tomentosoides		Lund, 1959
S. latissima		Endophyte Laminariocolax aecidioides	Host thalli becoming thicker and stiffer, lowering their 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	Vibrio 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 *et al*., 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	Gammeride 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-environmental impact

Seaweed farming is an extractive aquaculture whose very process of production of valuable biomass renders the sea's 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.

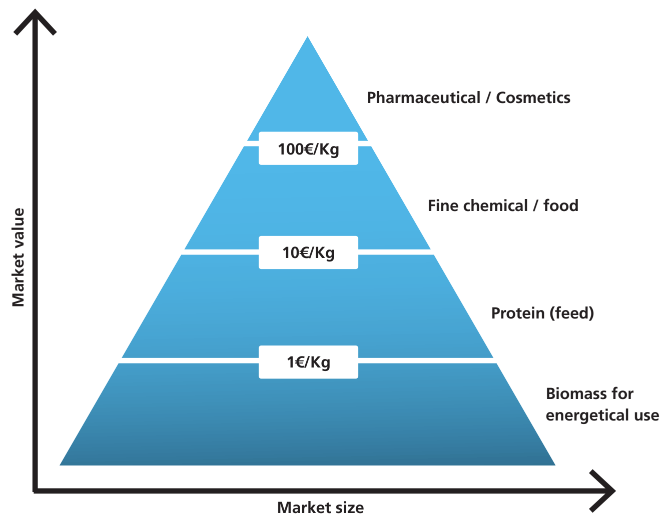
Shading and alkalization may harm and benefit different local biological activities, competing with phytoplankton and therefore filter feeders, but at the same time aiding calcification of shellfish and corals, which suffer from ocean acidification (Branch *et al*., 2013).

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, as claimed by Rodgers and Cox (1999), Smith *et al*., (2002) and Conklin and Smith (2005), and in India by Chandrasekaran *et al*. (2008), instead of bringing economic benefits to coastal families. However, the latest report on such bioinvasion and coral encroachment was negated by the report of Mandal *et al., (2010)* for the following reasons: (i) lack of a functional reproductive cycle; (ii) low spore viability; and (iii) the absence of microscopic phases in the life cycle of *Kappaphycus,* coupled with the abundant presence of herbivores, restricted the further spread of this alga.

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, more 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 and elsewhere 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 15 shows the pyramid of the seaweed product markets.

FIGURE 15.
Pyramid schematic of seaweed product markets



5.1 Food

Asians will continue to consume seaweeds as part of their daily diet. There is a rising awareness of health and nutritional benefits from seaweeds in the 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 more milk of the sow, decreased mortality by 50 percent, cut the use of antibiotics by 50 percent, improved health management, reduced feed intake (gut health), made hogs ready for slaughter two to three weeks earlier, improved taste (industrial taste panel), and doubled omega-3 in pork (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 *et al.,* 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).

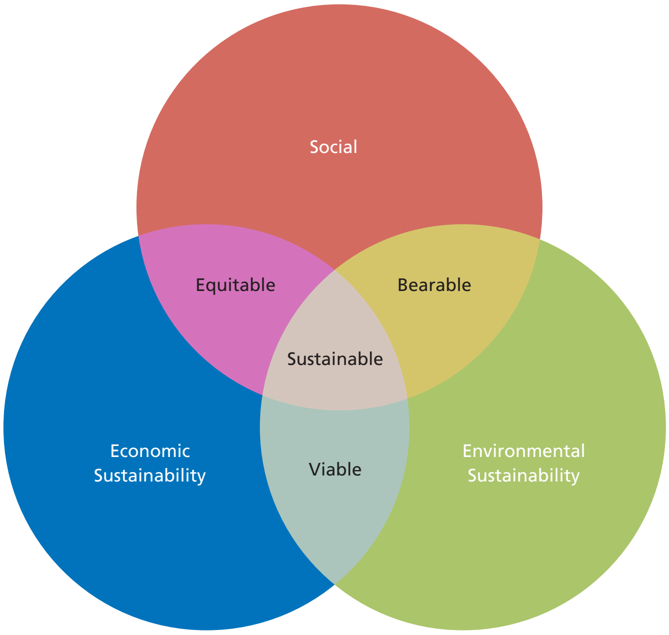
Though several preliminary investigations have been conducted to assess the technical feasibility, environmental viability and economic profitability of seaweed farming fo fuel (Watson, 2014; Valderamma *et al*., 2013; Watson *et al*., 2012), numerous parameters (such as method of cultivation, species 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 STRATEGIES

Conservation is a careful preservation and protection of resources that includes a well-planned management of said natural resource to prevent exploitation, destruction or neglect. There is biodiversity of seaweeds within species (genus), between species, and of ecosystems; hence, each species has 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: (i) economic development; (ii) social equity; and (iii) environmental protection. Sustainable development can be achieved if decisions are made to be economically profitable, biologically appropriate and socially acceptable (Figure 16) (Eigner-Thiel *et al.,* 2013) (Circular Ecology, 2016).

FIGURE 16.
Sustainability paradigm



Curtesy circularecology.com

Currently, with intensive fed aquaculture (finfish and shrimp) throughout the world is rapidly increasing, environmental impact is the main concern. A large amount of 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 elsewhere, the following are to be implemented: (i) expansion of farming areas, wherever possible and profitable, and subject to the needs of other sectors and of environmental health; (ii) 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; (iii) 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 (iv) 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
Sound 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
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. ENHANCEMENT PROGRAMME

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, mainland 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 Ph.D. programmes should incorporate generic skills and be formulated with direct engagement with employers and enterprises where appropriate. Training helps people improve their competencies, which leads to better performance appraisals.

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: (i) conceptualize and write a proposal; (ii) conduct the study with little supervision; (iii) collect, analyse and interpret the data; (iv) make conclusions; (v) write a manuscript for publication; and (vi) share the results to 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 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	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 Australia 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	China Phycological Society	• Builds China's largest professional information service platform, science and technology innovation platform, and brand promotion platform for the algae industry.
China - Taiwan Province	Taiwanese Phycological Society	• Enhances and strengthens algal academic research. • Promotes algal awareness and develops algal applications
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 in 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.
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. • A forum of national and foreign professionals interested in the world of algae.

Location	Name of organization/ society	Objectives
Spain	Spain Phycological Society (Sociedad Española de Ficologia)	• Establishes partnerships between phycologists, public and private research organizations, and companies interested in the study and applications of algae.
USA	International Phycological Society	• Develops phycology distribute phycological information; cooperates among international phycologists and phycological organizations; and convenes the International Phycological Congress every four years.
USA	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.
USA	International Society for Applied Phycology	• Promotes research, preservation of algal genotypes and the dissemination of knowledge concerning the utilization of algae.
USA	Marinalg International	• Promotes the image and uses of seaweed-derived hydrocoloids in food, pharmaceuticals and cosmetics.
USA	Phycological Society of America	• Promotes research and teaching in all fields of phycology; publishing the Journal of Phychology

9. SOURCES OF DATABASES

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: (i) biorefinery; (ii) algae growing; and (iii) energy production
Centre d'Etude et de Valorisation des Algues (CEVA) (www.ceva.fr)	Pleubian, France	Dedicated to the study and enhancement of algae (macro and micro) marine plants and marine biotechnology
MACRO – the Centre for Macroalgal Resources & Biotechnology (https://research.jcu.edu.au/macro)	James Cook University, Australia	Develops and commercializes marine and freshwater macro-algae 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	Norway, Portugal and Denmark	Focuses on large-scale cultivation (www.seaweedenergysolutions.com) of seaweed primarily for energy purposes

The biggest storage of seaweed information in terms of taxonomy, description and distribution is found in www.algaebase.com. All universities and research institutions that have seaweed programmes have an 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: (i) publication in peer-reviewed journals, symposium proceedings and books; (ii) presentation of results in different symposia and congresses; and (iii) writing in popularized magazines, newletters, brochures and flyers for the industry.

Networking is important in the seaweed community. There is a need to work together to develop seagriculture, or sea farming, in order to cater to the needs of the industry. Vertically integrated supply chains require 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 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 CO2 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: (i) ecological design, ecosystem interactions and biomitigative efficiency; (ii) system innovation and engineering; (iii) economic viability and societal acceptance; and (iv) 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 policy-makers and enable economic progress.

Network	Objectives
Netalgae (France, Ireland, Norway, Portugal, Spain, United Kingdom)	Creates a European network of relevant stakeholders within the marine macro-algae sector. Compiles information from different regions that will result in a wide-ranging policy study of existing practices within the macro-algae industry. Analyses the results that will establish a best practice model and suggests policies for the successful sustainable commercial utilization of marine macro-algae resources.
Nordic Algae Network (Denmark, Iceland, Norway, Sweden)	Helps the partners to a leading position in the algae field for commercial utilization of high- value products and energy from algae. Increases the synergy and facilitates collaboration between partners.
Norwegian Latin American Seaweed Network Norwegian Seaweeds Network	Encourages cooperation among the seaweed stakeholders across Latin America and Europe in order to support the development of the seaweed sector. Strengthens interest and knowledge of benthic algal taxonomy, systematics and species identification, and promotes collaboration and exchange of information.
REBENT (France – national network coordinated by IFREMER)	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: (i) 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; (ii) assurance of the quality of science and technological advancement through open, rigorous and inclusive peer review scientific publishing; and (iii) open interactions among scientists, engineers and students from across the globe.

The discovery of computer technology has opened many opportunities to gain access to more than one system to gather data or exchange information. Open access and exchange of information is one of the core values of academics; a computer system that limits access is frustrating at best. 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. Open access promotes knowledge transfer by mouse click. There are alternatives to expensive, restricted access to academic publications, for example, PLOS ONE, the Public Library of Science's international online journals. The publications can be accessed from any computer with an Internet connection; the author retains the copyright; manuscripts are published relatively quickly; they are peer reviewed by experts; quality and impact can be determined using post-publication tools; and users can discuss the articles in communities. 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 micro- and macro-algae (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. On the other hand, making the news often means bold and dramatic statements, which is sometimes risky. Science-based decision- making is not that straightforward. One can use models and mathematical equations to predict various outcomes, but one cannot guarantee those results. Thus, when real life does not follow model predictions, people lose faith in the science.

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 when 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 *et al., 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 *et al.,* 2015; Freitas *et al.,* 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 study. However, live test plants are allowed by the scientist to bring 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 is dominantly done 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 starting* around 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.

Use of plantlets from spores remains to be used in the lab for outplanting purposes with improvements in nutrition-temperature-light requirements. Although several successful studies were reported on the regeneration of plantlets of *Kappaphycus and Euchuema 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. 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 hybridization of *Saccharina japonica* using gametophytes and sporophytes in China (Dongfang No. 7) may provide a model for domestication to 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.

References

Agrios, G.N. 2005. *Plant pathology*. Fifth edition. Elsevier B.V. 922 pp.

