J Appl Phycol (2011) 23:789–796
DOI 10.1007/s10811-010-9570-2

The commercial red seaweed *Kappaphycus alvarezii*—an overview on farming and environment

M. S. Bindu · Ira A. Levine

Received: 2 February 2010 / Revised and accepted: 29 July 2010 / Published online: 14 August 2010

Abstract Commercial cultivation of the red alga *Kappaphycus alvarezii* (Doty) Doty has been satisfying the demand of the carrageenan industry for more than 40 years. For the past four decades, this species has been globally introduced to many maritime countries for experimental and commercial cultivation as a sustainable alternate livelihood for coastal villagers. Accompanying the introduction is an increasing concern over the species effects on the biodiversity of endemic ecosystems. The introductions of non-endemic cultivars have resulted in the adaptation of quarantine procedures to minimize bioinvasions of additional invasive species. The present review focuses on *Kappaphycus* farming techniques through the application of biotechnological tools, ecological interactions with endemic ecosystems, future *K. alvarezii* farming potentials in Asia, Africa, and the Pacific, and the challenges for prospective farmers, i.e., low raw material market value, diseases, grazing, etc. The introduction of *Kappaphycus* cultivation to tropical countries will continue due to the high production values realized, coastal villages searching for alternative livelihoods, and the increased global industrial demand for carrageenan.

Keywords Alternative livelihood · Commercial cultivation · Global introduction · *Kappaphycus alvarezii* · EIA

Introduction

Over the past four decades, considerable attention was given to the red seaweed, *Kappaphycus alvarezii* (Doty) Doty (Rhodophyta, Gigartinales, Areschougiaceae), an industrially important carrageenophyte. Reports state that the farming of this seaweed started in southern Mindanao in latter half of the 1960s in the Philippines using the local varieties selected from the wild (Doty 1973, 1978; Parker 1974). The farming has further expanded to other parts of the world, e.g., Indonesia, Fiji, Micronesia, Vietnam, China, South Africa and is well reviewed and documented by Ask et al. (2001). It is reported that the commercial cultivation of *K. alvarezii* was developed jointly by Marine Colloids Corporation (purchased by FMC Corporation in 1977, now part of BioPolymer; Ask et al. 2001) and by Dr Maxwell Doty of the University of Hawaii Botany Department (Parker 1974). Realizing the potential for commercial extraction of carrageenan, *K. alvarezii* was introduced to many countries for research, development, and commercialization by researchers and phycocolloid companies. The present paper is an attempt to compile and review the different aspects of global *Kappaphycus* farming introductions and environmental concerns. Reports of regional farming introductions and/or development after Ask et al. (2001) are cited in this review. As farming operations

M. S. Bindu (✉)
Department of Environmental Sciences,
University of Kerala,
Kariavattom Campus,
Kerala 695 581, India
e-mail: drmsbindu@yahoo.co.in
e-mail: drmsbindu@gmail.com

I. A. Levine
Natural & Applied Sciences, Lewiston-Auburn College,
University of Southern Maine,
51 Westminster Street,
Lewiston, ME 04240, USA
e-mail: ilevine@usm.maine.edu

expanded, growing apprehensions over the impact of the introduction of exotic species to new environments, their interactions with endemic species, and its effect on biodiversity were also reported (Russell 1983; Woo 2000; Smith et al. 2002; Conklin and Smith 2005; Pereira and Verlecar 2005; Anon 2006; Vijayalakshmi 2007; Chandrasekaran et al. 2008). However, after four decades of introductions resulting in *Kappaphycus* being the most widely cultivated commercial eucheumoid, there are only a few Environmental Impact Assessment (EIA) studies addressing the ecological impacts of *K. alvarezii* on the environment (Tewari et al. 2006; Tewari 2006), even though recommendations for EIA studies have been suggested by researchers (Woo et al. 1989; Mesia and Mapelamao 2006) and organizations (National Academy of Agricultural Sciences, India 2003).

Global *Kappaphycus* introductions

Kappaphycus has been introduced to more than twenty countries in the past 35 years for the development of farming efforts. The state of the *Kappaphycus* introductions was last reviewed by Ask et al. (2001) and subsequently new information relating to its introduction, farming, and ecological interactions has been reported. This review attempts to highlight new *Kappaphycus* farming initiatives by Asian, African, and Pacific Island nations post Ask et al. (2001), some of which include multitrophic aquaculture (polyculture) strategies. Additionally, efforts include cultivar enhancement programs utilizing molecular techniques to: increase productivity, resist disease, herbivory, and epiphytism (Cheney et al. 1997, 1998; de Paula et al. 2001; Lombardi et al. 2001, 2006; Yarish et al. 2001; Wu et al. 2003; Msuya and Salum 2006; Zuccarello et al. 2006; Hayashi et al. 2007a, b, Hayashi et al. 2008a, b; Hurtado and Biter 2007; Rodrigueza and Montano 2007; Yano et al. 2007). Considering the environmental importance of *Kappaphycus*, available reports on the ecological interactions of this species with local environments have been covered by Woo (2000); Smith et al. (2002); Oliveira and Paula (2003); Smith (2003); Barrios (2005); Conklin and Smith (2005); Pereira and Verlecar (2005); Vijayalakshmi (2007); Chandrasekaran et al. (2008).

