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Cultivation of tropical red seaweeds in the BIMP-EAGA region

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Abstract The Brunei–Indonesia–Malaysia–Philippines East Asia Growth Area (BIMP-EAGA) is located within the Coral Triangle, known to have the world's richest biodiversity in marine flora and fauna. This region lies within the 10° N and 10° S of the Equator where natural populations of both *Kappaphycus* and *Eucheuma* grow luxuriantly and abundantly. It is in this same region where commercial cultivation of *Kappaphycus* and *Eucheuma* began in the Philippines around the mid-1960s. Commercial farming of *Kappaphycus* (which was originally called *Eucheuma*) was successful in the Philippines from the early 1970s, after which the technology was transferred to Indonesia and Malaysia in the late 1970s. No seaweed cultivation has been reported in Brunei. At present, carrageenophytes are cultivated in sub-tropical to tropical countries circumferentially around the globe within the 10° N and S of the Equator. However, their combined production is still low as compared to Indonesia, the Philippines, and Malaysia. Notably, few improvements in farming techniques have been made since its first introduction. Some of the major improvements were the introduction of deep-water farming using hanging long lines, multiple rafts, and spider webs in the Philippines; the use of short and long 'loops', instead of plastic 'tie-tie' in Indonesia; and mechanization in harvesting and use of solar "greenhouse" drying in Malaysia. Commercial cultivation of tropical red seaweeds in the BIMP-EAGA region is dominated by *Kappaphycus* and *Eucheuma* (carrageenophytes) and *Gracilaria* (agarophytes) and the area became the major region for the production of carageenophytes and agarophytes globally. In particular, Indonesia is a major center for the production of *Gracilaria*. There is an increasing demand for other agarophytes/carrageenophytes in the international market such as *Gelidium* spp., *Pterocladia* spp., *Porphyroglossum* sp., and *Ptilophora* sp. for paper and ethanol production in Indonesia and Malaysia, and *Halymenia* for phycoerythrin pigments in the Philippines currently pursued in an experimental stage. A summary of the present status, problems, sustainability, and challenges for the cultivation of tropical red seaweeds in the BIMP-EAGA region are discussed in this paper.

Keywords Cultivation · Tropical red seaweeds · BIMP-EAGA region · *Kappaphycus* · *Eucheuma* · *Gracilaria* · *Gelidium*

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Introduction

Kappaphycus, a kappa carrageenan bearing seaweed, has been used extensively in varied applications in the global industries of food, pharmaceuticals, and nutraceuticals. Farming of this seaweed is a significant activity especially along the coastal areas between the 10° N and 10° S of the Equator. Recently, several studies were conducted to determine the potential of the biomass for applications in agricultural fertilizer (Zodape et al. 2009; Rajasulochana et al. 2012; Shah et al. 2013; Pramanick et al. 2013), pharmacological antioxidants (Hayashi and Reiss 2012), and as source of bioethanol (Meinita et al. 2012; Khambhaty et al. 2012; Hargreaves et al. 2013).

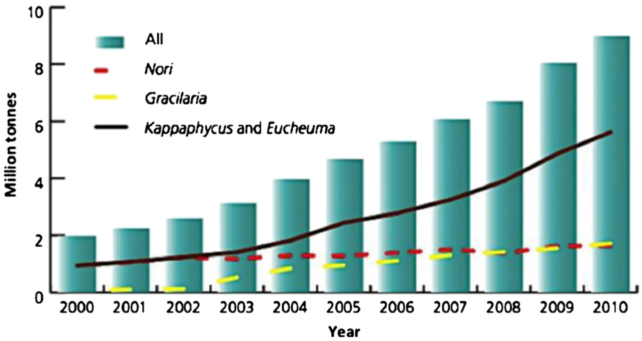


Fig. 1 Global production (t fresh weight) of red seaweeds by genus

Since 2004, farming of *Kappaphycus–Eucheuma* has dominated the production of cultivated and harvested red seaweed biomass (Fig. 1). Production of these red seaweeds surpassed the production of the brown seaweeds, such as *Undaria*, *Laminaria*, and *Ecklonia* and also the red seaweed *Porphyra* (FAO 2012, now known as *Pyropia*) (Sutherland et al. 2011). The Philippines was the largest producer of *Kappaphycus* from the initiation of successful commercial farming in 1972 until production was overtaken by Indonesia from 2008 (Table 1 and Fig. 2) (Bixler and Porse 2011). This increased production can be attributed primarily due to the enthusiastic support of the Indonesian government to expand the cultivation areas, coupled with additional strong support from the private sector. In terms of cultivable areas, Indonesia could further expand since it has more than 17,000 islands with a linear coastline of 52,716 km as compared to the Philippines which has more than 7,000 islands with 36,289 km coastline.

History on the introduction of *Kappaphycus–Eucheuma* farming

In 1966, experimental farms for *Kappaphycus* cultivation were established in Tapaan, Is. Siasi, Tawi-Tawi by Marine Colloids Philippines, the University of Hawaii, the Bureau of Fisheries and Aquatic Resources, and the University of the Philippines. This experimental effort was led by the late Dr. Maxwell S. Doty, the father of '*cottonii*' farming. The first commercial quantities of *Kappaphycus* (then called *Eucheuma* and '*cottonii*') were harvested from the cultivation areas in 1972. Since then, commercial cultivation of *Kappaphycus* (for kappa carrageenan) has been successful not only in Mindanao, but was also transferred to the Visayas and Luzon.