Akaike, S., Takiya, A., Tsuda F., Motoya, A. & Takahashi, K. 2002. Seasonal occurrence of a kelp-boring amphipod*, Ceinina japonica* along the coasts of Hokkaido from 1997 to 2001. Scientific Reports of Hokkaido Fisheries Experimental Station, 61:25–28.

Akiyama, K. 1977. Preliminary report on *Streblonema* disease in *Undaria*. Bulletin of Tohoku Regional Fisheries Research Laboratory, 37:39–41.

Andrews, J.H. 1976. The pathology of marine algae. *Biological Review*, 51: 211–253.

Apt, K.E. 1988. Galls and tumor-like growths on marine macroalgae. *Diseases of Aquatic Organisms*, 4: 211–217.

Araki, T. & Morishita, T. 1990. Fusion of protoplasts from wild type *Porphyra yezoensis* and green type *P. tenera* thalli (Rhodophyta). *Nippon Suisan Gakkaishi*, 56: 1161.

Araújo, P.G., Schmidt, E.C., Kreusch, M.G., Kano, C.H., Guimarães, S.M.P.B., Bouzon, Z.L., Fujii, M.S. & Yokoya, N.S. 2014. Ultrastructural, morphological, and molecular characterization of *Colaconema infestans* (Colaconematales, Rhodophyta) and its host *Kappaphycus alvarezii* (Gigartinales, Rhodophyta) cultivated in the Brazilian tropical region. *Journal of Applied Phycology,* 26: 1953–1961.

Ateweberhan, M., Rougier, A. & Rakotomahazo, C. 2015. Influence of environmental factors and farming technique on growth and health of farmed *Kappaphycus alvarezii* (*cottonii*) in south-west Madagascar. *Journal of Applied Phycology*, 27: 923–934.

Azanza, R.V. & Aliaza, T. 1999. *In vitro* carpospore release and germination in *Kappaphycus alvarezii* (Doty) Doty from Tawi-Tawi, Philippines. *Botanica Marina*, 42: 281–284.

Azanza-Corrales, R., Aliaza, T.T. & Montano, N.E. 1996. Recruitment of *Eucheuma* and

Kappaphycus on a farm in Tawi- Tawi, Philippines. *Hydrobiologia*, 326/327: 235–244.

Azanza-Corrales, R. & Ask, E. 2003. *Kappaphycus alvarezii* (Doty) Doty carposporeling growth and development in the laboratory. *In* A. Chapman, R.J.Anderson, V. Vreeland & I. Davison, eds. *Proceedings of the XVII International Seaweed Symposium*, pp. 95–99. New York, Oxford University Press.

Bansemir, A., Blume, M., Schröeder, S. & Lindequist, U. 2006. Screening of cultivated seaweeds for antibacterial activity against fish pathogenic bacteria. *Aquaculture*, 252: 79–84.

Barrington, K., Chopin, T. & Robinson, S. 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. *In* D. Soto, ed. *Integrated mariculture: a global review*, pp. 7–46. FAO Fisheries and Aquaculture Technical Paper No. 529. Rome, FAO (also available at www.fao.org/3/a-i1092e/i1092e02a.pdf).

Benet, H., Bruss, U., Duval, J.C. & Kloareg, B. 1994. Photosynthesis and photoinhibition in protoplasts of the marine brown alga *Laminaria saccharina*. *Journal of Experimental Botany*, 45: 211–220.

Benet, H., Gall, A.E., Asensi, A. & Kloareg, B. 1997. Protoplast regeneration from gametophytes and sporophytes of some species in the order Laminariales (Phaeophyceae). *Protoplasma*, 199:39–48. **Bernasconi, P., Cruz-Uribe, T., Rorrer, G., Bruce, N. & Cheney D.P.** 2004. Development of a TNT-detoxifying strain of the seaweed *Porphyra yezoensis* through genetic engineering. *Journal of Phycology*, 40: 31 (supplement).

Bhatnagar-Mathur, P., Vadez, V. & Sharma K.K. 2008. Transgenic approaches for abiotic stress tolerance in plants: retrospect and prospects. *Plant Cell Reports*, 27: 411–424.

Bixler, H.J & Porse, H. 2011. A decade of change in the seaweed hydrocolloids industry. *Journal of Applied Phycology,* 23: 321–335.

Bjork, M., Ekman, P., Wallin, A. & Pedersen, M. 1990. Effect of growth rate and other factors on protoplast yield from four species of *Gracilaria* (Rhodophyta). *Botanica Marina*, 33: 433–439.

Bolton, J.J., Robertson-Andersson, D.M., Troell, M. & Halling, C. 2006. Integrated systems incorporate seaweeds in South African abalone culture. *Global Aquaculture Advocate*, 9: 54–55.

Borges, M.T., Silva, P., Moreira, L. & Soares, R. 2005. Integration of consumer-targeted microalgal production with marine fish effluent biofiltration – a strategy for mariculture sustainability. *Journal of Applied Phycology,* 17: 187–197.

Borlongan, I.A.G., Tibudos, K.R., Yunque, D.A.T., Hurtado, A.Q. & Critchley, A.T. 2011. Impact of AMPEP on the growth and occurrence of epiphytic *Neosiphonia* infestation on two varieties of commercially cultivated *Kappaphycus alvarezii* grown at different depths in the Philippines. *Journal of Applied Phycology*, 23: 615–621.

Bouarab, K., Potin, P., Correa, J.A. & Kloareg, B. 1999. Sulfated oligosaccharides mediate the interaction between a marine red alga and its green algal pathogenic endophyte. *Plant Cell*, 11: 1635–1650.

Bouarab, K., Potin, P., Weinberger, F., Correa, J.A. & Kloareg B. 2001. The *Chondrus crispus- Acrochaete operculata* host-pathogen association, a novel model in glycobiology and applied phycopathology. *Journal of Applied Phycology*, 13: 185–193.

Branch, T.A., DeJoseph, B.M., Ray, L.J. & Wagner, C.A. 2013. Impacts of ocean acidification on marine seafood. *Trends in Ecology & Evolution*, 28: 178–186.

Brown, P., Plumb, J., Sanchez-Baracaldo, P., Hayes, P.K. & Brodie, J. 2003. Sequence heterogeneity of green (Chlorophyta) endophytic algae associated with a population of *Chondrus crispus* (Gigartinaceae, Rhodophyta). *European Journal of Phycology*, 38: 153–163.

Bruton, T., Lyons, H., Lerat, Y., Stanley, M. & Rasmussen M.B. 2009. A review of the potential of marine algae as a source of biofuel in Ireland. Dublin, Ireland, Sustainable Energy Ireland.

Bulboa, C.R., de Paula, E.J. & Chow, F. 2007. Laboratory germination and sea out-planting of tetraspore progeny from *Kappaphycus striatum* (Rhodophyta) in subtropical waters of Brazil. *Journal of Applied Phycology*, 19: 357–363.

Burkhardt, E. & Peters, A.F. 1998. Molecular evidence from nrDNA ITS sequences that *Laminariocolax* (Phaeophyceae, Ectocarpales *sensu lato*) is a worldwide clade of closely related kelp endophytes. *Journal of Phycology*, 34: 682–691.

Buschmann, A.H., Hernandez-Gonzalez, M.C., Aroca, G. & Gutierrez, A. 2001. Seaweed farming in Chile: A review. *The Advocate*, 68–69.

Buschmann, A.H., Troell, M., Kautsky, N. & Kautsky, E. 1996. Integrated tank cultivation of salmonids and *Gracilaria chilensis* (Gracilariales, Rhodophyta). *Hydrobiologia*, 326/327: 75–86.

Butler, D.M. & Evans, L.V. 1990. Cell and tissue culture of macroalgae. *In* I. Akatsuka, ed. *Introduction to applied phycology*, pp. 629–645. The Hague, The Netherlands, SPB Academic Publishing.

Butler, D.M., Ostgaard, K., Boyen, C., Evans, L.V., Jensen, A. & Kloareg, B. 1989. Isolation condition for high yields of protoplasts from *Laminaria saccharina* and *L. digitata* (Phaeophyceae). *Journal of Experimental Botany*, 40: 1237–1246.

Carmona, R., Kraemer, G.P. & Yarish C. 2006. Exploring Northeast American and Asian species of *Porphyra* for use in an integrated finfish-algal aquaculture system. *Aquaculture*, 252: 54–65.

Chandrasekaran, S., Nagendran, N.A., Pandiaraja, D., Krushnankutty, N. & Kamalakannan B. 2008. Bioinvasion of *Kappaphycus alvarezii* on corals in the Gulf of Mannar, India. *Current Science*, 94: 1167–1172.

Chen, L.C. & Taylor, A.R. 1978. Medullary tissue culture of the red alga *Chondrus crispus*. *Canadian Journal of Botany*, 56: 883–886.

Chen, Y.C. & Shih, H.C. 2000. Development of protoplasts of *Ulva fasciata* (Chlorophyta) for algal seed stock. *Journal of Phycology*, 36: 608–615.

Cheney, D. 1990. Genetic improvement of seaweeds through protoplasts fusion. *In* C. Yarish, C. Penniman & P. Van Patten, eds. *Economically important marine plants of the Atlantic: their biology and cultivation,* pp. 15–25. Storrs, USA, University of Connecticut Sea Grant Program.

Cheney, D.P., Mathiesen, A. & Schubert, D. 1981. The application of genetic improvement techniques to seaweed cultivation: I. strain selection in the carrageenophyte *Chondrus crispus*. *International Seaweed Symposium*, 10: 559–567.

Cheney, D., Metz, B. & Stiller, J. 2001. *Agrobacterium*-mediated genetic transformation in the macroscopic marine red alga *Porphyra yezoensis*. *Journal of Phycology*, 37 (Suppl): 11.

Chess, J.R. 1993. Effects of the stipe-boring amphipod *Peramphithoe stypotrupetes* (Corophioidea: Ampithoidae) and grazing gastropods on the kelp *Laminaria setchellii*. *Journal of Crustacean Biology*, 13: 638–646.

Chopin, T., Buschmann, A.H., Halling, C., Troell, M., Kautsky, N., Neori, A., Kraemer, G.P., Zertuche-Gonzalez, J.A., Yarish, C. & Neefus, C. 2001. Integrating seaweeds into marine aquaculture systems: a key towards sustainability. *Journal of Phycology*, 37: 975–986.

Chopin, T., MacDonald, B., Robinson, S., Cross, S., Pearce, C., Knowler, D., Noce, A., Reid, G., Cooper, A., Speare, D., Burridge, L., Crawford, C., Sawhney, M., Ang, K.P., Backman, C. & Hutchinson, M. 2013. The Canadian Integrated Multi-Trophic Aquaculture Network (CIMTAN– A Network for a New Era of Ecosystem Responsible Aquaculture. *Fisheries*, 38: 297–308.

Chopin, T., Robinson, S.M.C., Troell, M., Neori, A., Buschmann, A.H. & Fang, J. 2008. Multi- trophic integration for sustainable marine aquaculture. *In* S.E. Joeresen, ed. Encyclopedia of Ecology, 463–2475. *Ecological Engineering*, 3. Oxford, Elsevier.