Pacific Island countries

Commercial Pacific Island *Kappaphycus* cultivation was initiated in the mid 1970s. Pickering and Forbes (2002), Mate et al. (2003), Teitelbaum (2003), Ponia (2005), Namudu and Pickering (2006), Mesia and Mapelamao (2006), and Pickering (2006) highlighted the importance of this species to various Pacific Islands as a means of income generation and coastal community economic development. Pickering and Forbes (2002) pointed out that *Kappaphycus* ventures in Fiji are regarded as a consolidation and diversification of its aquaculture industry after an earlier false start. The report advocated for legislative amendments strengthening government oversight of aquaculture via the collection of statistics. Additionally, the aquaculture industry association was encouraged to represent private sector interests, contribute to policy development, and adopt specific training requirements. Simultaneously, Teitelbaum (2003) published a manual that assists Pacific Island seaweed farmers in the farming of *K. alvarezii*. The manual describes different aspects of *Kappaphycus* farming including: site selection, seedling selection, relevant tools and equipment, methods of rope and raffia knot-tying, hanging of lines, harvesting, construction of drying frames, drying techniques, cleaning, processing and sale of the seaweed. The manual highlights the cause, effect, and solutions to commonly encountered problems, such as territorial grazing by herbivores, epiphytic algae, and ice-ice disease. Mate et al. (2003) reported the significance of the Fijian government workshop on farming *K. alvarezii* held in 2003. The report includes Fijian government policies for seaweed farming and the role of extension officers, and a brief summary of research findings on Fijian seaweed farming. Suggestions for environmental safeguards, profitability and stock replenishment of *Kappaphycus* farming in Pacific islands was offered by Ponia (2005). The success of southwest Pacific regional commercial seaweed aquaculture was reported for two species, *K. alvarezii* in Kiribati, Fiji, and Solomon Islands and *Cladosiphon* sp. in Tonga (Pickering 2006). The report states that the southwest Pacific region is environmentally ideal for seaweed aquaculture, overcoming the challenges of distance from main markets, vulnerability to world price fluctuations, and socio-economic issues. The report concluded that regional seaweed farming could make a useful contribution to income supplementation and a significant economic boost for isolated outer islands where few alternative income-generating opportunities exist. Cultivation initiative assessments focus on social factors as compared to technical issues in determining the success of rural development projects. A survey has been developed enabling the determination of community suitability for seaweed cultivation; Namudu and Pickering (2006) reported the results of social survey techniques carried out among eight communities within Fiji. Though developed for Fijian case studies, the survey can be applied to other rural Asia/Pacific localities (Namudu and Pickering 2006). Secretariat of the Pacific Community in 2006 gave an overview of Papua New Guinea aquaculture and the governmental interest in piloting *Kappaphycus* and sea cucumber multitrophic aquaculture. *Kappaphycus* and black lip pearl multitrophic aquaculture farms participated in a regional initiative aimed at identifying the root causes of coastal area and watershed degradation and to promote sustainable coastal fisheries by creating marine protected areas in the western province of the Solomon Islands (Mesia and Mapelamao 2006). The authors suggest the sustainable development of marine resources can only be achieved through the establishment of resource management plans in partnership with the local communities.

African countries

The farming of *Eucheuma* and *Kappaphycus* developed rapidly during the mid-1980s in Tanzania and commercial production began along the east coast of Zanzibar and Pemba Islands in 1989 and expanded rapidly throughout the 1990s (Ask 2001). Lundsor (2001) developed an alternative method for the commercial cultivation of *E. denticulatum* and *K. alvarezii* outside Paje on the east coast of Unguja Island, Zanzibar, Tanzania, termed the "broadcast system" (independent of tidal cycles resulting in greater yields) consisting of rectangular pens instead of lines. Mtorela (2003) investigated the potential effects of seagrass coverage on algal productivity by comparing the productivity of *E. denticulatum* and *K. alvarezii* in Paje (low seagrass cover) and Uroa (high seagrass cover), Zanzibar. The growth rate of *E. denticulatum* in Paje was 20–75% lower than in Uroa and was seasonal. Zanzibar *E. denticulatum* and *K. alvarezii* exhibited different growth rates as a function of stocking densities and culture duration (Msuya and Salum 2006). However, increasing production of *K. alvarezii* has been hampered in recent years by disease and predation (Rice and Savoie 2005). The total annual production of carrageenophytes in Tanzania, including Zanzibar, Pemba, and Mafia Islands, as well as the 1,400 km-long mainland coast exceeded 7,000 dried metric tons in 2002, making Tanzania the world's sixth largest producer with a farm gate value of US$ 1.4 million. Production has been reduced to Pemba and Unguja Islands producing ~5,000 tons of *E. denticulatum* from each area in 2008 (E. Ask, per comm.). The seaweed farm gate production value represents over 99% of Tanzania's aquaculture industrial output.

As a means of improving the local village livelihoods, off-bottom rope cultivation of commercial eucheumoids was investigated at three sites on the southern Kenyan coast, (Wakibia et al. 2006). *E. denticulatum* and *K. alvarezii* relative growth rates were highest at a mangrove system's sandy flat (Gazi; 5.6% d^{-1}), lowest in an intertidal reef flat (Kibuyuni; 3.2% d^{-1}) and intermediate in a lagoon (Mkwiro; 4.8% d^{-1}). Results suggest that commercial cultivation of eucheumoids in Kenya is feasible.