The first attempt to farm '*spinosum*' (now known as *Eucheuma denticulatum* (Burman) Collins *et* Harvey, a source of iota carrageenan) in Indonesia, was made in Thousand Islands, Pulau Pari by Soerjodinoto and Hariadi Adnan in 1967; however, it did not progress further. Prompted by insufficient and unsustainable supplies of wild stocks, the Trueblue Expedition organized by Auby (Sanofi), Copenhagen Pectin (CP Kelco), Marine Colloids (MC), and Indonesian Fisheries, LPPL was made to focus on cultivation. The CP and MC farming projects at Pulau Samaringa, Sulawesi, and Riau Islands in 1975–1977 were inconclusive, and hence the project moved to Bali. From 1978 to 1984, CP continued farming in Bali and success was achieved at Nusa Lembongan. Free seedlings and farm materials were provided to fishermen and the resulting production of '*spinosum*' biomass steadily increased to commercial levels. From 1985 to 1986, CP also initiated farms in Indonesia to supplement those initiated by FMC and Sanofi (now Cargill). Commercial '*cottonii*' seaweed farming finally arrived in Indonesia in 1985.

The introduction of '*cottonii*' farming in Sabah, Malaysia in 1978 and other tropical and subtropical countries was technically feasible and economically viable in areas where the provision of employment to tens of thousands coastal people is a significant factor (Fig. 3).

Common cultivars used in commercial farming and their seasonality

Successful carrageenophyte farming in the Philippines, Indonesia, Malaysia, and elsewhere has been dominated by a relatively small number of species and individual cultivars, in particular strains of two major genera: *Kappaphycus alvarezii* (Doty) Doty and *Kappaphycus striatum* (Schmitz)

Table 1 Comparative production (t fresh weight) of the major *Kappaphycus* producing countries (2000–2010) (FAO FishSTAT 2012)

Year 2000			Year 2010		
Top 5 producers	Quantity (thousand wet tonnes)	Share (%)	Top 5 producers	Quantity (thousand wet tonnes)	Share (%)
World	**944**	**100.0**	**World**	**5,623**	**100.0**
Philippines	679	71.9	Indonesia	3,399	60.5
Indonesia	197	20.9	Philippines	1,795	31.9
Tanzania[1]	51	5.4	Malaysia	208	3.7
Kiribati	11	1.2	Tanzania[a]	132	2.3
Fiji, Republic of	5	0.6	China	64	1.1
Top 5 total	**943**	**99.9**	**Top 5 total**	**5,599**	**99.6**

Source: FAO FishSTAT. Carrageenan seaweeds under cultivation include *Kappaphycus* and *Eucheuma denticulatum*

[a] Including Zanzibar

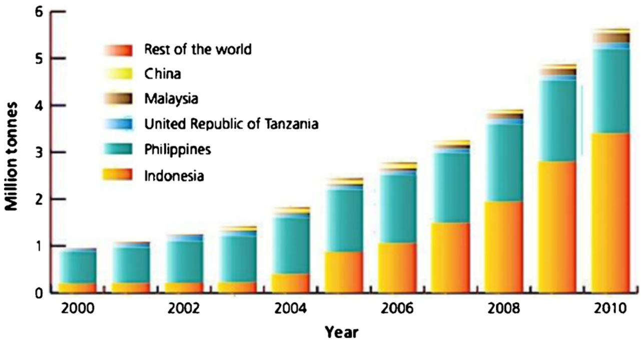


Fig. 2 Major production of *Kappaphycus-Eucheuma* (t fresh weight) by country

Doty (these represent the '*cottonii*' type and major source of kappa carrageenan) and *E. denticulatum* (the '*spinosum*' type and major source of iota carrageenan). Further to their domestication, these represent a limited genetic stock. Their subsequent vegetative multiplication has been exclusively through vegetative propagation, i.e., relatively simple, repeated cutting of young branches from the same plant to form 'seedlings'. The same method of cropping ensured the availability of new material for the next harvest and has been practiced and perpetuated by the seaweed farmers to the present time.

The phenotypic plasticity of *Kappaphycus* that resulted in different variations could parallel the report of Santelices and Valera (1993) on *Gracilaria chilensis* Bird, McLachlan, and Oliveira that were developed from spores showing significant differences in growth and morphology. The authors reported that intra-clonal variability followed by fragmentation and reattachment may increase intra-population variation in *G. chilensis*, which is often larger than inter-population variation, a phenomenon presently observed in *Kappaphycus*.

Currently, there are a variety of different strains, some with different color morphotypes of both *K. alvarezii* and *K. striatum*, as reported by Hurtado et al. (2008a, b), Dang et al. (2008), and Hurtado (2013b). This ecoplasticity when transplanted to geographical locations, outside of the original sites of cultivation, make these species very difficult to identify. However, Zuccarello et al. (2006), Conklin et al. (2009), and Tan et al. (2012a, b) showed that genetic identification of the different strains was possible.

Furthermore, there is a marked seasonality of *Kappaphycus* in the regions of cultivation which is greatly affected by the predominant wind direction. The "wet season" (July–October) in the Philippines is much earlier than in either Malaysia (November–March) or Indonesia (October–March). The Philippines is an archipelagic country facing the Pacific Ocean on the east, and the West Philippine Sea to the west. This country is frequently visited by tropical cyclones during the wet season, hence, production is greatly affected, especially the typical outdoor drying practices. Production during the wet season is lean. Indonesia and Malaysia have almost identical months for their wet and dry seasons, in addition, there are no typhoons but only monsoon rains. It appears that when the Philippines experiences heavy and prolonged cyclonic rains, Indonesia and Malaysia are normally dry (Table 2). The prevailing weather conditions in Indonesia, especially during the Philippines' lean months of production, results in the former having peak months of production. Malaysia has similar weather conditions to Indonesia, which similarly favors commercial farming of *Kappaphycus.* In order to expand production, Malaysia has to become more enthusiastic to expand its cultivation areas, and introduced further efficient and effective innovations in their farming techniques, harvesting, and drying.