Chopin, T., Yarish, C., Wilkes, R., Belyea, E., Lu, S. & Mathieson, A. 1999. Developing *Porphyra*/salmon integrated aquaculture for bioremediation and diversification of the aquaculture industry. *Journal of Applied Phycology*, 11: 463–472.

Chopin, T. & Sawhney, M. 2009. Seaweeds and their mariculture. *The encyclopedia of ocean sciences,* pp*. 4477–4487.* Oxford, Elsevier.

Chopin, T. & Robinson, S. 2004. Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practices: introduction to the workshop and positioning of the issues. *Bulletin of the Aquaculture Association of Canada*, 104: 4–10.

Chou, H.N. & Lu, H.K. 1989. Protoplasts from seaweeds: isolation, culture and fusion. *In* S. Miyachi, I. Karube & Y. Ishida, eds. *Current topics in marine biotechnology*, pp. 227–230. Jap Soc Mar Biotechnol, Tokyo.

Chung, I.K. & Lee, J.A. 2014. *Mitigation potential of seaweed aquaculture beds in Asia-Pacific countries*. Paper presented at World Aquaculture 2015 Gunagzhou, China. 18–21 December 2014.

Circular Ecology. 2016. *Sustainable development*. (also available at www.circularecology.com/sustainability-and-sustainable-development.html#.WBZjJ4WcHg8).

Conklin, E.J. & Smith, J.E. 2005. Abundance and spread of the invasive red algae, *Kappaphycus* spp., in Kane'ohe Bay, Hawai'i and an experimental assessment of management options. *Biological Invasions*, 7: 1029–1039.

Corey, P., Kim, J.K., Duston, J. & Garbary, D.J. 2014. Growth and nutrient uptake by *Palmaria palmata* integrated with Atlantic halibut in a land-based aquaculture system. *Algae*, 29: 35–45.

Cornwall, C.E., Hepburn, C.D., Pritchard, D., Currie, K.I., McGraw, C.M., Hunter, K.A. & Hurd, C.L. 2012. Carbon-use strategies in macroalgae: differential responses to lowered pH and implications for ocean acidification. *Journal of Phycology*, 48: 137–144.

Correa, J.A. & Flores, V. 1995. Whitening, thallus decay and fragmentation in *Gracilaria chilensis* associated with an endophytic amoeba. *Journal of Applied Phycology*, 7: 421–425.

Correa, J.A. & McLachlan, J.L. 1991. Endophytic algae of *Chondrus crispus* (Rhodophyta). 3. Host specificity. *Journal of Phycology*, 27: 448–459.

Correa, J.A. & McLachlan, J.L. 1992. Endophytic algae of *Chondrus crispus* (Rhodophyta). 4. Effects on the host following infections by *Acrochaete operculata* and *A. heteroclada* (Chlorophyta). *Marine Ecology Progress Series*, 81: 73–87.

Correa, J.A. & McLachlan, J.L. 1994. Endophytic algae of *Chondrus crispus* (Rhodophyta). 5. Fine structure of the infection by *Acrochaete operculata* (Chlorophyta). *European Journal of Phycology*, 29: 33–47.

Coury, D.A., Naganuma, T., Polne-Fuller, M. & Gibor, A. 1993. Protoplasts of *Gelidium robustum* (Rhodophyta). *Hydrobiologia*, 260/261: 421–427.

Craigie, J.S. & Correa, J.A. 1996. Etiology of infectious diseases in cultivated *Chondrus crispus* (Gigartinales, Rhodophyta). *Hydrobiology*, 116: 97–104.

Critchley, A.T., Largo, D., Wee, W., Bleicher-L'honneur, G., Hurtado, A.Q. & Schubert, J. 2004. A preliminary summary on *Kappaphycus* farming and the impact of epiphytes. *Japan Journal of Phycology*, 52: 231–232.

Cromey, C.J., Nickell, T.D. & Black, K.D. 2002. DEPOMOD-modelling the deposition and biological effects of waste solids from marine cage farms. *Aquaculture*, 214: 211–239.

Dai, J., Zhang, Q. & Bao, Z. 1993. Genetic, breeding and seedling raising experiments with *Porphyra* protoplasts. *Aquaculture*, 111: 139–145.

Dawes, C.J. & Koch, E.W. 1991. Branch micropropagule and tissue culture of the red alga *Eucheuma denticulatum* and *Kappaphycus alvarezii* farmed in the Philippines. *Journal of Applied Phycology*, 3: 247–257.

Dawes, C.J., Trono, G.C. Jr. & Lluisma, A.O. 1993. Clonal propagation of *Eucheuma denticulatum* and *Kappaphycus alvarezii* for Philippine seaweed farms. *Hydrobiologia*, 260/261: 379–383.

De Paula, E.J., Pereira, R.T.L. & Ohno, M. 1999. Strain selection in *Kappaphycus alvarezii* var. *alvarezii* (Solieriaceae, Rhodophyta) using tetraspore progeny. *Journal of Applied Phycology*, 11: 111–121.

Dewey, F.M., Donnelly, K.A. & Foster, D. 1983. *Penicillium waksmanii* isolated from a red seaweed, *Eucheuma striatum. Transactions of the British Mycological Society*, 81: 433–434.

Dewey, F.M., Hunter-Blair, C.M. & Banbury, G.H. 1984. Isolation of *Scopulariopsis brevicaulis* from *Eucheuma striatum* and its ability to degrade seaweeds and their soluble products. *Transactions of the British Mycological Society*, 83: 621–629.

Ding, H. & Ma, J. 2005. Simultaneous infection by red rot and chytrid diseases in *Porphyra yezoensis* Ueda. *Journal of Applied Phycology*, 17:51–56. doi: 10.2225/vol13-issue2-fulltext-7.

Doty, M.S. 1973. Farming the red seaweed, *Eucheuma*, for carrageenans. *Micronesica*, 9:59–73.

Doty, M.S. & Alvarez, V. 1973. Seaweed farms: a new approach for U.S. industry. *Marine Technology Society Annual Conference Paper*, 9: 701–708.

Doty, M.S. & Alvarez, V.B. 1981. *Eucheuma* farm productivity. *International Seaweed Symposium*, 8: 688–691.

Edwards, M. & Watson, L. 2011. Cultivating *Laminaria digitata*. *Aquaculture Explained No. 26*. Bord lascaigh Mhara, Irish Sea Fisheries Board. 72 pp.

Egan, S., James, S., Holmstrom, C. & Kjelleberg, S. 2001. Inhibition of algal spore germination by the marine bacterium *Pseudoalteromonas tunicata*. *FEMS Microbiology and Ecology*, 35: 67–73.

Eigner-Thiel, S., Schmehl, M., Ibendorf, J. & Geldermann, J. 2013. Assessment of different bioenergy concepts in terms of sustainable development. *In* H. Ruppert, M. Kappas & J. Ibendorf, eds. *Sustainable bioenergy production – an integrated approach,* 339–384. Dordrecht, Springer, Netherlands.

Enomoto, K. & Hirose, H. 1972. Culture studies on artificially induced aplanospores in the marine alga *Boergesenia forbesii* (Harvey) Feldman (Chlorophyceae, Siphonocladales). *Phycologia*, 11: 119–122.

Ezura, Y., Yamamoto, H. Kimura, T. 1988. Isolation of a marine bacterium that produces red-spots on the culture bed of makonbu *Laminaria japonica* cultivation. *Nippon Suisan Gakkaishi*, 54: 665– 672.

Fang, J.G, Kuang, S., Sun, H., Li, F., Zhang, A., Wang, X. & Tang, T. 1996a. Mariculture status and optimizing measurements for the culture of scallop *Chlamys farreri* and kelp *Laminaria japonica* in Sanggou Bay. *Mar Fish Res*, 17: 95–102.

Fang, J.G., Sun, H.L., Yan, J.P., Kuang, S.H., Feng, L.I., Newkirk, G.F. & Grant, J. 1996b. Polyculture of scallop *Chlamys farreri* and kelp *Laminaria japonica* in Sungo Bay. *Chinese Journal of Oceanology and Limnology*, 14:322–329.

Fang, J. & Zhang, J. 2015. Types of integrated multi-trophic aquaculture practiced in China. *World Aquaculture*, 46: 26–30.

Fang, J., Zhang, J., Xiao, T., Huang, D. & Liu, S. 2016. Integrated multi-trophic aquaculture (IMTA) in Sanggou Bay, China. *Aquaculture Environment Interactions*, 8: 201–205.

FAO. 2014. Fishery and Aquaculture Statistics 2012. Rome.

Folke, C. & Kautsky, N. 1989. The role of ecosystems for a sustainable development of aquaculture. *Ambio*, 18: 234–243

Forster, J. 2008. Off-shore aquaculture – the great American debate. *Global Aquaculture Advocate*, 10: 18–20.

Freitas, J.R.C. Jr., Morrondo, J.M.S. & Ugarte, J.C. 2016. *Saccharina latissima* (Laminariales, Ochrophyta) farming in an industrial IMTA system in Galicia (Spain). *Journal of Applied Phycology*, 28: 377–385.

Fujimura, T., Kawai, T., Shiga, M., Kajiwara, T. & Hatanaka, A. 1989. Regeneration of protoplasts into complete thalli in the marine green alga *Ulva pertusa*. *Nippon Suisan Gakkaishi*, 55: 1353–1359.

Fujita, Y. 1993. Crossbreeding of green and red algae by cell fusion. *Kaiyo Monthly*, 25: 690–695.

Fujita, Y. & Migita, S. 1985. Isolation and culture of protoplasts from seaweeds. *Bulletin Faculty of Fisheries*, *Nagasaki University*, 57: 39–45.

Fujita, Y. & Migita, S. 1987. Fusion of protoplasts from thalli of two different color types in *Porphyra yezoensis* Ueda and development of fusion products. *Japan Journal of Phycology*, 35: 201–208.

Fujita, Y. & Saito, M. 1990. Protoplasts isolation and fusion in *Porphyra* (Bangiales, Rhodophyta). *Hydrobiologia*, 204/205: 161–166.

Gan, S.Y., Qin, S., Othman, R.Y., Yu, D. & Phang, S.M. 2003. Transient expression of *lacZ* in particle bombarded *Gracilaria changii* (Gracilariales, Rhodophyta). *Journal of Applied Phycology*, 15: 345–349.

Gan, S.Y., Qin, S., Othman, R.Y., Yu, D. & Phang, S.M. 2004. Development of a transformation system for *Gracilaria changii* (Gracilariales, Rhodophyta), a Malaysian red alga via microparticle bombardment. The 4th Annual Seminar of National Science Fellowship. *BIO*, 08: 45–48.

Garrett, K.A., Nita, M., De Wolf, E.D., Gomez, L. & Sparks, A.H. 2009. Plant pathogens as indicators of climate change. *In* T. Letcher, ed. *Climate change: observed impacts on planet Earth*, pp. 425–437. Dordrecht: Elsevier.