Recommendations to improve African *K. alvarezii* cultivation include: adoption of the Indonesian-style deep water, logline cultivation method with predator-excluding perimeter netting, submerging seed stock to deeper saline waters during the rainy season, and to capture and culture rabbit fish *Siganus* spp. as an adjunct to seaweed farming serving a dual function of removing key seaweed predators from cultivation sites and providing an alternative cash crop to seaweeds (Rice and Savoie 2005). Bryceson (2001) reported several thousand farmers, mostly women, engaged in the production and the sale of seaweeds, providing much needed income. Environmental effects appear minimal; in fact some herbivorous fishes actually gain an extra source of food when they graze on the farmed seaweed. Conflicts with other users of the coast appear manageable when zoning is applied to fishing boats and tourist activities. A significant challenge experienced is the extremely low price paid to farmers compared to the very high prices fetched for phycocolloid products by the pharmaceutical and food industries—the enormous profits made by transnational corporations raise important ethical questions in this era of globalization (Bryceson 2001).

Asian countries

Kappaphycus alvarezii constitutes 80% of the Philippine seaweed export, which is sold as both fresh and dried forms; although dried seaweed has a greater demand, fresh seaweed are highly valued in restaurants (Hurtado 2003). The Philippines has the largest carrageenan refinery in Asia supporting the introduction to other Asian countries, e.g. Indonesia, Malaysia, Japan, China, India, and Vietnam. Farming introductions continue to new localities. Indian *K. alvarezii* mariculture, located in Okha on the west coast, was initiated in the mid 1990s for kappa carrageenan production (Mairh et al. 1995). Subsequent *Kappaphycus* commercial cultivation was established in Mandapam, southeast coast of India, during 1995–1997. Initially, bag and net cultivation were practiced; later fishermen and women of Self Help Groups introduced the raft method for commercial cultivation. They adopted the Kudumpam model cultivation system with the cooperation of industries and nationalized banks (Eswaran and Jha 2006). Eswaran et al. (2002) evaluated the field and laboratory Mandapam *K. alvarezii* biomass yields and growth rates were much higher (nearly 3% per day) in December through February. The report indicated the potential for further large-scale cultivation efforts in Mandapam region. Highlighting the far-reaching societal impacts of this development, His Excellency Dr. A P J Abdul Kalam, then the President of India, encouraged the *Kappaphycus* seaweed cultivation for the livelihood support as a mission mode project of the coastal poor (*Technology Empowers the Nation*—address by the Honorable president of India at New Delhi on 11 May 2006, Technology Day). Subsequently, *Kappaphycus* experimental and field cultivation was initiated in several Indian coastal areas and results indicate the possibility of large-scale *Kappaphycus* commercial cultivation in Indian waters as a means of income generation (Sakthivel 1999; Subba Rao et al. 2004, 2008; Abhiram 2006; Bindu 2006, 2007, 2009; Bindu and Kumaraswamy Achary 2006; Reeta 2006; Sahoo 2006).

Dung and Nhan (2001) report the successful experimental cultivation of *K. alvarezii* in Haiquan Lagoon and Cat Ba Bay, Vietnam utilizing floating rafts and hanging-on plastic lines. The growth rates realized from the open sea are higher than those achieved in sheltered bays and ranged from 5.18–9.82% d^{-1} and 5.25–7.90% d^{-1}, respectively. *Kappaphycus alvarezii* is considered a highly efficient cultivar generating jobs and supplemental income for the poor in Vietnam coastal areas (Nang 2005). Additionally, significant contributions to ecological balance and the bioremediation of coastal area nutrient enrichment are realized through the use of cultivation frames set on the bottom of shallow areas during the cool season with rapid water circulation, high wind, and waves, hot and sunny season with limited water circulation, minimal wind, and wave energies. Reductions in the concentration of ammonia, nitrite, nitrate, phosphate, and phosphorus content in the water ranged from 10–80% (Nang 2005). Quality of Vietnamese cultivated *Eucheuma* is high, meeting the required standards for sustainable commercial *Eucheuma* cultivation, particularly in the southern Vietnamese waters. Yarish et al. (2001) reported a prototype model that may illustrate the importance of integrating seaweed cultivation activities in the maintenance and health of coastal embayments, a model being explored for Xincun Bay, southeastern Hainan Province, China. The annual nitrogen and phosphorus removal capacity of *Kappaphycus* in Xincun Bay are 53.8 and 3.7 t, respectively, during the 1999–2000 growing season. Reports are also available on the cultivation of *Eucheuma* and *Kappaphycus* in Sabah, Malaysia where two factories for production of semi-refined carrageenan have been established and the inventory of Malaysian seaweeds continues (Phang 2006).

American countries

There are few reports on *K. alvarezii* introduction and commercial cultivation from the western hemisphere and most efforts concentrate on strain improvement and genetic manipulation through the use of modern biotechnological techniques (Ask and Azanza 2002). However, bioinvasive reports from Hawaii (Woo et al. 1989; Rodgers and Cox 1999; Smith 2003; Conklin and Smith 2005) and Venezuela (Barrios 2005) have focused on the ecological effects of eucheumoid introductions on local communities.