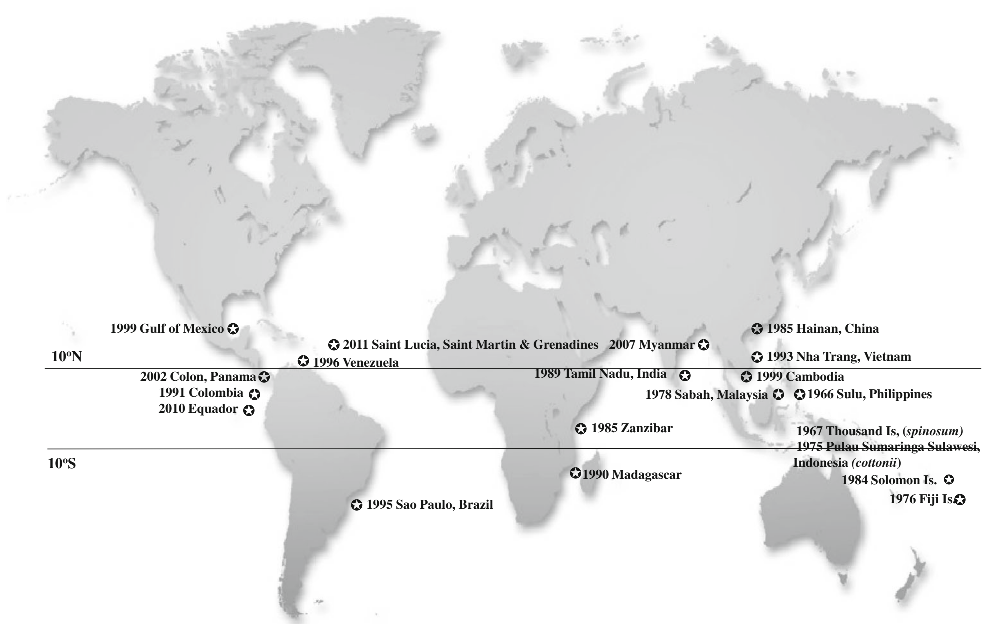


Fig. 3 Global history for the introduction of *Kappaphycus* farming

Table 2 Wet and dry seasons in Indonesia, Malaysia, and the Philippines

Season	Indonesia	Malaysia	Philippines
Wet	October–March (Heavy rainfall)	November–March (Heavy rainfall)	July–October (Heavy rainfall)
Dry	April–September	May–September	December–May

Cultivation techniques

Vegetative or self-propagation has been the only widely used method for the development of biomass for carrageenophyte cultivation in the Southeast Asian region and elsewhere. Young, robust, and healthy branches were cut from a selected 'mother plant' and then tied to soft plastic rope, called 'tie-tie, or loops which had been previously wound around a cultivation rope (i.e., mono-filament rope, polyethylene rope, or flat binder). Five methods of culturing *Kappaphycus* were first introduced in the Philippines (see Doty 1973; Ricohermoso and Deveau 1979), viz: (1) off-bottom mono-line, presently called "fixed-off bottom", (2) broadcast, (3) floating bamboo, (4) net system, and (5) the tubular net. However, the "off-bottom mono-line", "single floating-raft", and "hanging long-lines" (adapted in shallow waters) are the most popular methods adopted in recent times, not only in the Philippines (Hurtado-Ponce et al. 1996; Hurtado and Agbayani 2000; Hurtado et al. 2008a), but also in Indonesia (Luxton 1993) and Malaysia (Yasir 2012). Recently, farmers in the Philippines, particularly in the Zamboanga Peninsula, expanded their farming operations into deeper water areas by adopting the "multiple raft long line" (Hurtado and Agbayani 2002; Hurtado et al. 2008b; Hurtado 2013a), the "spider web" (Hurtado et al. 2008b; Hurtado 2013a), and the "free-swing" in Sitangkai, Tawi-Tawi (Hurtado et al. 2008b), while Sabah, Malaysia used the "hanging basket" in deeper waters (Kaur and Ang 2009). Table 3 and Fig. 4a–h show the common cultivation techniques used in the region.

Recent developments in cultivation, harvesting, and drying

The use of a commercial extract from the brown seaweed *Ascophyllum nodosum* (Linnaeus) Le Jolis, for the promotion of vigorous growth in *K. alvarezii*, was reported in the field by Hurtado et al. (2012). The authors showed that dipping *Kappaphycus* in a low-concentration solution produced multiple shoots, which later developed to several young branches as early 10–15 days. Earlier reports claimed that the effects of the *A. nodosum* extract were attributable to a variety of constituents

Table 3 Common cultivation techniques used in the farming of *Kappaphycus*

Cultivation techniques	Indonesia	Malaysia	Philippines
Shallow waters			
fixed off-bottom	■	■	■
Deeper waters			
free-swing			■
hanging long-line	■	■	■
hanging basket		■	
multiple raft long-line			■
single raft long-line	■		■
spider web			■
triangular			■