Gong, Q., Yu, W., Dai, J., Liu, H., Xu, R., Guan, H. & Pan, K. 2005. Efficient gusA transient expression in *Porphyra yezoensis* protoplasts mediated by endogenous beta-tubulin flanking sequences. *Journal of Ocean University of China*, 6: 21–25.

Gowen, R.J. & Bradbury, N.B. 1987. The ecological impact of salmonid farming in coastal waters: a review. *Oceanography and Marine Biology Annual Review*, 25: 563–575.

Gutierrez, A., Correa, T., Muñoz, V., Santibañez, A., Marcos, R., Caceres, C. & Buschmann, A.H. 2006. Farming of the giant kelp *Macrocystis pyrifera* in southern Chile for development of novel food products. *Journal of Applied Phycology*, 18: 259–267.

Hado, M., Okauchhi, M., Murase, N. & Mizukami, Y. 2003. Transient expression of GUS gene using Rubisco gene promoter in the protoplasts of *Porphyra yezoensis*. *Suisan Zoushoku*, 51: 355–360.

Hafting, J.T. 1999. A novel technique for propagation of *Porphyra yezoensis* Ueda blades in suspension cultures via monospores. *Journal of Applied Phycology*, 11: 361–367.

Handå, A. 2012. *Cultivation of mussels (*Mytilus edulis*): feed requirements, storage and integration with salmon (*Salmo salar*) farming*. Ph.D. Dissertaion at Norwegian University of Science and Technology, Trondheim, Norway. 164 pp.

Handayani, T., Alimuddin, A., Widyastuti, U., Suryati, E. & Parengrengi, A. 2014. Binary vector construction and *Agrobacterium tumefaciens*-mediated transformation on lyzsozome gene in seaweed *Kappaphycus alvarezii. BIOTROPIA*, 21: 80–90.

Hanniffy, D. & Kraan, S. 2006. BIOPURALG: reducing the environmental impact of land-based aquaculture through cultivation of seaweeds. (also available at www.thefishsite.com).

Hayashi, L., Bulboa, C., Kradolfer, P., Soriano, G. & Robledo, D. 2014. Cultivation of red seaweeds: a Latin American perspective. *Journal of Applied Phycology*, 26: 719–727.

Hayashi, L., Yokoya, N.S., Kikuchi, D.M. & Oliveira, E.C. 2008. Callus induction and micropropagation improved by colchicines and phytoregulators in *Kappaphycus alvarezii* (Rhodophyta, Solieriacea). *Journal of Applied Phycology*, 20: 653–659.

He, P., Yao, Q., Chen, Q., Guo, M., Xiong, A., Wu, W. & Ma, J. 2001. Transferring and expression of glucose oxidase gene in *Porphyra yezoensis*. *Journal of Phycology*, 37: 23 (supplement).

Heesch, S. & Peters, A.F. 1999. Scanning electron microscopy observation of host entry by two brown algae endophytic in *Laminaria saccharina* (Laminariales, Phaeophyceae). *Phycological Research*, 47: 1–5.

Hirata, H., Yamasaki, S., Maenosono, H., Nakazono, T., Yamauchi, T. & Matsuda, M. 1994. Relative budgets of pO_2 and pCO_2 in cage polycultured red sea bream, *Pagrus major* and sterile *Ulva* sp. *Suisanzoshoku*, 42: 377–381.

Ho, J. & Hong, J.S. 1988. Harpacticoid copepods (Thalestridae) infesting the cultivated Wakame (brown alga, *Undaria pinnatifida*) in Korea. *Journal of Natural History*, 22: 1623–1637.

Holdt, S.L. 2011. *Bioactive components in algae*. Paper presented at Algal Plant Bioteck, Denmark Meeting. 3–4 March 2011.

Holdt, S.L. & Edwards, M.D. 2014. Cost-effective IMTA: a comparison of the production efficiencies of mussels and seaweed. *Journal of Applied Phycology*, 26: 933–945.

Huang, X., Weber, J.C., Hinson, T.K., Mathieson, A.C. & Minocha, S.C. 1996. Transient expression of the GUS reporter gene in the protoplasts and partially digested cells of *Ulva lactuca* L (Chlorophyta). *Botanica Marina*, 39: 467–474.

Huddy, S.M., Meyers, A.E. & Coyne, V.E. 2013. Protoplast isolation optimization and regeneration of cell wall in *Gracilaria gracilis* (Gracilariales, Rhodophyta). *Journal of Applied Phycology*, 25: 433–443.

Hughes, A.D., Black, K.D., Campbell, I., Heymans, J.J., Orr, K.K., Stanley, M.S. & Kelly, M.S. 2013. Comments on “Prospects for the use of macroalgae for fuel in Ireland and UK: an overview of marine management issues”. *Marine Policy*, 38: 554–556.

Hurtado, A.Q. & Biter, A. 2007. Plantlet regeneration of *Kappaphycus alvarezii* var. *adik adik* by tissue culture. *Journal of Applied Phycology*, 19: 783–786.

Hurtado, A.Q. & Cheney, D.P. 2003. Propagule production of *Eucheuma denticulatum* (Burman) Collins et Hervey by tissue culture. *Botanica Marina*, 46: 338–341.

Hurtado, A.Q. & Critchley, A.T. 2006. Seaweed industry of the Phillipines and the problem of epiphytism in *Kappaphycus* farming. *In* S.M. Phang, A.T. Critchley & P.O. Ang, eds. *Advances in seaweed cultivation and utilisation in Asia*, pp. 21–28. University of Malaya, Kuala Lumpur.

Hurtado, A.Q., Critchley, A.T., Trespoey, A. & Bleicher-L'Honneur, G. 2006. Occurrence of *Polysiphonia* epiphytes in *Kappaphycus* farms at Calaguas Island, Camarines Norte, Philippines. *Journal of Applied Phycology*, 18: 301–306.

Hurtado, A.Q., Gerung, G.S., Yasir, S. & Critchley, A.T. 2014. Cultivation of tropical red seaweeds in the BIMP-EAGA region. *Journal of Applied Phycology*, 26: 702–718.

Hurtado, A.Q., Yunque, D.A., Tibubos, K. & Critchley, A.T. 2009. Use of Acadian marine plant extract powder from *Ascophyllum nodosum* in tissue culture of *Kappaphycus* varieties. *Journal of Applied Phycology*, 21: 633–639.

Hurtado-Ponce, A.Q. 1993. Harvesting *Gracilariopsis hetroclada* (Gracilariales, Rhodophyta in Iloilo), Philippines. *Philippine Journal of Science*, 122: 413–423.

Hurtado-Ponce, A.Q., Agbayani, R.F. & Samonte-Tan, G.P.B. 1997. Growth rate, yield and economics of *Gracilariopsis bailinae* (Gracilariales, Rhodophyta) using fixed-bottom long line method. *Philippine Journal of Science*, 126: 251–259.

Hurtado-Ponce, A.Q, Samonte, G., Luhan, G.P.B., Ma, R.J. & Guanzon, N.G., Jr. 1992. *Gracilaria* farming in Western Visayas, Philippines. *Aquaculture*, 105: 233–240.

Hwang, E.K., Hwang, I.K., Park, E.J., Gong, Y.G. & Park, C.S. 2014. Development and cultivation of F_2 hybrid between *Undariopsis peterseniana* and *Undaria pinnatifida* for abalone feed and commercial mariculture in Korea. *Journal of Applied Phycology*, 26: 747–752.

Hwang, E.K., Baek, J.M., & Park, C.S. 2009. Cultivation of the green alga, *Codium fragile* (Suringar) Hariot) by aritificial seed production in Korea. *Journal of Applied Phycology,* 20: 19-25.

Inoue, A., Kagaya, M. & Ojima, T. 2008. Preparation of protoplasts from *Laminaria japonica* using native and recombinant abalone alginate lyases. *Journal of Applied Phycology*, 20: 633–640.

Ishikawa, Y. & Saga, N. 1989. Diseases of economically valuable seaweeds and their pathology in Japan. Proceedings of the First International Marine Biotechnology Conference (IMBC '89), pp. 215–218. Tokyo, Japan.

Israel, A. & Hophy, M. 2002. Growth, photosynthetic properties and Rubisco activities and amounts of marine macroalgae grown under current and elevated seawater CO_2 concentrations. *Global Change Biology,* 8: 831–840.

Japan Ministry of Agriculture, **Forestry and Fisheries**, 2014.

Ji, Y., Xu, Z., Zou, D. & Gao, K. 2016. Ecophysiological responses of marine macroalgae to climate change factors. *Journal of Applied Phycology*, 28: 2953-2967.

Jiang, J., Ma, Y., Zhang, Z. & Xu, H. 1997. The histopathological study on "green decay diseases" of *Undaria pinnatifida* in Dalian. *Journal of Dalian Fisheries*, *University/Dalian Shuichan Xueyuan Xuebao,* 12: 7–12.

Jiang, P., Qin, S. & Tseng, C.K. 2002. Expression of hepatitis B surface antigen gene (*HBsAg*) in *Laminaria japonica* (Laminariales, Phaeophyta). *Chinese Science Bulletin*, 47: 1438–1440.

Jiang, P., Qin, S. & Tseng, C.K. 2003. Expression of the lacZ reporter gene in the sporophytes of the seaweed *Laminaria japonica* (Phaeophyceae) by gametophyte-targeted transformation. *Plant Cell Report*, 21: 1211–1216.

Jiang, Z., Fang, J. & Zhang, J. 2009. Nutrient budget in marine fish cage culture system and integrated multi-trophic aquaculture (IMTA) scheme. In *2nd YSLME Regional Mariculture Conference Towards Sustainability in Yellow Sea Mariculture.*16–18 June. (Abstract only)

Jie, K. 1987. Protoplast fusion of *Enteromorpha linza* and *Ulva pertusa*. Marine Fisheries Research, 08.

Kakinuma, M., Ikeda, M., Coury, D.A., Tominaga, H., Kobayashi, I. & Amano, H. 2009. Isolation and characterization of the *rbcS* genes from a sterile mutant of *Ulva pertusa* (Ulvales, Chlorophyta) and transient gene expression using the *rbcS* gene promoter. *Fisheries Science*, 75: 1015–1028.

Kang, J.W. 1982. Some seaweed diseases occurred at seaweed farms along the south-eastern coast of Korea. *Bulletin of the Korean Fisheries Society*, 14: 165–170.

Kawashima, Y. & Tokuda, H. 1993. Regeneration from the callus of *Undaria pinnatifida* (Harvey) Suringar (Laminariales, Phaeophyta). *Hydrobiologia*, 260/261: 385–389.

Kelly, M.S. & Dworjanyn, S. 2008. The potential of marine biomass for anaerobic biogas production: a feasibility study with recommendations for further research. (also available at www.thecrownestate.com)

Kim, Y.D., Park, M.S., Min, B.H., Jeong, S.J., Kim, H.C., Yoo, H.I., Won-Chan Lee, W.C. & Choi, J.S. 2014. Study on growth characteristics of *Sargassum fulvellum* in the integrated multi-trophic aquaculture (IMTA) system. *Journal of Environmental Science International*, 23: 1703–1718.