de Paula et al. (2002) reported on *K. alvarezii* commercial cultivation as technically feasible practice for Ubatuba Bay, Sao Paulo State, Brazil using floating raft cultivation technologies. Laboratory-grown branches of *K. alvarezii*, with mean weights ranging from 2.97 to 4.25 g, were successfully developed to produce thalli for monthly outplanting in Ubatuba Bay (see also Hiyashi et al. 2007a, b). Branch transplantation produced in unialgal cultures, avoids the risk of unwanted species introduction (de Paula et al. 2002). Ask et al. (2001) recommended research priorities including: replacement of "tie–tie system", use of spores/sporelings in cultivation, multifactorial experiments considering nutrients, salinity, light, etc. to meet seasonality challenges, mitigation of pests, herbivores and diseases, strain improvement and transgenic development, and increasing the quality of extract through superior post-harvest handling methods. Recommendations for exploring, publicizing and utilizing practical and effective quarantine procedures for commercial eucheumoids introductions are also discussed. Three color strains of *K. alvarezii* were cultivated in Dzilam, Yucatan, Mexico using the fixed off-bottom monoline cultivation method to determine the technical viability of commercially producing this seaweed in the Yucatan peninsula's tropical waters (Munoz et al. 2004). The study illustrated that *K. alvarezii* can be grown during the dry and part of the wet season, and concluded that seaweed farming could be attempted as an alternative activity in the area. Bulboa and de Paula (2005) compared the growth rates of *K. alvarezii* and *K. striatum*, in vitro under different light and temperature regimes in the sea off the southeastern coast of Ubatuba, São Paulo, Brazil. *Kappaphycus alvarezii* is physiologically distinct and grows faster than *K. striatum.* Additionally, as the risk of uncontrolled *Kappaphycus* propagation is of great concern, *K. striatum* field production was discontinued after monitoring efforts revealed the production of viable tetraspores. *K. alvarezii* was determined to be the more profitable and ecologically safer species for local cultivation programs.

Polyculture and multitrophic aquaculture

The solution to conflicting demands between development of intensive mariculture and protection of a marine environment may rely on multitrophic aquaculture (polyculture) interaction between primary producers and consumers (Wu et al. 2003). A number of reports point out the potential of *K. alvarezii* as a candidate species for viable multitrophic aquaculture (polyculture) practices (Lombardi et al. 2006; Namudu and Pickering 2006). Wu et al. (2003) discuss the effects of premium quality pearl yields from polycultured oysters cultivated and raised with *K. alvarezii* as compared to monocultured oysters. Mesia and Mapelamao (2006) report on *Kappaphycus* and black lip pearl farms in the western province of the Solomon Islands. Similarly, floating cages seeded with Pacific white marine shrimp, *Litopenaeus vannamei*, and *K. alvarezii* in open marine waters were deployed by the Aquaculture Research Center, State Fishery Institute in Ubatuba, Sao Paulo, Brazil (Lombardi et al. 2001) and the results supported using floating polyculture cages as a viable alternative. Algae:shrimp polyculture provides shelter, shade, and a bed for additional organisms, which could improve natural food, supply for the shrimp. A recent report (Lombardi et al. 2006) indicated Pacific white shrimp *Litopenaeus vannamei* production rates as high as 3.23 kg m^2 y^{-1} and *K. alvarezii* production rates of 23.70 kg m^2 y^{-1} utilizing experimental grow-out cages with polyester/PVC mesh fixed in PVC floating frames in Brazilian cultivation trials.

Molecular genetics and manipulation

Attempts to produce new strains of commercial eucheumoids through somatic hybridization and mutagenesis for field cultivation with improved growth rates and biochemical characteristics were reported by Cheney et al. (1997, 1998). As a result of advancements in protoplast fusion techniques and cell–cell fusion, new strains of *E. denticulatum* and *K. alvarezii*, demonstrated significantly faster growth rates (up to 14% per day) in extensive field trials. Using cell–cell fusion technique, a hybrid between *E. denticulatum* and *K. alvarezii* was produced which exhibits a novel carrageenan composition (Cheney et al. 1998). The report also describes several new techniques developed at the Seaweed Biotechnology Laboratory of Northeastern University, which have made the production of genetically improved cultivars of red seaweeds not only possible but also practical. *K. alvarezii* strain enhancement utilizing tissue culture and micropropagation was developed for the optimization of in vitro culture (Hayashi et al. 2008a, b). A series of cultivars and life history forms were tested (brown, green, red tetrasporophytes, brown female gametophyte, and germinated tetraspores). The germinated tetraspore samples exhibited the highest percentage of callus forming explants and regeneration potential in Von Stosch's 50% solution, indicating a high micropropagation potential. Indole-3-acetic acid and benzylaminopurine stimulated the regeneration process and colchicine produced high regeneration potential explants.

Kappaphycus and *Eucheuma* (Areschougiaceae) systematics and taxonomy is complicated by their morphological plasticity, lack of adequate specific identification characters, and commercial names of convenience. Genetic variation and taxonomic relations of commercial, wild, and herbarium samples were determined utilizing a variety of molecular tools (Giuseppe et al. 2006). Mitochondrial *cox*2-3 and plastidal RuBisCo spacers were sequenced and clear genetic distinctions between *K. alvarezii* ("cottonii") and *K. striatum* ("sacol") were revealed. Hawaiian and African *K. alvarezii* were also found to be genetically distinct. Giuseppe et al. (2006) reported all currently cultivated *K. alvarezii* have similar mitochondrial haplotype. African samples of *Eucheuma denticulatum* ("spinosum") appear to be genetically distinct. Data suggest that currently cultivated *E. denticulatum* may have been "domesticated" several times, whereas cultivated *K. alvarezii* have not. Kimberly et al. (2009) used three molecular markers (partial nuclear 28S rRNA, partial plastid 23S rRNA, and mitochondrial 5′ COI), and followed a DNA barcoding-like approach to identify Hawaiian *Eucheuma* and *Kappaphycus* samples. Neighbor-joining analyses were congruent in their separation of *Eucheuma* and *Kappaphycus*, and the resulting clusters were consistent with those revealed for global comparisons with the mitochondrial *cox*2-3 spacer and GenBank data.