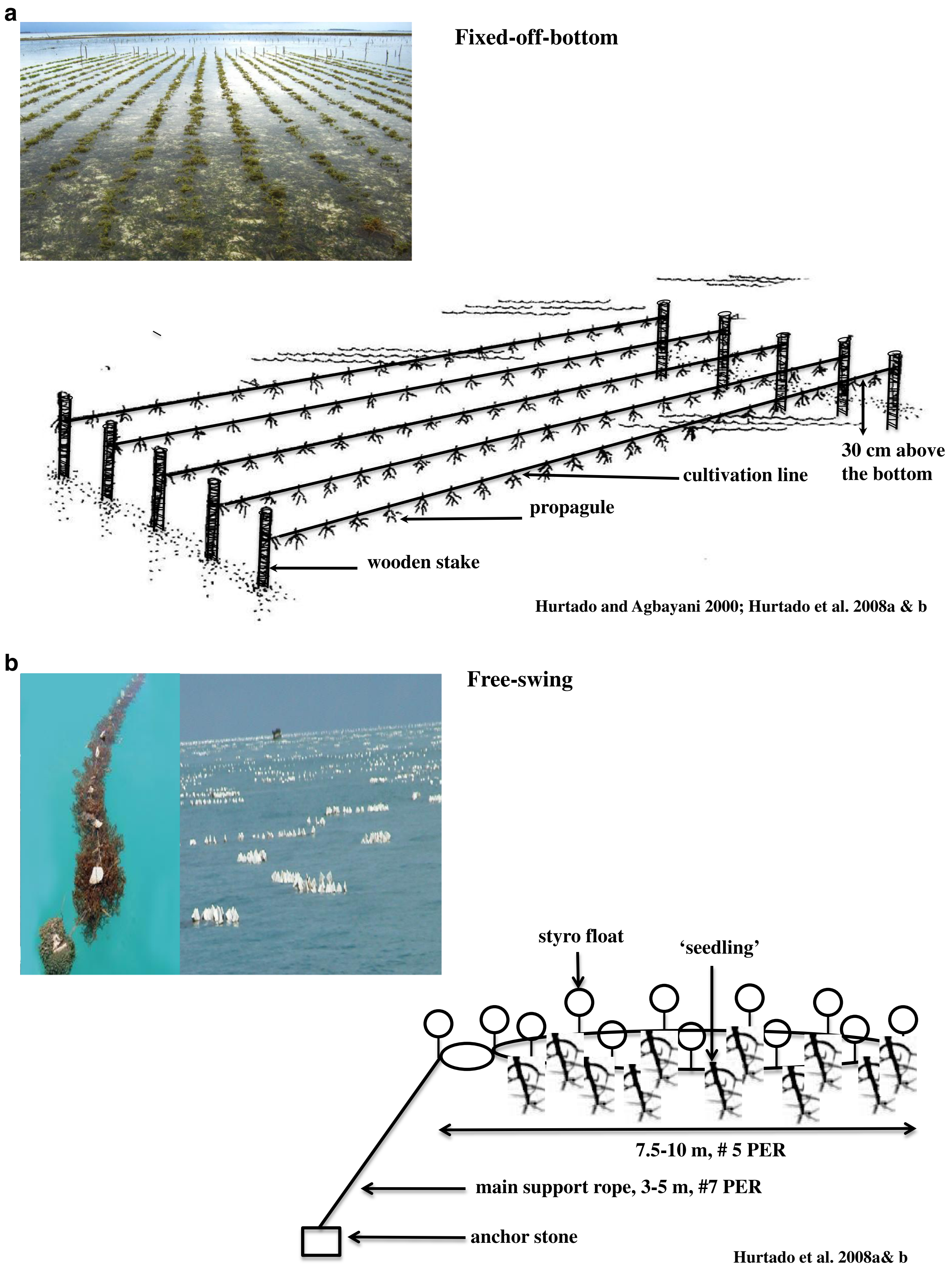
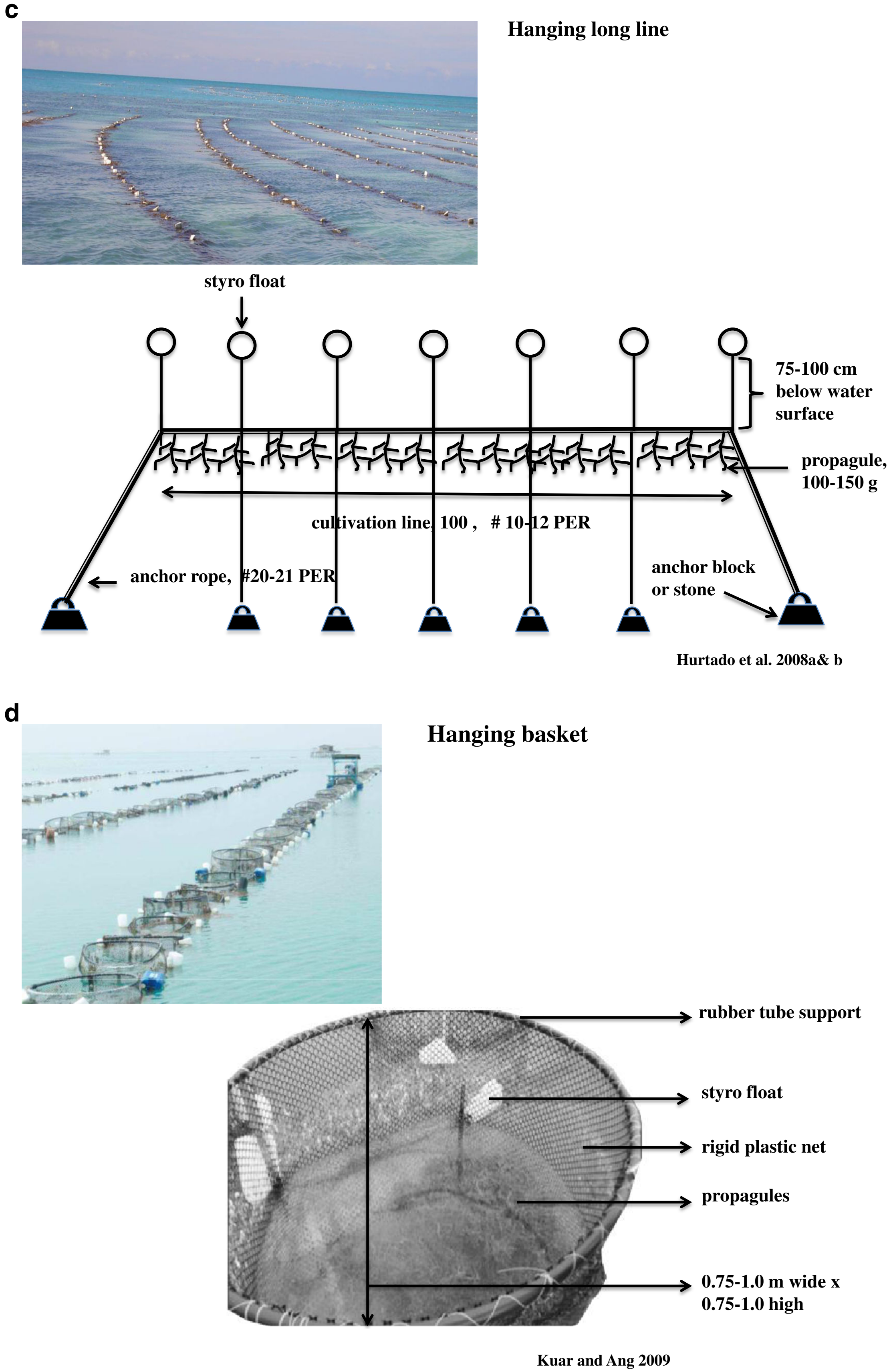