Kim, J.K., Yarish, C., Hwang, E.K. Park, M., & Kim, YD. 2017. Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services. *Algae*, 32: 1-13.

Kimura, T., Ezura, Y. & Tajima, K. 1976. Microbiological study of a disease of wakame (*Undaria pinnatifida*) and of the marine environments of wakame culture sites in Kesennuma Bay. *Bulletin of the Tohoku Regional Fisheries Research Laboratory*, 36: 57–65.

Kito, H., Akiyama, K. & Sasaki, M. 1976. Electron microscopic observations on the diseased thalli of *Undaria pinnatifida* (Harvey) Suringar, caused by parasitic bacteria. *Bulletin of the Tokohu Regional Fisheries Research Laboratory*, 36: 67–73.

Kito, H., Kunimoto, M., Kamanishi, Y. & Mizukami, Y. 1998. Protoplasts fusion between *Monostroma nitidum* and *Porphyra yezoensis* and subsequent growth of hybrid plants. *Journal of Applied Phycology*, 10: 15–2.

Kloareg, B., Polne-Fuller, M. & Gibor, A. 1989. Mass production of viable protoplasts from *Macrocystis pyrifera* (L.) C. Ag. (Pheophyta). *Plant Science*, 62: 105–112.

Klochkova, T.A., Shin, Y.J., Moon, K.H., Motomura, T. & Kim, G.H. 2016. New species of unicellular obligate parasite, *Olpidiopsis pyropiae* sp. nov., that plagues *Pyropia* sea farms in Korea. *Journal of Applied Phycology,* 28: 73–83.

Kobayashi, K. 1975. Growth of extra cellular protoplast of *Bryopsis maxima* in an agar medium. *Bulletin of Tokyo Gakugei University*, 27: 1–5.

Kohlmeyer, J. 1968. Revisions and descriptions of algicolous marine fungi. *Phytopathologische Zeitschrift*, 63: 341–363.

Korea Ministry of Oceans and Fisheries. 2015.

Kraan, S. 2010. Mass-cultivation of carbohydrate rich macroalgae, a possible solution for sustainable biofuel production. *Mitigation and Adaption Strategies for Global Change,* 18(1): 1–20. doi: 10.1007/s11027-010-9275-5.

Kraan, S. 2015. IMTA in an international context and the applications of harvested biomass. Paper presented at Horsen, Denmark, 15 June 2015.

Kuang, M., Wang, S.J., Li, Y., Shen, D.L. & Zeng, C.K. 1998. Transient expression of exogenous GUS gene in *Porphyra yezoensis* (Rhodophyta). *Chinese Journal of Oceanology and Limnology*, 16: 56–61.

Kurtzman, A.M. & Cheney, D.P. 1991. Direct gene transfer and transient expression in a marine red alga using the biolistic method. *Journal of Phycology*, 27: 42 (supplement).

Lamprianidou, F., Telfer, T. & Ross, L. 2015. A model for optimization of the productivity and bioremediation efficiency of marine integrated multitrophic aquaculture. *Estuarine, Coastal and Shelf Science*, 164: 253–264.

Largo, D.B., Diola, A.G. & Marabahol, M.S. 2016. Development of an integrated multi-trophic aquaculture (IMTA) system for tropical marine species in southern Cebu, Central Philippines. *Aquaculture Reports*, 3: 67–76.

Largo, D.B., Fukami, F., Nishijima, T. & Ohno, M. 1995a. Laboratory-induced development of the ice-ice disease of the farmed red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology*, 7: 539–543.

Largo, D.B., Fukami, K. & Nishijima, T. 1995b. Occasional pathogenic bacteria promoting ice-ice disease in the carrageenan-producing red algae *Kappaphycus alvarezii* and *Eucheuma denticulatum* (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology*, 7: 545–554.

Largo, D.B., Fukami, K. & Nishijima, T. 1999. Time-dependent attachment mechanism of bacterial pathogen during ice-ice infection in *Kappaphycus alvarezii* (Gigartinales, Rhodophyta). *Journal of Applied Phycology*, 11: 129–136.

Lavilla-Pitogo, C.R. 1992. Agar-digesting bacteria associated with "rotten thallus syndrome" of*Gracilaria* sp. *Aquaculture*, 102: 1–7.

Lefebvre, S., Barillé, L. & Clerc, M. 2000. Pacific oyster (*Crassostrea gigas*) feeding responses to a fish-farm effluent. *Aquaculture*, 187: 185–198.

Li, F., Qin, S., Jiang, P., Wu, Y. & Zhang, W. 2009. The integrative expression of GUS gene driven by FCP promoter in the seaweed *Laminaria japonica* (Phaeophyta). *Journal of Applied Phycology*, 21: 287–293.

Li, H., Liu, J. & Pang. T. 2015. Callus induction and morphogenesis of callus in *Kappaphycus alvarezii. Acta Oceanologica Sinica*, 37: 52–61.

Li, X., Zhang, Z., Qu, S., Liang, G., Sun, J., Zhao, N., Cui, C., Cao, Z., Li, Y., Pan, J., Yu, S., Wang, Q., Li, X., Luo, S., Song, S., Guo, L. & Yang, G. 2016. Improving seedless kelp (*Saccharina japonica*) during its domestication by hybridizing gametophytes and seedling-raising from sporophytes. *Scientific Reports*, 6: 21255. doi: 10.1038/srep21255.

Liu, C., Wang, L., Wang, M. & Tang, X. 2002. Difference analysis of infection activity of alginic acid decomposing bacteria infecting *Laminaria japonica*. *Marine sciences/Haiyang Kexue*, 26: 44– 47.

Liu, J.G., Pang, T., Wang, L., Li, J. & Lin, W. 2009. The reasons causing catastrophic death in tropical carrageenan producing seaweeds and their difference in resistance to illness. *Oceanology et Limnologia Sinica*, 40: 235–241.

Liu, Q.Y., Chen, L.C.M. & Taylor, A.R.A. 1992. Ultrastructure of cell wall regeneration by isolated protoplasts of *Palmaria palmata* (Rhodophyta). *Botanica Marina*, 35: 21–33.

Liu, S., Pan, X., Wang, C. & Yue, H. 2003. Surveying and analysis of diseases of aquacultured species in Shandong. *Transactions of Oceanology and Limnology/Haiyang Huzhao Tongbao*, 97: 78–88.

Luhan, M.R.J. & Sollesta, H. 2010. Growing the reproductive cells (carpospores) of the seaweed, *Kappaphycus striatum*, in the laboratory until outplanting in the field and maturation to tetrasporophyte. *Journal of Applied Phycology*, 22:5 79–585.

Lund, S. 1959. The marine algae of East Greenland. I. Taxonomical part. *Meddr Grnland*, 156: 1–247. **Ma, Y., Yang, Z., Wan, L., Ge, M. & Zhang, K.** 1998. *Pathogenic bacteria of spot decay disease found in* Undaria pinnatifida. Proceedings of International Symposium on Progress and Prospect of Marine Biotechnology (ISPPMB '98). Qingdao, China. pp. 356–360.

Ma, Y., Zhang, Z., Fan, C. & Cao, S. 1997a. Study on the pathogenic bacteria of spot decay disease of *Undaria pinnatifida* in Dalian. *Journal of Fishery Sciences of China/Zhongguo Shuichan Kexue*, 4: 62–65.

Ma, Y., Zhang, Z., Liu, C., Fan, C. & Cao, S. 1997b. Study on the pathogenic bacteria of green decay disease of *Undaria pinnatifida* in Dalian. *Journal of Fishery Sciences of China/Zhongguo Shuichan Kexue*, 4: 66–69.

Mandal, S., Freije, W.A., Guptan, P. & Banerjee, U. 2010. Metabolic control of G1-S transition: cyclin E degradation by p53-induced activation of the ubiquitin-proteasome system. *JCB*, 88: 473– 479.

Marinho, G.S., Holdt, S.L., Birkeland, M.J. & Angelidaki, I. 2015. Commercial cultivation and bioremediation potential of sugar kelp, *Saccharina latissima*, in Danish waters. *Journal of Applied Phycology*, 27: 1963–1973.

Martin, S. & Gattuso, J.P. 2009. Response of Mediterranean coralline algae to ocean acidification and elevated temperature. *Global Change Biology*, 15: 2089–2100.

Matos, J., Costa, S., Rodrigues, A., Pereira, R. & Sousa-Pinto, I. 2006. Experimental integrated aquaculture of fish and red seaweeds in Northern Portugal. *Aquaculture,* 252: 31-42.

Matsumoto, M., Kawashima, Y. & Fukui, E. 1995. Transduction of high temperature-tolerant to *Porphyra* by cell fusion. *Kaiyo Monthly*, 27: 677–682.

Matsumura, W., Yasui, H. & Yamamoto, H. 2000. Mariculture of *Laminaria japonica* (Laminariales, Phaeophyceae) using protoplast regeneration. *Phycology Research*, 48: 169–176.

Metaxa, E., Deviller, G., Pagand, P., Alliaume, C., Casellas, C. & Blancheton, J.P. 2006. High rate algal pond treatment for water reuse in a marine fish recirculation system: water purification and fish health. *Aquaculture*, 252: 92–101.

Mikami, K. 2013. Current advances in seaweed transformation. *In G.R.* Baptista, ed. An integrated view of the molecular recognition and toxinology: from analytical procedures to biomedical applications. *Intech,* 323–347.

Mikami, K., Hirata, R., Takahashi, M., Toshiki Uji, T. & Saga, N. 2011. Transient transformation of red algal cells: breakthrough toward genetic transformation of marine crop *Porphyra* Species. *In* M.A. Alvarez, ed. *Genetic Transformation*, 241–258.

Mikami, K., Uji, T., Li, L., Takahashi, M., Yasui, H. & Saga, N. 2009. Visualization of phosphoinostides via the development of the transient expression system of a cyan fluorescent protein in the red alga *Porphyra yezoensis*. *Marine Biotechnology*, 11: 563–569.

Millner, P.A., Callow, M.E. & Evans, L.V. 1979. Preparation of protoplasts from the green alga *Enteromorpha intestinalis* (L.). *Planta* (Berlin), 147: 174–177.

Mizukami, Y., Hado, M., Kito, H., Kunimoto, M. & Murase, N. 2004. Reporter gene introduction and transient expression in protoplasts of *Porphyra yezoensis*. *Journal of Applied Phycology*, 16: 23–29.

Mizukami, Y., Okauchi, M., Kito, H., Ishimoto, S., Ishida, T. & Fuseya, M. 1995. Culture and development of electrically fused protoplasts from red marine algae, *Porphyra yezoensis* and *P. suborbiculata*. *Aquaculture*, 132: 361–367.