Ecological interactions and bioinvasive reports

The global introduction of *K. alvarezii* to new ecosystems has created concerns over its non-endemic nature, affect on biodiversity, and alteration of local ecological community health and balance. The introduction of commercial invasive cultivars is gathering attention and is being considered as one of the potential challenges to algal cultivation as an economic development engine for coastal fishing communities. The ecological interactions of this species were first reported from the Hawaiian Islands (Woo et al. 1989) and subsequent reports of Rodgers and Cox (1999), Smith (2003), Barrios (2005), and Chandrasekaran et al. (2008) branded it as an 'invasive species'. Apparently, there are practically no reports from countries where it has been introduced for cultivation purposes (Ask et al. 2001) and the cultivation practices are still going on providing income for thousands of families.

Woo et al. (1989) determined the role of herbivory (grazing) on *K. striatum* abundance and concluded grazing intensity is low and unable to affect algal biomass. Conversely, recent conversations with Indian *Kappaphycus* fishermen indicate that approximately 30% of the algal biomass is lost to herbivory. Woo et al. (1989) called for additional studies to assess the ability of the alga to reproduce vegetatively, as well as a qualitative assessment of the possible impact of algal overgrowth on live coral, to estimate further spread, habitat alteration, and ecological impact. Spread of *K. alvarezii*, *K. striatum*, and *Gracilaria salicornia* was measured on barrier reef, patch reef, and fringing reef in Kaneohe Bay, Oahu, Hawaii by Rodgers and Cox (1999). The report assessed the extent of these algae in the bay to determine their rate of spread with a manta tow board survey. The abundance of these species was determined by detailed reef transects in the central bay and reported the establishment of these species. Smith (2003) presented some of the first quantified evidence of significant negative impacts of Non Indigenous Marine Algae in tropical waters. Interactions between *K. alvarezii* and coral abundance were examined using photoquadrats and results indicate that the invader is causing coral death as a result of overgrowth and shading. Conklin and Smith (2005) conducted a study to quantify *Kappaphycus* spp. abundance both spatially and temporally, and to investigate control options including manual removal and the use of biocontrol agents in Kaneohe Bay, Hawaii, USA and recommended that rapid management action should be taken to prevent further damage and spread to other Hawaiian coral reefs.

Barrios (2005) reported *K. alvarezii* vegetative tissues were borne as a crust of small cells radially arranged with a large-cell central medulla with rhizoidal filaments. The lack of *K. alvarezii* limiting structures preventing thalli dispersal when farmed in open waters constitutes a risk of algal dissemination into the surrounding environment. High growth rates, asexual reproduction capacity via fragmentation, resistance to grazing and colonization by fouling organisms make *Kappaphycus* a potential invader to new environments. Chandrasekaran et al. (2008) reported the bioinvasion of *K. alvarezii* onto branching corals (*Acropora* sp.) in Kurusadai Island, the Gulf of Mannar Marine Biosphere Reserve, South India. The report quantifies the invasion and establishment of *K. alvarezii* on live and dead corals, corral rubble and pavements, resulting in significant shadowing and smothering of the coral colonies.

Environmental impact assessment studies

Although concerns of the transfer and introduction of *K. alvarezii* are increasing, Environmental Impact Assessment studies to address the issue are meager. EIA carried out on Indian *Kappaphycus* commercial cultivation is discussed with reference to a global scenario by Tewari et al. (2006a, b). Controversial issues include uncontrolled algal growth, invasion via spores and fragmentation, coral damage, and nutrient depletion. The Indian environmental impact assessment study has shown that *Kappaphycus* commercial cultivation has many positive impacts and a few negative environmental impacts. Planned scientific farming, including regular monitoring of the environment, could mitigate negative impacts. Impacts of *Kappaphycus* farming will differ from environment to environment; therefore, the negative impact experienced by one environment may not necessarily be experienced in another. Commercial cultivation of Indian *K. alvarezii* is not considered harmful to the environment. Alternatively, Pereira and Verlecar (2005) reported *K. alvarezii* on the verge of becoming invasive in southern India and its spread in the Gulf of Mannar. National Academy of Agricultural Sciences, India seaweed cultivation and utilization policy paper (2003) developed marine macroaglal commercial cultivation and processing recommendations and declared it as a national priority. Indian research and development priorities include: creation of baseline seaweed taxonomic database; formation of germplasm and herbaria library; classical and molecular strain improvement programs; diversification of algal products; and ecological and EIA studies pertaining to the introduction of exotic species.

In the light of available literature and verified reports, the present review concludes that the introduction of *Kappaphycus* cultivation to new localities will continue for the foreseeable future in tropical countries due to the high production values realized, coastal villages searching for alternative livelihoods, and the increased global industrial demand for carrageenan.

Acknowledgments MS Bindu is thankful to the United States India Education Foundation (USIEF), New Delhi for the award of Fulbright Fellowship under the Indo-American Environmental Leadership Program (F-IAELP) 2008 and also to the Council for International Exchange of Scholars (CIES), Washington DC for facilitating the Program. The authors express their deep sense of gratitude to the Lewiston-Auburn College, University of Southern Maine for providing the necessity facilities for the program. The authors are also thankful to Dr. Dinabandhu Sahoo, University of Delhi for his constant encouragement and support.