Fig. 4 **a**–**h** Common cultivation techniques used in the farming of *Kappaphycus*



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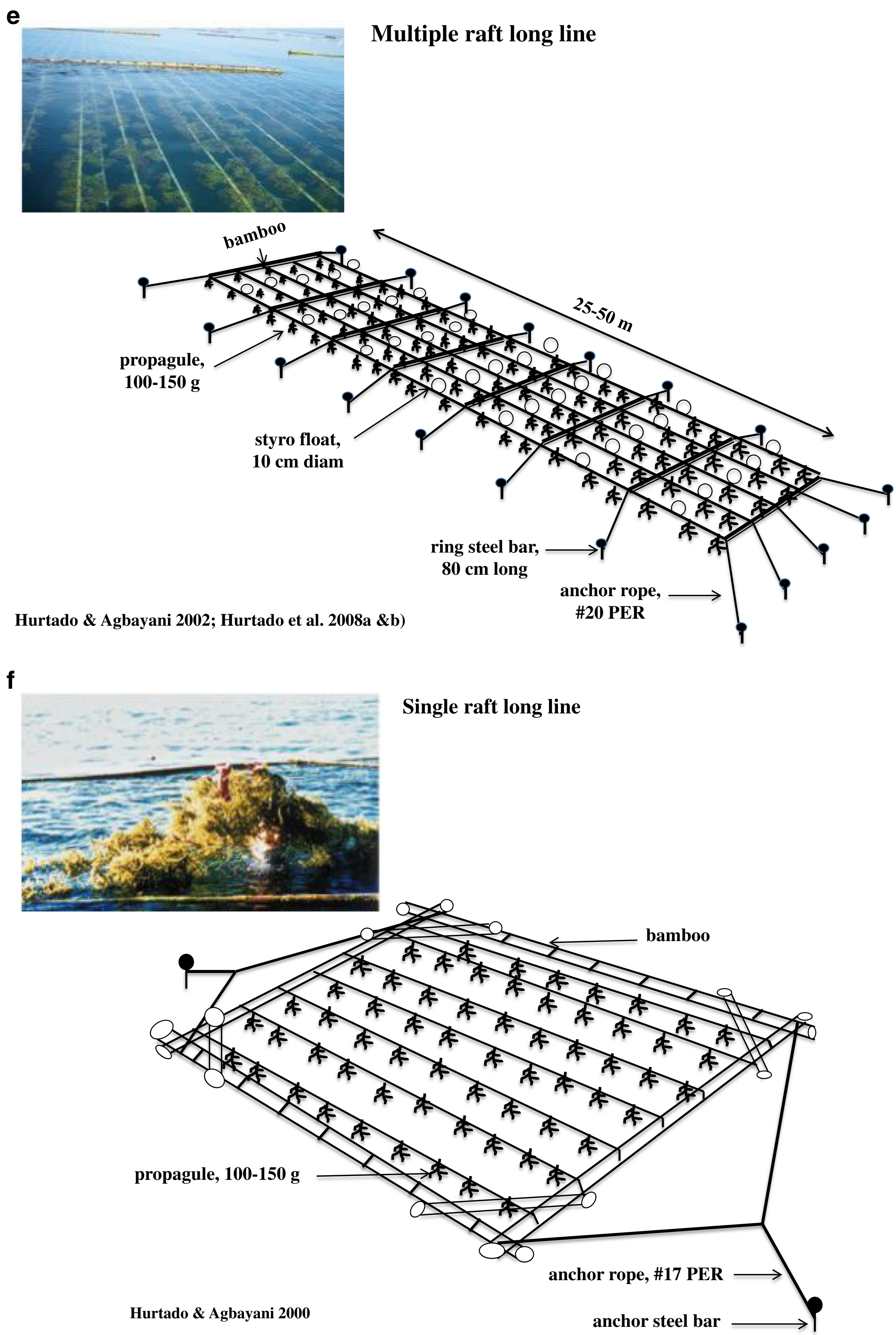