Msuya, F.E., Buriyo, A., Omar, I., Pascal, B., Narrain, K., Ravina, J.J.M., Mrabu, E. & Wakibia, J.G. 2014. Cultivation and utilisation of red seaweeds in the Western Indian Ocean (WIO) Region. *Journal of Applied Phycology*, 26: 699–705.

Muñoz, J., Cahue-López, A., Patiño, R. & Robledo, D. 2006. Use of plant growth regulators in micropropagation of *Kappaphycus alvarezii* (Doty) in airlift bioreactors. *Journal of Applied Phycology*, 18: 209–218.

Murphy, F., Devlin, G., Deverell, R. & McDonnell, K. 2013. Biofuel production in Ireland – an approach to 2020 targets with a focus on algal biomass. *Energies*, 6: 6391–6412.

Myers, A.A. 1974. *Amphitholina cuniculus* (Strebing), a little known marine amphipod crustacean new to Ireland. *Proceedings of the Royal Irish Academy*, 74: 463–469.

Nakao, Y., Onohara, T., Matsubara, T., Fujita, Y. & Zenitani, B. 1972. Bacteriological studies on diseases of cultured laver. I. Green spot rotting-like deterioration of laver frond by bacteria in vitro. *Bulletin of the Japanese Society of Scientific Fisheries*, 38: 561–564.

Neori, A., Troell, M., Chopin, T., Yarish, C., Critchley, A. & Buschmann, A. 2007. The need for a balanced ecosystem approach to blue revolution aquaculture. *Environment*, 49: 37–43.

Neves, F.A.S., Simioni, C., Bouzon, Z.L. & Hayashi, L. 2015. Effects of spindle inhibitors and phytoregulators on the micropropagation of *Kappaphycus alvarezii* (Rhodophyta, Gigartinales). *Journal of Applied Phycology*, 27: 437–445.

Nielsen, R. 1979. Culture studies on the type species of *Acrochaete*, *Bolbocoleon* and *Entocladia* (Chaetophoraceae, Chlorophyceae). *Botaniska Notiser*, 132: 441–449.

Nikolaeva, E.V., Usov, A.I., Sinitsyn, A.P. & Tambiev, A.H. 1999. Degradation of agarrophytic red algal cell wall components by new crude enzyme preparations. *Journal of Applied Phycology* 11: 385–389.

Norambuena, F., Hermon, K., Skrzypczyk, V., Emery, J.A., Sharon, Y., Beard, A. & Turchini, G.M. 2015. *Algae in fish feed: performances and fatty acid metabolism in juvenile Atlantic salmon*. PLoS ONE 10(4): e0124042. doi:10.1371/journal.pone.0124042.

Okauchi, M. & Mizukami, Y. 1999. Transient β-Glucuronidase (GUS) gene expression under control of *CaMV 35S* promoter in *Porphyra tenera* (Rhodophyta). *Bulletin of National Research Institute of Aquaculture*, 4: 13–18 (supplement).

Pang, T., Liu, J., Liu, Q. & Lin, W. 2011. Changes of photosynthetic behaviors in *Kappaphycus alvarezii* infected by epiphyte. eCAM. doi: 10.1155/2011/658906.

Pang, T., Liu, J., Lin, Q. & Zhang, L. 2012. Impacts of glyphosate on photosynthetic behaviors in *Kappaphycus alvarezii* and *Neosiphonia savatieri* detected by JIP-text. *Journal of Applied Phycology*, 24: 467–473.

Pang, T., Liu, J., Qian Liu, Q., Li, H. & Li, J. 2015. Observations on pests and diseases affecting a eucheumatoid farm in China. *Journal of Applied Phycology*, 27: 1975–1984.

Paravano, L. 2015. *Myths and genuine opportunities in seaweed industries, the* Gracilaria *case*. Third Indonesia Seaweed Forum, Makassar, Indonesia. 12–14 November 2015.

Park, T.S., Rho, Y.G., Gong, Y.G. & Lee, D.Y. 1990. A harpacticoid copepod parasitic in the cultivated brown alga *Undaria pinnatifida* in Korea. *Journal of the Korean Fisheries Society*, 23: 439–442.

Parker, H.S. 1974. The culture of the red algal genus *Eucheuma* in the Philippines. *Aquaculture*, 3: 425–439.

Patwary, M.U. & van der Meer, J.P. 1982. Genetics of *Gracilaria tikvahiae* (Rhodophyceae). VIII. Phenotypic and genetic characterization of some selected morphological mutants. *Canadian Journal of Botany*, 60: 2556–2564.

Patwary, M.U. & van der Meer, J.P. 1983. Genetics of *Gracilaria tikvahiae* (Rhodophyceae) IX: Some properties of agars extracted from morphological mutants. *Botanica Marina*, 26: 295–299.

Pedersen, PM. 1976. Marine, benthic algae from southernmost Greenland. *Meddelelser om Grønland*, 199: 1–80.

Peters, A.F. 2003. Molecular identification, taxonomy and distribution of brown algal endophytes, with emphasis on species from Antarctica. *Proceedings of the International Seaweed Symposium*, 17: 293–302.

Peters, A.F. & Ellertsdottir, E. 1996. New record of the kelp endophyte *Laminarionema elsbetiae* (Phaeophyceae, Ectocarpales) at Helgoland and its life history in culture. *Nova Hedwigia*, 62:3 41–349

Phap, T.T. & Thuan, L.T.N. 2002. Tam Giang Lagoon aquatic systems health assessment. In J.R. Arthur, M.J. Phillips, R.P.Subasinghe, M.B. Reantaso, & I.H. MacRae, eds. *Primary aquatic animal health care in rural, small-scale, aquaculture development*, pp. 225–234. FAO Fisheries Technical Paper No. 406.

Phillipsen, A., Wild, M. & Verchick, A. 2014. Energy input, carbon intensity and cost for ethanol produced from farmed seaweed. *Renewable and Sustainable Energy Review*, 36: 609–623.

Polne-Fuller, M. & Gibor, A. 1987. Calluses and callus-like growth in seaweeds: induction and culture. *Hydrobiologia*, 151/152: 131–138.

Polne-Fuller, M., Rogerson, A., Amano, H. & Gibor, A. 1990. Digestion of seaweeds by the marine amoeba *Trichosphaerium*. *Hydrobiologia*, 204/205: 409–413.

Porse, H. & Rudolph, B. 2017. The seaweed hydrocolloids industry: 2016 updates, needs and outlook..Journal of Applied Phycology. DOI 10.1007/s10811-017-1144-0

Potin, P., Bouarab, K., Küpper, F. & Kloareg, B. 1999. Oligosaccharide recognition signals and defence reactions in marine plant-microbe interactions. *Current Opinion in Microbiology*, 2: 276– 283.

Potin, P., Bouarab, K., Salaun, J.P., Pohnert, G. & Kloareg, B. 2002. Biotic interactions of marine algae. *Current Opinion in Plant Biology*, 5: 308–317.

Putro, S.P., Widowati, W., Suhartana, S. & Muhammad, F. 2015. The application of integrated multi-trophic aquaculture (IMTA) using stratified double net rounded cage (SDFNC) for aquaculture sustainability. *International Journal of Scientific Engineering*, 9: 85–89.

Qin, S., Jiang, P., Li, X., Wang, X. & Zeng, C. 1998. A transformation model for *Laminaria japonica* (Phaeophyta, Laminariales). *Chinese Journal of Oceanology and Limnology*, 16: 50–55 (supplement 1).

Radulovich, R., Amir Neori, A., Valderrama, D., Reddy, C.R.K., Cronin, H. & Forster, J. 2015. Farming of seaweeds 2015.. In *Seaweed sustainability*. (also available at http://dx.doi.org/10.1016/B978-0-12-418697-2.00003-9).

Reddy, C.R.K. & Fujita, Y. 1989. Protoplast isolation and fusion of *Ulva pertusa* and *U. conglobata*. In S. Miyachi, I. Karube & Y. Ishida, eds. *Current topics in marine biotechnology*, pp. 235–238. Japan Society of Marine Biotechnology, Tokyo,

Reddy, C.R.K., Iima, M. & Fujita, Y. 1992. Induction of fast growing and morphologically different strains through intergeneric protoplasts fusion of *Ulva* and *Enteromorpha* (Ulvales, chlorophyta). *Journal of Applied Phycology*, 4: 57–65.

Reddy, C.R.K., Migita, S. & Fujita, Y. 1989. Protoplasts isolation and regeneration of three species of *Ulva* in axenic culture. *Botanica Marina*, 32: 483–490.

Reddy, C.R.K., Dipakkore, S., Rajakrishan Kumar, G., Jha, B., Cheney, D.P. & Fujita, Y. 2006. An improved enzyme preparation for rapid mass production of protoplast as seed stock for aquaculture of macrophytic marine green algae. *Aquaculture*, 260: 290–297.

Rheinheimer, G. 1992. *Aquatic microbiology*. Chichester, John Wiley & Sons. 363 pp.

Rho, Y.G., Gong, Y.G., Lee, D.Y., Cho, Y.C. & Jang, J.W. 1993. On the parasitic copepod (Harpacticoida) in the cultivated brown alga, *Undaria pinnatifida* (Harvey) Suringar. *Bulletin of National Fisheries Research and Development Institute (Korea)*, 47: 197–210.

Ridler, N., Barrington, K., Robinson, B., Wowchuk, M., Chopin, T., Robinson, S., Page, F., Reid, G., Szemerda, M., Sewuster, J. & Boyne-Travis, S. 2007. Integrated multi-trophic aquaculture. Canadian project combines salmon, mussels, kelps. *Global Aquaculture Advocate*, 10: 52–55.

Roberts, T. & Upham, P. 2012. Prospects for the use of macro-algae for fuel in Ireland and the UK: an overview of marine management issues. *Journal of Marine Policy*, 36: 1047–1053.

Robertson-Anderson, D.V., Potgieter, M., Hansen, J., Bolton, J.J., Troell, M., Anderson, R.J., Halling, C. & Probyn, T. 2008. Integrated seaweed cultivation on an abalone farm in South Africa. *Journal of Applied Phycology*, 20: 579–595.

Rodgers, S.K. & Cox, E.F. 1999. Rate of spread of introduced rhodophytes *Kappaphycus alvarezii, Kappaphycus striatum*, and *Gracilaria salicornia* and their current distributions in Kaneohe Bay, Oahu, Hawaii. *Pacific Science*, 53: 232–241.

Roleda, M.Y., Morris, J.N., McGraw, C.M. & Hurd, C.L. 2012. Ocean acidification and seaweed reproduction: increased CO_2 ameliorates the negative effect of lowered pH on meiospore germination in the giant kelp *Macrocystis pyrifera* (Laminariales, Phaeophyceae). *Global Change Biology*, 18: 854–864.

Rusing, A.M. & Cosson, J. 2001. Plant regeneration from protoplasts of *Enteromorpha intestinalis* (Chlorophyta, Ulvaphyceae) as seedstock for macroalgal culture. *Journal of Applied Phycology*, 13: 103–108.