References

Abhiram S (2006) *Kappaphycus* cultivation along Tamil Nadu coast. Abstracts, International Conference on Applied Phycology, Algae in Biotechnology and Environment, New Delhi, 9–10

Anon (2006) Culture of exotic seaweed species hits indigenous ones. The Hindu, 1 November 2006

Ask El (2001) Creating sustainable commercial *Eucheuma* cultivation industry: the importance and necessity of human factor. Proceedings, 17th International Seaweed Symposium, Chapman ARO, Anderson RJ, Vreeland VJ, Davison IR (eds), Cape Town, 13–18

Ask EI, Azanza RV (2002) Advances in cultivation technology of commercial eucheumatoid species: a review with suggestions for future research. Aquaculture 206:257–277

Ask EI, Batibasaga A, Zertuche-González JA, de San M (2001). Three decades of *Kappaphycus alvarezii* (Rhodophyta) introduction to non-endemic locations. Proceedings, 17th International Seaweed Symposium, Chapman ARO, Anderson RJ, Vreeland VJ, Davison IR (eds), Cape Town, 49–57

Barrios JE (2005) Spread of exotic algae *Kappaphycus alvarezii* (Gigartinales: Rhodophyta) in the northeast region of Venezuela. Bol Inst Oceanogr Venez 44(1):29–34

Bindu MS (2006) Success in the pilot scale cultivation of *Kappaphycus alvarezii* in Vizhinjam bay, southwest coast of India. Training

Manual, National Training Workshop on Seaweed Farming and Processing for Food, The Thassim Beevi Abdul Kader College for Women, India, 54–60

Bindu MS (2007) Empowerment of coastal communities in cultivation of economically important seaweeds of Kerala. Project Report, Science & Society Division, Department of Science & Technology, Government of India, 25 pp

Bindu MS (2009) Empowerment of coastal communities in cultivation and processing of *Kappaphycus alvarezii*—a case study at Vizhinjam village, Kerala, India. Abstract, 7th Asia-Pacific Conference on Algal Biotechnology, New Delhi, 21

Bindu MS, Kumaraswamy Achary GP (2006) Experimental field cultivation of *Kappaphycus alvarezii* (Doty) Doty at Vizhinjam Bay, south west coast of Kerala, Abstracts, International Conference on Applied Phycology, Algae in Biotechnology and Environment, New Delhi, 58

Bryceson I (2001) Coastal aquaculture developments in Tanzania: sustainable and non-sustainable experiences, Book of Abstracts, 2nd Western Indian Ocean Marine Science Association (WIOMSA) Scientific Symposium, Zanzibar, Tanzania, 2

Bulboa CR, de Paula EJ (2005) Introduction of non-native species of *Kappaphycus* (Rhodophyta, Gigartinales) in subtropical waters: comparative analysis of growth rates of *Kappaphycus alvarezii* and *Kappaphycus striatum* in vitro and in the sea in southeastern Brazil. Phycol Res 53:183–188

Chandrasekaran S, Nagendran NA, Pandiaraja D, Krishnankutty N, Kamalakannan B (2008) Bioinvasion of *Kappaphycus alvarezii* on corals in the Gulf of Mannar, India. Curr Sci 94(9):1167–1172

Cheney D, Metz B, Levy KI, Levine I, Rudolph B (1997) Genetic manipulation and strain improvement of commercially valuable, phycocolloid-producing seaweeds. *Abstracts,* 4th International Marine Biotechnology Conference, 58

Cheney D, Rudolph B, Wang LZ, Metz B, Watson K, Roberts K, Levine I (1998) Genetic manipulation and strain improvement in commercially valuable red seaweeds. In: Le Gal and Halvorson (eds) New Developments in Marine Biotechnology 101–104

Conklin EJ, Smith JE (2005) Abundance and spread of the invasive red algae, *Kappaphycus spp*., in Kaneohe Bay, Hawaii and an experimental assessment of management options. Biol Invasions 7:1029–1039

de Paula EJ, Erbert C, Pereira RT (2001). Growth rate of the carrageenophyte *Kappaphycus alvarezii* (Rhodophyta, Gigartinales) in vitro. Phycol Res 49(3):155–161

de Paula EJ, Pereira RT, Ohno M (2002) Growth rate of the carrageenophyte *Kappaphycus alvarezii* (Rhodophyta, Gigartinales) introduced in subtropical waters of Sao Paulo State, Brazil. Phycol Res 50:1–9

Doty MS (1973) Farming the red seaweed, *Eucheuma*, for carrageenans. Micronesia 9:59–73

Doty MS (1978) *Eucheuma*—current marine agronomy. In: Krauss RW (ed) The marine plant biomass of the Pacific Northwest coast. Oregon State University Press, Corvallis, OR, pp 203–214

Dung PH, Nhan PT (2001) Some results of study on experimental culture of Elkhorn Sea moss *Kappaphycus alvarezii* in Cat Bay, Hai Phong. Proceedings, Marine Fisheries Research. Tuyen tap cac cong trinh nghien cuu nghe ca bien 2: 537–547

Eswaran K, Jha B (2006) Commercial cultivation of *Kappaphycus alvarezii* in India. Training Manual, National Training Workshop on Seaweed Farming and Processing for Food, The Thassim Beevi Abdul Kader College for Women, Kilakarai, India, 40–46