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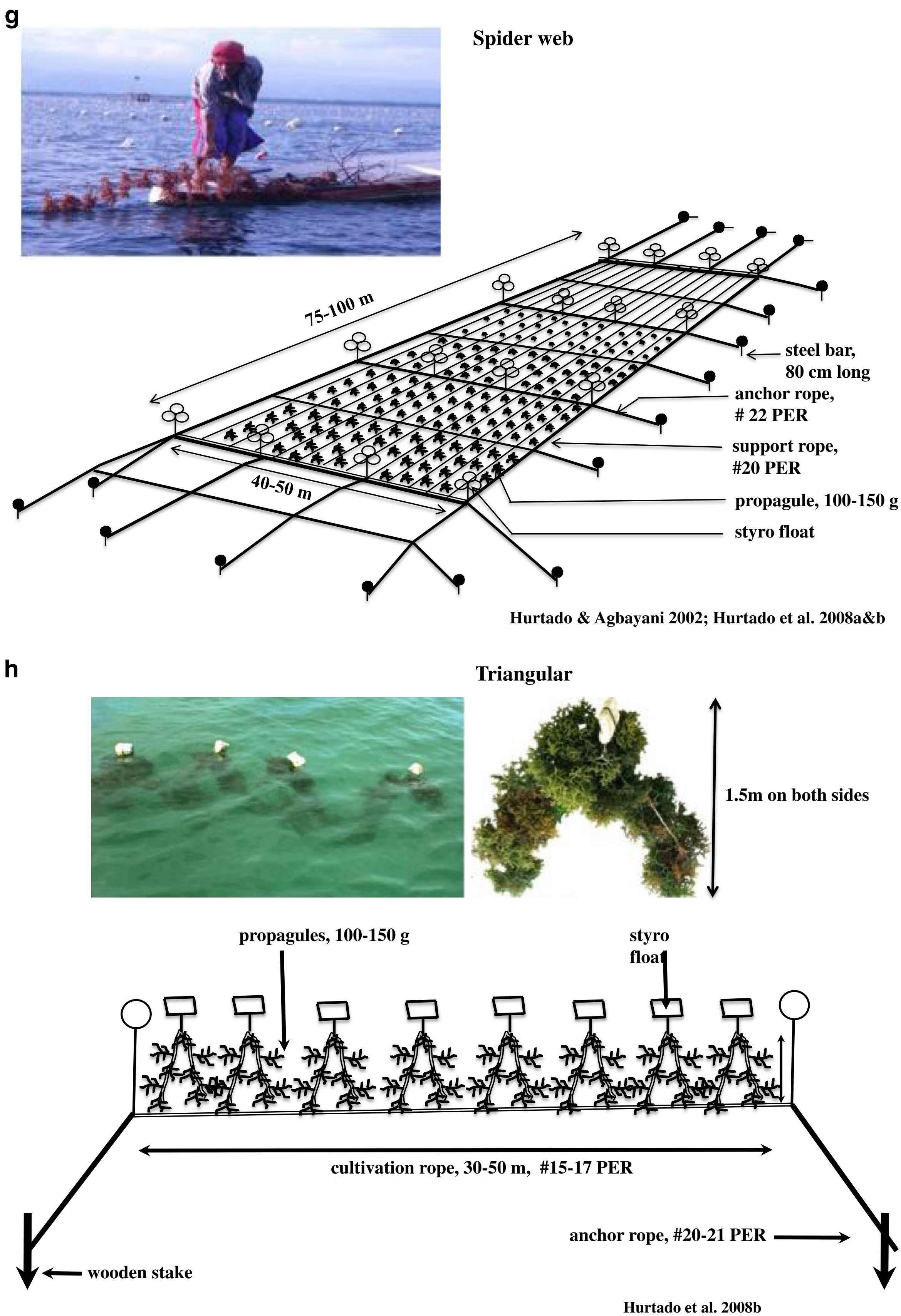

Fig. 4 (continued)

including betaines, plant nutrients (both micro and macro), and compounds which stimulated phytohormonal activity (Khan et al. 2009). The beneficial effects of the seaweed extract appeared to be modulated by elicitation of endogenous phytohormone biosynthesis in extract-treated seaweed.

It was also reported that dipping *Kappaphycus* in *A. nodosum* extract, reduced the percentage occurrence of the red algal filamentous epiphyte *Neosiphonia* spp., (Borlongan et al. 2011), a known pest (epiphytic filamentous algae, EFA) which causes massive infestations in various seaweed farms in the Philippines, Indonesia, Malaysia, and Tanzania (Critchley et al. 2004; Hurtado and Critchley 2006; Hurtado et al. 2006a, b; Vairappan 2006; Vairappan et al. 2008) and China (Pang et al. 2012). Such massive infestations lead to the reduced quality and quantity of K*appaphycus.* As a consequence, the lack of availability of good quality propagules for the farming cycle becomes a large problem for the seaweed farmers. The use of the *A. nodosum* extract to help reduce the incidence of *Neosiphonia* infestation has been reported as an efficient and effective tool for the management of *Kappaphycus* which improves tolerance to abiotic stresses, which are normally attributable to the weakening of the cultured *Kappaphycus*.