Saga, N. 1984. Isolation of protoplasts from edible seaweeds. *Botany Magazine of Tokyo*, 97: 423–427.

Saga, N. & Sakai, Y. 1984. Isolation of protoplast from *Laminaria* and *Porphyra*. *Nippon Suisan Gakkaishi*, 50: 1085.

Saga, N., Polne-Fuller, M. & Gibor, A. 1986. Protoplasts from seaweeds: production and fusion. *Beih Nova Hedwigia*, 83: 37–43.

Salvador, R.C. & Serrano, A.E. 2005. Isolation of protoplasts from tissue fragments of Philippine cultivars of *Kappaphycus alvarezii* (Solieriaceae, Rhodophyta). *Journal of Applied Phycology*, 17: 15–22.

Sanderson, J.C. 2015. Maximizing production of *Palmaria palmata* (*Linnaeus*) *Weber & Mohr, 1805*. Final report to MASTS under visiting fellowship scheme.

Santelices, B. 1992. Strain selection of clonal seaweeds. *In* F.E. Round & D.J. Chapman, eds. *Progress in Phycological Research*, 8: 86–115.

Sawabe, T. & Ezura, Y. 1996. Regeneration from *Laminaria japonica* Areschoug (Laminariales, Phaeophyceae) protoplasts isolated with bacterial alginase. *Plant Cell Report*, 15: 892.

Sawabe, T., Ezura, Y. & Kimura, T. 1993. Application of an alginate lyase from *Alteromonas* sp. for isolation of protoplasts from a brown algae *Laminaria japonica*. *Bulletin of Japanese Society of Science and Fisheries*, 59: 705–709.

Sawabe, T., Ezura, Y. & Yamamoto, H. 1997. Plant regeneration from protoplasts of *Laminaria japonica* Areschoug (Laminariales, Phaeophyceae) in a continuous-flow culture system. *Plant Cell Report*, 17: 109–112.

Schatz, S. 1984. Degradation of *Laminaria saccharina* by saprobic fungi. *Mycologia*, 76: 426–432.

Schenk, P.M., Thomas-Hall, S.R., Stephens, E., Marx, U.C., Mussgnug, J.H., Posten, C., Kruse, O. & Hankamer, B. 2008. Second generation biofuels: high-efficiency microalgae for biodiesel production. *Bioenergy Research*, 1: 20–43.

Shan, T.S., Pang, S.J. & Gao, S.Q. 2013. Novel means for variety breeding and sporeling production in the brown seaweed *Undaria pinnatifida* (Phaeophyceae): crossing female gametophytes from parthenosporophytes with male gametophyte clones. *Phycological Research*, 61: 154–161.

Singh, D.V. 2007. Plant pathology (introductory plant pathology). 48 pp.

SINTEF. 2014. A new Norwegian bioeconomy based on cultivation and processing of seaweeds. Opportunities and research and development needs. SINTEF Fisheries and Aquaculture, Norway

Skar, C.K. & Mortensen, S. 2007. Fate of infectious salmon anaemia virus (ISAV) in experimentally challenged blue mussels *Mytilus edulis*. *Diseases of Aquatic Organisms*, 74: 1–6.

Smith, J.E., Hunter, C.L. & Smith, C.M. 2002. Distribution and reproductive characteristics of non-indigenous and invasive marine algae in the Hawaiian Islands. *Pacific Science*, 56: 299–315.

Solis, M.J.L., Draeger, S. & dela Cruz, T.E.E. 2010. Marine-derived fungi from *Kappaphycus alvarezii* and *K. striatum* as potential causative agents of *ice-ice* disease in farmed seaweeds. *Botanica Marina*, 53: 587–594.

Son, S.H., Ahn, J.W., Uji, T., Choi, D.W., Park, E.J., Hwang, M.S., Liu, J.R., Choi, D., Mikami, K. & Jeong, W.J. 2012. Development of a transient gene expression system in the red macroalga, *Porphyra tenera*. *Journal of Applied Phycology*, 24: 79–87.

Song, H.S. & Chung, G.H. 1988. Isolation and purification of protoplasts from *Porphyra tenera* thalli. *Aquaculture*, 1: 103–108.

Stanley, S.J. 1992. Observations on the seasonal occurrence of marine endophytic and parasitic fungi. *Canadian Journal of Botany*, 70: 2089–2096.

Stirling, H. & Okumus, I. 1995. Growth and production of mussels (*Mytilus edulis* L.) suspended at salmon and shellfish farms in two Scottish sea lochs. *Aquaculture*, 134: 193–210.

Sukiman, S., Rahman, F., Rohyani, I.S. & Akhyadi, H. 2014. Growth of seaweed *Eucheuma cottonii* in multi-trophic sea farming systems at Gerupuk Bay, Central Lombok, Indonesia. *Bioscience*, 6: 82–85.

Sulistiani, E., Soelistyowati, D.T., Alimuddin & Yani, S.A. 2012. Callus induction and filaments regeneration from callus of cottonii seaweed (*Kappaphycus alvarezii* (Doty) collected from Natuna Islands, Riao Island Province. *Biotropia*, 19: 103–114.

Sutherland, G.K. 1915. New marine phycomycetes. *Transactions of the British Mycological Society*, 5: 147–155

Sylvester, A.W. & Waaland, R. 1983. Cloning the red alga *Gigartina exasperata* for culture on artificial substrates. *Aquaculture*, 31: 305–318.

Takahashi, M., Uji, T., Saga, N. & Mikami, K. 2010. Isolation and regeneration of transiently transformed protoplasts from gametophytic blades of the marine red alga *Porphyra yezoensis*. *Electronic Journal of Biotechnology*, March 15, 2010, Vol. 13, No. 2 [cited date]. (also available at www.ejbiotechnology.cl/content/vol13/issue2/full/7/index.html. ISSN 0717-3458).

Tang, Q., Fang, J., Zhang, J., Jiang, Z. & Liu, H. 2013. Impacts of multiple stressors on coastal ocean ecosystems and integrated multi-trophic aquaculture. *Progress in Fisheries Science*, 34: 1–11.

Tang, X.X., Wang, Y., Huang, J., Yang, Z. & Gong, X.Z. 2001. Action of reactive oxygen species in *Laminaria japonica* against infection by alginic acid decomposing bacteria. *Acta Botanica Sinica*, 43: 1303–1306.

Tatewaki, M. & Nagata, K. 1970. Surviving protoplasts in vitro and their development in *Bryopsis*. *Journal of Phycology*, 6: 401–403.

Tisera, W. & Naguit, M.R.A. 2009. Ice-ice disease occurrence in seaweed farms in Bais Bay, Negros Oriental and Zamboanga del Norte. *The Threshold*, 4: 1–16.

Titlyanov, E.A., Titlyanova, T.V., Kadel, P. & Luning, K. 2006a. Obtaining plantlets from apical meristem of the red alga *Gelidium* sp. *Journal of Applied Phycology*, 18: 167–174.

Titlyanov, E.A., Titlyanova, T.V., Kadel, P. & Luning, K. 2006b. New methods of obtaining plantlets and tetraspores from fragments and cell aggregates of meristematic and submeristematic tissue of the red alga *Palmaria palmata*. *Journal of Experimental Marine Biology and Ecology*, 339: 55–64.

Tokuda, H. & Kawashima, Y. 1988. Protoplast isolation and culture from a brown alga, *Undaria pinnatifida*. *In* T. Stadler, J. Mollion, M.C. Verdus, Y. Karamanos, H. Morvan & D. Christaen, eds. *Algal Biotechnology*, pp. 151–157. London, Elsevier Applied Science.

Torney, F., Moeller, L., Scarpa, A. & Wang, K. 2007. Genetic engineering approaches to improve bioethanol production from maize. *Current Opinion in Biotechnology*, 18: 193–199.

Troell, M., Halling, C., Nilsson, A., Buschmann, A.H., Kautsky, N. & Kautsky, L. 1997. Integrated marine cultivation of *Gracilaria chilensis* (Gracilariales, Rhodophyta) and salmon cages for reduced environmental impact and increased economic output. *Aquaculture*, 156: 45–61.

Tsiresy, G., Preux, J., Lavitra, T., Dubois, P., Lepoint, G. & Eeckhaut, I. 2016. Phenology of farmed seaweed *Kappaphycus alvarezii* infestation by the parasitic epiphyte *Polysiphonia* sp. in Madagascar. *Journal of Applied Phycology*, 28: 2903-2914..

Tsukidate, J. 1971. Microbiological studies of *Porphyra* plants. III. Abnormality of the growth of *Porphyra* plants by the disturbance of the bacterial flora accompanying the plant. *Bulletin of the Nansei Regional Fisheries Research Laboratory,* 4: 1–12.

Tsukidate, J. 1977. Microbiological studies of *Porphyra* plants 5. On the relation between bacteria and *Porphyra* diseases. *Bulletin of the Nansei National Fisheries Research Institute*, 10: 101–112.

Tsukidate, J. 1991. *Seaweed disease. Fish health management in Asia-Pacific*. Report on a regional study and workshop on fish disease and fish health management, pp. 397–408. Bangkok, Thailand, ADB/NACA.

Uchida, T. & Arima, S. 1992. Regeneration of protoplasts isolated from the sporophyte of *Cladosiphon okamuranus* Tokida (Chordariaceae, Phaeophyta). *Japan Journal of Phycology*, 40: 261–266.

Uchida, A., Yoshikawa, T., Ishida, Y. & Saga, N. 1992. Stable protoplasts isolation and its regeneration into thallus of the marine green alga *Ulva pertusa*. *Nippon Suisan Gakkaishi*, 58: 153– 157.

Uji, T., Takahashi, M., Saga, N. & Mikami, K. 2010. Visualization of nuclear localization of transcription factors with cyan and green fluorescent proteins in the red alga *Porphyra yezoensis*. *Marine Biotechnology*, 212: 150–159.

Uppalapati, S.R. & Fujita, Y. 2002. A simple method for mass isolation of protoplasts from species of *Monostroma, Enteromorpha* and *Ulva* (Chlorophyta, Ulvales). *Journal of Applied Phycology*, 14: 165–168.

Uyenco, F.R., Saniel, L.S. & Gomez, E.D. 1977. Microbiology of diseased *Eucheuma striatum* Schmitz. *Journal of Phycology*, 13: 70–70.

Vairappan, C.S. 2006. Seasonal occurrences of epiphytic algae on the commercially cultivated red alga *Kappaphycus alvarezii* (Solieriaceae, Gigartinales, Rhodophyta). *Journal of Applied Phycology*, 18: 611–617.

Vairappan, C.S., Chung, C.S., Hurtado, A.Q., Msuya, F., Bleicher-L'Honneur, G. & Critchley, A.T. 2008. Distribution and malaise of epiphyte infection in major carrageenophyte-producing farms. *Journal of Applied Phycology*, 20: 477–483.