Eswaran K, Ghosh PK, Mairh OP (2002) Experimental field cultivation of *Kappaphycus alvarezii* (Doty) Doty ex. P. Silva at Mandapam region. Seaweed Res Util 24(1):67–72

Giuseppe CZ, Critchley AT, Smith J, Sieber V, Lhonneur GB, West JA (2006) Systematics and genetic variation in commercial shape *Kappaphycus* and shape *Eucheuma* (Solieriaceae, Rhodophyta). J Appl Phycol 18:643–651

Hayashi L, Jose PE, Fungyi C (2007a) Growth rate and carrageenan analyses in four strains of *Kappaphycus alvarezii* (Rhodophyta, Gigartinales) farmed in the subtropical waters of Sao Paulo State, Brazil. J Appl Phycol 19:393–399

Hayashi L, Oliveira EC, Bleicher LG, Boulenguer P, Pereira RTL, Seckendorff R, Shimoda VT, Leflamand A, Vallee P, Critchley AT (2007b) The effects of selected cultivation conditions on the carrageenan characteristics of *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae) in Ubatuba Bay, Sao Paulo, Brazil. J Appl Phycol 19:505–511

Hayashi L, Yokoya NS, Kikuchi DM, Oliveira EC (2008a) Callus induction and micro propagation improved by colchicine and phytoregulators in *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae). J Appl Phycol 20:653–659

Hayashi L, Yokoya NS, Ostini S, Pereira RTL, Braga ES, Oliveira EC (2008b) Nutrients removed by *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae) in integrated cultivation with fishes in recirculating water. Aquaculture 277:185–191

Hurtado A (2003) Farming the seaweed *Kappaphycus*. SEAFDEC Asian Aquacult 25(3):23

Hurtado AQ, Biter AB (2007) Plantlet regeneration of *Kappaphycus alvarezii* var. adik-adik by tissue culture. J Appl Phycol 19:783–786

Kimberly YC, Kurihara A, Sherwood AR (2009) A molecular method for identification of the morphologically plastic invasive algal genera *Eucheuma* and *Kappaphycus* (Rhodophyta, Gigartinales) in Hawaii. J Appl Phycol 21:691–699

Lombardi JV, Marques HLA, Barreto OJS, Gelli VC, Pereira RTL, de Paula EJ (2001) Floating cages as an alternative for growing the marine shrimp *Litopenaeus vannamei* in open seawater. Book of Abstracts, Aquaculture 2001, 384 p

Lombardi JV, de Almeida Marques HL, Pereira RTL, Barreto OJS, de Paula EJ (2006) Cage polyculture of the Pacific white shrimp *Litopenaeus vannamei* and the Philippines seaweed *Kappaphycus alvarezii*. Aquaculture 258:412–415

Lundsor E (2001) *Eucheuma* farming on Zanzibar broadcast system: an alternative method for seaweed farming. Book of Abstracts, 2nd Western Indian Ocean Marine Science Association (WIOMSA) Scientific Symposium, Zanzibar (Tanzania) p. 29

Mairh OP, Zodape ST, Tewari A, Rajyaguru MR (1995) Culture of marine red alga *Kappaphycus striatum* (Schmitz) Doty on the Saurashtra region, West coast of India. Indian J Mar Sci 24:24–31

Mate F, Namudu M, Lasi F (2003) Report on the outcomes of the train-the-trainers workshop on *Kappaphycus* seaweed farming in Pacific island countries. Tech Rep Mar Stud Programme Univ South Pac 6: 26 pp

Mesia P, Mapelamao T (2006) International Waters Program (SI): working towards a sustainable future in Solomon Islands. Melanes Geo 3:24–26

Msuya FE, Salum D (2006) The Effect of cultivation duration, seasonality, and nutrient concentration on the growth rate and biomass yield of the seaweeds *Kappaphycus alvarezii* and *Eucheuma denticulatum* in Zanzibar, Tanzania. Western Indian Ocean Marine Sciences Association (WIOMSA), Zanzibar (Tanzania)

Mtorela MSP (2003) Effect of seagrass cover and mineral content on *Kappaphycus* and Eucheuma productivity in Zanzibar, West Indian Ocean. J Mar Sci 2:163–170

Munoz J, Freile-Pelegrin Y, Robledo D (2004) Mariculture of *Kappaphycus alvarezii* (Rhodophyta, Solieriaceae) color strains in tropical waters of Yucatan, Mexico. Aquaculture 239:161–177

Namudu MT, Pickering TD (2006) Rapid survey technique using socio-economic indicators to assess the suitability of Pacific island rural communities for *Kappaphycus* seaweed farming development. J Appl Phycol 18:241–249

Nang HQ (2005) Results of study on production of *Eucheuma, Kappaphycus alvarezii* in Vietnam and development orientations. Fish Rev 3:17–21

National Academy of Agricultural Sciences, India (2003) Seaweed cultivation and utilization, Policy paper 22, 6 pp

Oliveira EC, Paula EJ (2003). Exotic seaweeds: friends or foes? Proceedings, 17th International Seaweed Symposium, Chapman ARO, Anderson RJ, Vreeland VJ, Davison IR (eds.), Cape Town, 425–434

Parker HS (1974) The culture of the red algal genus *Eucheuma* in the Philippines. Aquaculture 3:425–439