Harvesting *Kappaphycus* is a laborious activity among the various operations of farming. When production is high, during the peak growing months (March–April), additional hired labor is required. The adoption of the "comb-like harvester" in Sabah, Malaysia (Yasir 2012) is one innovation that helped accelerate the amount of seaweed harvested per day. The productivity of a farmer increased, as compared to the traditional system where the harvested lines were brought to land and plants were removed individually.

One of the biggest problems facing seaweed post-harvest management is drying. Since the start of seaweed farming in the early 1970s, sun drying on platforms, or hanging the harvested lines were the only known methods to dry the harvested biomass. A drying house or solar "greenhouse" not only shortens the required drying time to 2–3 days, as compared with drying for 3–5 days, the solar "greenhouse" also markedly improved the subsequent quality of the raw dried seaweed (Yasir 2012).

Other economically important red seaweeds

The marine flora of the Coral Triangle is highly diverse. For more than 40 years, *Kappaphycus* and *Eucheuma* were the major red seaweeds which had programs of R&D and commercialization. There remain a number of other red seaweeds which can be selected, domesticated, and developed as raw materials for production, especially for the diverse field of pharmaceuticals and reservedly, even perhaps biofuels. Table 4 shows other red seaweeds which have been explored and presently under development as potential commercial stocks of raw material for industrial processing in the region.

Indonesia was the first to conduct field cultivation of the red alga *Gelidium amansii* (Lamouroux) Lamouroux in the BIMP-EAGA region. Initial results are encouraging (Grevo, unpublished data). The field trials were made in preparation of large-scale commercial cultivation as a source of bio-ethanol (You and Gerung 2008). Other red seaweeds in Indonesia, under exploration for bio-ethanol and paper pulp production are: *Pterocladia* sp. and *Ptilophora* sp. Likewise, Malaysia is pursuing *G. amansii* for experimental bio-ethanol and paper pulp production. The Philippines is in the experimental stages of evaluating *Halymenia durvillaei* (Bory de Saint-Vincent) production, mainly for food and as source of pigment. *Gracilaria* is also known for its good quality agar and agarose which are mainly used for food and pharmaceutical and biotechnological applications. Indonesia, Malaysia, and the Philippines are cultivating *Gracilaria* and *Gracilariopsis* mainly in brackish-water ponds, and adjoining canals for the agar industry, and also as sea vegetables for human consumption and the production of feed for abalone (Capinpin & Corre 1996). Among the three countries, Indonesia is the only one known to have a state-of-the-art agar processing plant.

Major technical problems

Table 5 shows the major constraints for seaweed cultivation, recommendations, and suggested strategies to address these problems. After 40 years of vegetative, or self-propagation of

Table 4 Other cultivated red seaweeds of economic value

	Species	Status	Applications	References
Indonesia	***Gelidium amansii***	**Experimental**	**Bio-ethanol, paper pulp industry**	**You and Gerung 2008**
	***Pterocladia* sp.**			
	***Ptilophora* sp.**			
	Gracilariopsis heteroclada	**Commercial**	**Agar industry**	**Neish, Pers. Communication**
Malaysia	***Gelidium amansii***	**Experimental**	**Bio-ethanol, paper pulp industry**	**Phang, Pers. Communication**
	Gracilaria	**Commercial**	**Direct human food**	**Abdullah, Pers. Communication**
Philippines	***Gracilariopsis heteroclada***	**Commercial**	**Abalone feed, agar industry**	**Capinpin and Corre 1996**
	Halymenia durvillaei	**Experimental**	**Human Food and pigment source**	**Montano, Pers. Communication**

Table 5 Major technical problems in farming *Kappaphycus* and suggested potential solutions

Major technical problems	Recommendations	Strategies
Production		
• Unavailability of good quality cultivars/propagules	• Access to good quality cultivars/propagules • Access to technologies developed from R&D program of the academe and research institutions	• Establishment of sea-based nurseries in strategic areas • Use of tissue culture and mutagenesis, natural sporulation, protoplast, and hybridization techniques to accelerate mass production of new and improved plantlets • Establishment of gene banks and land-sea-based nurseries for young plants developed from tissue culture and natural sporulation techniques
• Weak linkages between the academe–scientist–experts group and the seaweed farmers	• Closer interaction and collaboration between the seaweed farmers and the academe–scientist–experts group	• Collaborative projects in the verification of studies in order to confirm technologies • Joint projects in the pilot farm demonstration of matured technologies towards commercialization • Openness of both parties by sharing experiences and information • Education and technology transfer (strain selection; appropriate cultivar and farming technique for the season and location; duration of culture days; clearance of propagule from the water surface (50–75 cm below the water surface)
• Low productivity of cultivar/ propagules	• Selection of good farming site (moderate water movement) for the wet and dry seasons • Use of fast-growing cultivars • Extended duration of culture days (□45 days) • Use of appropriate culture technique which are technically and economically viable • Avoid mass cultivation during known 'poor' months to minimize outbreak of 'ice–ice' malaise and *Neosiphonia* infestation • Improved "seedling" and site management	• Practice fallowing to give rest to the area • Application of nutrients derived from marine plants to propagules (concentration and duration) to accelerate growth, and to improve tolerance to biotic and abiotic stresses