Vairappan, C.S., Suzuki, M., Motomura, T. & Ichimura, T. 2001. Pathogenic bacteria associated with lesions and thallus bleaching symptoms in the Japanese kelp *Laminaria religiosa* Miyabe (Laminariales, Phaeophyceae). *Hydrobiologia,* 445: 183–191.

Valderrama, D., Cai, J., Hishamunda, N. & Ridler, N. 2013. *Social and economic dimensions of carrageenan seaweed farming*. Fisheries and Aquaculture Technical Paper No. 580. Rome, FAO. 204 pp. (also available at www.fao.org/docrep/019/i3344e/i3344e00.htm).

Valente, L.M.P., Gouveia, A., Rema, P., Matos, J., Gomes, E.F. & Pinto, I.S. 2006. Evaluation of three seaweeds *Gracilaria bursa-pastoris, Ulva rigida* and *Gracilaria cornea* as dietary ingredients in European sea bass (*Dicentrarchus labrax*) juveniles. *Aquaculture*, 252: 85–91.

Van den Burg, S., Bikker, P., van Krimpen, M. & van Dujin, A.P. 2013. *Economic feasibility of offshore seaweed production in the North Sea*. Presentation at the Aquaculture Europe Conference. Trondheim, Norway. (also available at www.slideshare.net/svdburg/economic-feasibility-of- offshroe-seaweed-production-in-the-north-sea).

Walker, A.B., Fournier, H.R., Neefus, C.D., Nardi, G.C. & Berlinsky, D.L. 2009. Partial replacement of fish meal with laver *Porphyra* spp. in diets for Atlantic cod. *North American Journal of Aquaculture*, 71: 39–45.

Wan, A.H.L., Soler-Vila, A., O'Keeffe, D., Casburn, P., Fitzgerald, R. & Johnson, M.P. 2016. The inclusion of *Palmaria palmata* macroalgae in Atlantic salmon (*Salmo salar*) diets: effects on growth, haematology, immunity and liver function. *Journal of Applied Phycology*. 28: 3091-3100.

Wang, L.Z. 1993. *Hybridization of macroscopic red algae by somatic cell fusion*. Master's thesis. Northeastern University, Boston, Massachusetts. 72 pp.

Wang, J., Jiang, P., Cui, Y., Deng, X., Li, F., Liu, J. & Qin, S. 2010a. Genetic transformation in *Kappaphycus alvarezii* using micro-particle bombardment: a potential strategy for germplasm improvement. *Aquaculture International*, 18: 1027–1034.

Wang, J., Jiang, P., Cui, Y., Guan, X. & Qin, S. 2010b. Gene transfer into conchospores of *Porphyra haitanensis* (Bangiales, Rhodophyta) by glass bead agitation. *Phycologia*, 49: 355-360.

Wang, Q.K., Shi, C.L. & Ma, J.C. 1983. Isolation and cultivation of MLO associated with coiling-stunt disease of sea tangle. *Acta Microbiologica Sinica*, 23: 73–74.

Wang, Y., Tang, X., Yang, Z. & Yu, Z. 2006. Effect of alginic acid decomposing bacterium on the growth of *Laminaria japonica* (Phaeophyceae). *Journal of Environmental Science China*, 18: 543–55.

Watson, L. 2014. *Profiting from seaweed farming*. Paper presented at the Farmed Irish Seaweed: An Ocean Wonder Food? Limerick, Ireland, 18–19 November 2014.

Watson, L., O'Mahony, F., Edwards, M., Dring, M.L. & Werner, A. 2012. The economics of seaweed aquaculture in Ireland *Laminaria digitata* and *Palmaria palmata.* Paper presented at AQUA 2012, Global Aquaculture Securing our Future. Prague, Czech Republic, 1–5 September 2012.

Wei, N., Quarterman, J. & Jin, Y.S. 2013. Marine macroalgae: an untapped resource for producing fuels and chemicals. *Trends in Biotechnology*, 31: 70–77.

Weinberger, F., Pohnert, G., Berndt, M-L., Bouarab, K., Kloareg, B. & Potin, P. 2005. Apoplastic oxidation of L-asparagine is involved in the control of the green algal endophyte *Acrochaete operculata* Correa & Nielsen by the red seaweed *Chondrus crispus* Stackhouse. *Journal of Experimental Botany*, 56: 1317–1326.

Wilke, T., Faulkner, S., Murphy, L., Kealy, L., Kraan, S. & Brouns, F. 2015. Seaweed enrichment of feed supplied to farm-raised Atlantic salmon (*Salmo salar*) is associated with higher total fatty acid and LC n-3 PUFA concentrations in fish flesh. *European Journal of Lipid ScienceTechnology*, 116: 1–6.

Wilson, I.M. & Knoyle, J.M. 1961. Three species of *Didymosphaeria* on marine algae: *D. danica* (Berlese) comb. nov., *D. pelvetiana* Suth. and *D. fucicola* Suth. *Transactions of the British Mycological Society*, 44: 55–71.

Wiltshire, K.H., Tanner, J.E., Gurgel, C.F.D. & Deveney, M.R. 2015. *Feasibility study for integrated multitrophic aquaculture in southern Australia*. Report to the Fisheries Research & Development Corporation. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2015/000786-1. SARDI Research Report Series No. 883. 115 pp.

Wu, C.Y., Dou, C. & Jiajun, L. 1983. On the diseases of cultivated *Laminaria japonica*. *In* C.K. Tseng, ed. *Proceedings of the Joint China-U.S. Phycology Symposium*, pp. 211–220. Beijing, Science Press.

www.acadianseaplants.com

www.algaebase.com

www.Thefishsite.com

www.c-weed-culture.com

Yamada, K., Yoshimizu, M., Ezura, Y. & Kimura, T. 1990. Distribution of *Alteromonas* sp., the red- spot causative agent on the culture bed of makonbu *Laminaria japonica*, in coastal areas of Hokkaido. *Bulletin of the Faculty of Fisheries, Hokkaido University*, 41: 221–226.

Yamaguchi, K., Araki, T., Aoki, T., Tseng, C. & Kitamikado, M. 1989. Algal cell wall degrading enzymes from viscera of marine animals. *Nippon Suisan Gakkaishi*, 55: 105–110.

Yamazaki, A., Nakanishi, K. & Saga, N. 1998. Axenic tissue culture and morphogenesis in *Porphyra yezoensis* (Bangiales, Rhodophyta). *Journal of Phycology*, 34: 1082–1087.

Yan, Z.M. 1984. Studies on tissue culture of *Laminaria japonica* and *Undaria pinnatifida*. *Hydrobiologia*, 116/117: 314–316.

Yan, X.H. & Wang, S.J. 1993. Regeneration of whole plants from *Gracilaria asiatica* Chang et Xia protoplasts (Gracilariaceae, Rhodophyta). *Hydrobiologia*, 260/261: 429–436.

Yeong, H.Y., Khalid, N. & Phang, S.M. 2008. Protoplast isolation and regeneration from *Gracilaria changii* (Gracilariales, Rhodophyta). *Journal of Applied Phycology*, 20: 641–651.

Yokoya, N.S., West, J.A. & Luchi, A.E. 2004. Effects of plant growth regulators on callus formation, growth and regeneration in axenic tissue culture of *Gracilaria tenuistipitata* and *Gracilaria perple*xa (Gracilariales, Rhodophyta). *Phycological Research*, 52: 244–254.

Yokoyama, H. 2013. Growth and food source of the sea cucumber *Apostichopus japonicus* cultured below fish cages – potential for integrated multi-trophic aquaculture. *Aquaculture*, 372–375: 28– 38.

Yong, W.T.L., Ting, S.H., Yong, Y.S., Thien, V.Y., Wong, S.H., Chin, W.L., Rodrigues, K.F. & Anton, A. 2014. Optimization of culture conditions for the direct regeneration of *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae). *Journal of Applied Phycology*, 26: 1597–1606.

Yoshida, T. & Akiyama, K. 1978. *Streblonema* (Phaeophyceae) infection in the frond of cultivated *Undaria* (Phaeophyceae). *Proceedings of the International Seaweed Symposium*, 9: 219–223.

Ystanes, L. & Fougner, M.W. 2012. *Seaweed to biofuels – future perspectives by industry presented actor*. Paper presented at the Seaweed to Biofuel Workshop, 25–26 September 2012.

Yu, D.Z., Qin, S., Sun, G.Q. & Tzeng, C.K. 2002. Transient expression of *lacZ* reporter gene in the economic seaweed *Undaria pinnatifida*. *High Scientific Letters*, 12: 93–95.

Yumoto, I., Ezura, Y. & Kimura, T. 1989a. Distribution of the *Alteromonas* sp., the causative agent of red-spots on the culture bed of makonbu, *Laminaria japonica*, in the coastal area of Funka Bay. *Nippon Suisan Gakkaishi*, 55: 453–462.

Yumoto, I., Yamaguchi, K., Yamada, K., Ezura, Y. & Kimura, T. 1989b. Relationship between bacterial flora and occurrence of the *Alteromonas* sp., the causative agent of red-spots on the culture bed of makonbu, *Laminaria japonica*, in the coastal area of Funka Bay. *Nippon Suisan Gakkaishi*, 55: 1907–1914

Yunque, D.A.T., Tibubos, K.R., Hurtado, A.Q. & Critchley, A. 2011. Optimization of culture conditions for tissue culture production of young plantlets of carrageenophyte *Kappaphycus. Journal of Applied Phycology*, 23: 433–438.

Zablackis, E., Vreeland, V. & Kloareg, B. 1993. Isolation of protoplasts of *Kappaphycus alvarezii* var. *tambalang* (Rhodophyta) and secretion of iota-carrageenan fragments by cultured cells. *Journal of Experimental Botany*, 44: 1515–1522.

Zhang, D. 1983. Study on the protoplasts preparation, culture and fusion of somatic cells from two species of green algae *Ulva linza* and *Monostroma angicava* Kjellm. *Journal of Shandong College of Oceanology*, 13: 57–65.

Zhang, J. 1982. Some experiments and observations on the tissue and cell cultured of *Undaria pinnatifida*. *Journal of Shandong College of Oceanology*, 12: 29–38

Zhang, Y.C., Jiang, P., Gao, J.T., Liao, J.M., Sun, S.J., Shen, Z.L. & Qin, S. 2008. Recombinant expression of rt-PA gene (encoding Reteplase) in gametophytes of the seaweed *Laminaria japonica* (Laminariales, Phaeophyta). *Sciencia China Series*, 51: 1116–1120.

Zhang Z.H., Lu, J.B., Ye, S.F. & Zhu, M.Y. 2007. Values of marine ecosystem services in Sanggou Bay. *China Journal of Applied Ecology*, 18: 2540–2547.

Zitta, C.S., Rover, T., Hayashi, L., Zenilda, L. & Bouzon, Z.L. 2013. Callus ontogeny of the *Kappaphycus alvarezii* (Rhodophyta, Gigartinales) brown tetrasporophyte strain. *Journal of Applied Phycology*, 25: 615–62.