Pereira N, Verlecar XN (2005) Is Gulf of Mannar heading for marine bioinvasion? Curr Sci 89:1309–1310

Phang SM (2006) Seaweed resources in Malaysia: current status and future prospects. Aquat Ecosyst Health Manag 9(2):185–202

Pickering T (2006) Advances in seaweed aquaculture among Pacific island countries. J Appl Phycol 18:227–234

Pickering T, Forbes A (2002) The progress of aquaculture development in Fiji. Technical Report, Marine Studies Programme, University of South Pacific 2002/1: 40 pp

Ponia B (2005) A quiet achiever: aquaculture in the Pacific. Fisheries News letter, Secretariat of Pacific Community 115:41–43

Reeta J (2006) Open Sea farming of *Kappaphycus* in India. Training Manual, National Training Workshop on Seaweed Farming and Processing for Food, The Thassim Beevi Abdul Kader College for Women, Kilakarai, India 47–53

Rice MA, Savoie RM (2005) Expanding and diversifying aquaculture in Tanzania: overview and some recommendations. J Shellfish Res 24(4):1269

Rodgers SK, Cox EF (1999) Rate of spread of introduced rhodophytes *Kappaphycus alvarezii, Kappaphycus striatum,* and *Gracilaria salicornia* and their current distributions in Kaneohe Bay, Oahu, Hawaii. Pac Sci 53:232–241

Rodrigueza MRC, Montano MNE (2007) Bioremediation potential of three carrageenophytes cultivated in tanks with seawater from fish farms. J Appl Phycol 19:755–762

Russell DJ (1983) Ecology of the imported red seaweed *Eucheuma striatum* Schmitz on Coconut Island, Oahu, Hawaii. Pac Sci 37:87–108

Sahoo DB (2006). Creating a million jobs through large-scale seaweed cultivation—a mission towards blue revolution. Abstracts, International Conference on Applied Phycology, Algae in Biotechnology and Environment, New Delhi, 11

Sakthivel M (1999) Resource potential, present status and solutions to the problems of seaweed cultivation in India. Seaweed Res Util 21(1&2):15–19

Smith JE (2003) Invasive macroalgae on tropical reefs: impacts, interactions, mechanisms and management. J Phycol 39(S1):53

Smith JE, Hunter CL, Smith CM (2002) Distribution and reproductive characteristics of non-indigenous and invasive marine algae in the Hawaiian Islands. Pac Sci 56:299–315

Subba Rao PV, Mantri VA, Thakur MC (2004) Field cultivation of *Kappaphycus alvarezii* (Doty) Doty on Okhamandal coast, Gujarat. Abstracts, Seaweeds-2004, National Symposium and Exposition, Cochin, India, 26

Subba Rao PV, Suresh Kumar K, Ganesan K, Chandra TM (2008) Feasibility of cultivation of *Kappaphycus alvarezii* (Doty) Doty at different localities on the northwest coast of India. Aquac Res 39:1107–1114

Teitelbaum A (2003). Farming seaweed in Kiribati: a practical guide for seaweed farmers. Hand Book, SPC, 38 pp

Tewari A (2006). Environmental impact assessment of *Kappaphycus* cultivation on the Tamil Nadu coast of India, Abstracts, International Conference on Applied Phycology, Algae in Biotechnology and Environment, New Delhi, 38–39

Tewari A, Basha S, Trivedi RH, Raghunathan C, Sravan Kumar VG, Khambhaty Y, Joshi HV, Kotiwar OS (2006) Environmental impact assessment of *Kappaphycus* cultivation in India in context to global scenario. In: Vol. 1: Seaweed taxonomic identification, aquaculture, resource, environment, fouling and disease. Pp. 262–287

Vijayalakshmi E (2007) PepsiCo endangers biodiversity hot spot in Gulf of Mannar. Down to Earth, 7

Wakibia JG, Bolton JJ, Keats DW, Raitt LM (2006) Factors influencing the growth rates of three commercial eucheumoids at coastal sites in southern Kenya. J Appl Phycol 18:565–573

Woo M (2000) Ecological impacts and interactions of the introduced red alga *Kappaphycus striatum* in Kaneohe Bay, Oahu. Master Thesis, Department of Botany, University of Hawaii, Honolulu

Woo M, Smith C, Smith W (1989) Ecological interactions and impacts of invasive *Kappaphycus striatum* in Kaneohe Bay. Proceedings, First National Conference, Tropical Reef Marine Bioinvasions, 186

Wu M, Mak SKK, Zhang X, Qian P (2003) The effect of co-cultivation on the pearl yield of *Pinctada martensi* (Dumker). Aquaculture 221:347–356

Yano M, Isao T, Masao O (2007) Growth rates of green and brown types of *Kappaphycus alvarezii* cultivation in the Tosa Bay, warm waters. Bull Mar Sci Fish, Kochi Univ 25:59–62

Yarish C, Rawson MV Jr, Chopin T, Wang DR, Chen C, Carmona R, Chen C, Wang L, Ji R, Sullivan J (2001) Ecosystem modeling: a tool to understand the interactions between extractive and feed aquaculture. J Phycol 37(S3):56

Zuccarello GC, Critchley AT, Smith J, Sieber V, Lhonneur GB, West JA (2006) Systematics and genetic variation in commercial shape *Kappaphycus* and shape *Eucheuma* (Solieriaceae, Rhodophyta). J Appl Phycol 18:643–651