Kappaphycus, it is high time to use plantlets derived from: (1) reproductive plants (carposporophytes and/or tetrasporophytes), (2) calli produced by tissue culture techniques and mutagenesis, (3) protoplasts, and (4) hybridization. The cultivation of

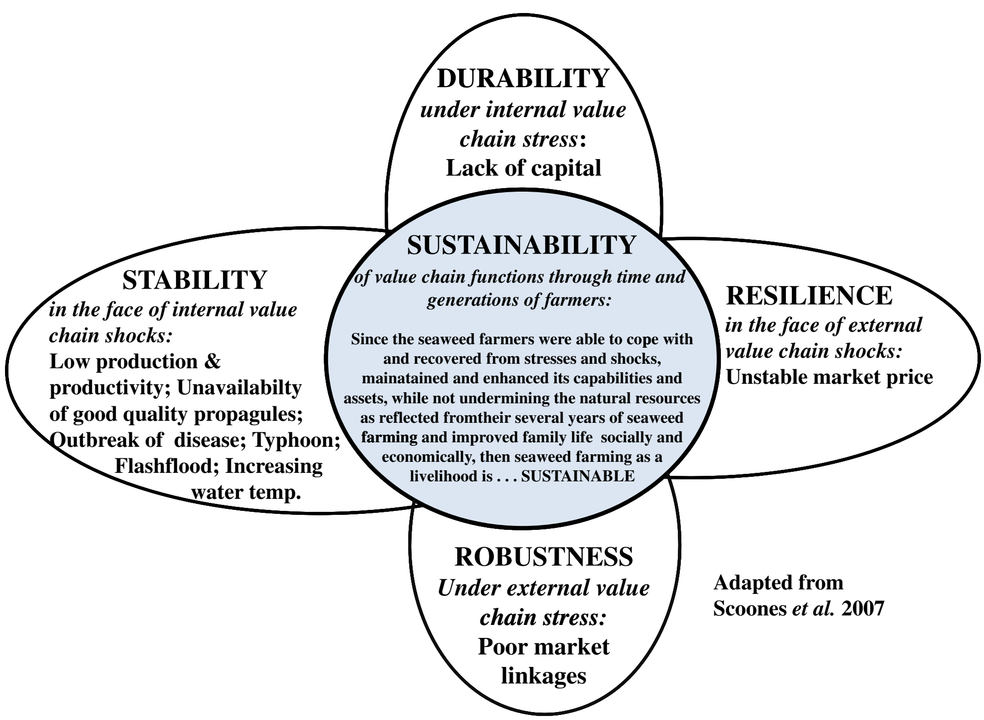

Fig. 5 Sustainability of *Kappaphycus* farming

temperate species such as *Hizikia*, *Monostroma*, *Laminaria*, *Porphyra (Pyropia)*, and *Undaria* have used spore-generation techniques since the start of commercial cultivation (Ohno and Largo 1998; Sohn 1998; Chaoyuan and Wu 1998). As a consequence, the vigor of these cultivated seaweeds has remained relatively stable, and consequently productivity and production are high. For the start of every cropping cycle, new plantlets are generated from spores, thus the sustainability of the industry is assured and remains economically stable. The increase in the world total production of *Kappaphycus* and *Eucheuma* in 2010 as compared to the total production of *Undaria*, *Laminaria*, and *Ecklonia* (FAO 2012) was mainly due to expansion of cultivation areas and not due to increased productivity per unit area.

The major technical problems for *Kappaphycus–Eucheuma* cultivation in this region will only be solved by strong, harmonious, and committed working relationships between the major stakeholders, representing each stage of the whole value chain of the industry, i.e., from the farmers, traders, exporters, processors, academics, research institutions, and associated government agencies. Likewise, the multi-national seaweed-carrageenan companies (MNCs) based in the region will also play a significant role.

Academe and research institutions need to receive full financial support from the government or the MNCs in order to conduct the necessary R&D to generate and perfect technologies in response to the needs of the industry. Their success is dependent on the strength of the R&D component and investment made for future development. At the same time, the seaweed farmers must be increasingly exposed and educated in the recent developments and improvements to techniques which R&D can provide so that the refinements and later commercialization of the technology are readily available and adapted for increased benefits of sustainable production, income to the farmers, and quality of biomass to the industrial processors. Print media (flyers, manuals, and brochures) and audio-visual aids should be readily available to the farmers as part of an organized education/training program, including visits to research institutions, reciprocal visits to pilot farm demonstrations. Continuing education by seminars and local and international congresses will enrich the expertise and future of the seaweed farmers. Table 5 shows the major technical problems of *Kappaphycus* cultivation and some possible solutions.

Sustainability of seaweed farming

The sustainability of *Kappaphycus–Eucheuma* cultivation in the BIMP-EAGA region over time and various generations of farmers, is tested by its: (1) durability under internal value chain stress; (2) stability in the face of internal value chain shocks; (3) robustness under external value chains stress; and (4) resilience in the face of external value chain shocks (summarized in Fig. 5) (Scoones et al. 2007).

Future challenges

Despite the increased production mainly achieved through increased total area of coastal waters brought into the activity of cultivation, challenges to the sustainability of *Kappaphycus–Eucheuma* cultivation in the BIMP-EAGA region, still exist, e.g.: (1) inclement weather conditions (climate change); (2) disease outbreaks; (3) uncertain and fluctuating market conditions; (4) competition from other employment sectors (e.g., fisheries, tourism, and urban development); and (5) general lack of local opportunities for value addition to the dried seaweed biomass.

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