Review

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Seaweed aquaculture: cultivation technologies, challenges and its ecosystem services

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Seaweed aquaculture technologies have developed dramatically over the past 70 years mostly in Asia and more recently in Americas and Europe. However, there are still many challenges to overcome with respect to the science and to social acceptability. The challenges include the development of strains with thermo-tolerance, disease resistance, fast growth, high concentration of desired molecules, the reduction of fouling organisms and the development of more robust and cost efficient farm systems that can withstand storm events in offshore environments. It is also important to note that seaweed aquaculture provides ecosystem services, which improve conditions of the coastal waters for the benefit of other living organisms and the environment. The ecosystem services role of seaweed aquaculture and its economic value will also be quantitatively estimated in this review.

Key Words: ecosystem services; *Eucheuma*; *Gracilaria* / *Gracilariopsis*; *Kappaphycus*; kelp; *Pyropia* / *Porphyra*; *Sargassum*; seaweed aquaculture

INTRODUCTION

According to an archaeological study, cooked and partially eaten seaweeds have been found at a 14,000-year-old site in southern Chile, suggesting seaweed have been part of the human diet in the Western Hemisphere for a very long time (Dillehay et al. 2008). In the past four hundred years, seaweeds have been an important part in Asian cuisine more so than in western cultures. Global seaweed aquaculture production occupies approximately 20% of the total world marine aquaculture production by weight, with an annual value of US $6.7 billion in 2013 (Bjerregaard et al. 2016, Cottier-Cook et al. 2016, FAO 2017). Most production occurs in Asia. Seaweed aquaculture production is dominated (>81% of total production) by relatively few species: the brown kelps, *Saccharina japonica* and *Undaria pinnatifida*; and the red seaweeds including *Pyropia* / *Porphyra* spp. ('nori' in Japanese or 'gim' in Korean), *Kappaphycus alvarezii* and *Eucheuma striatum* (carrageenophytes) and *Gracilaria* / *Gracilariopsis* spp. (agarophytes).

Currently 54,000 tons of seaweed are cultivated in the Americas and Europe with an annual value of US $51 million in 2014 (FAO 2017), which is less than the value of seaweed products that Korea exported to the United States during the same period (US $67 million) (Meekyi-

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ung Kim, Korea Agro-Trade Center personal communication). Although seaweed aquaculture is a relatively new industry in North America and Europe, the demand by western markets is expected to increase rapidly due to consumer desire for new protein sources and healthy food supplements, plus food industry's interest in sustainable textural additives and food security.

Seaweed aquaculture technologies have developed dramatically in Asia, but there are still many challenges to overcome. These challenges vary for different species and in different countries. In this study, we will discuss the challenges to seaweed cultivation of major aquacultured species. Seaweed aquaculture also provides ecosystem services through nutrient removal upon harvest. This ecosystem services role by seaweed aquaculture will also be addressed in this study.

CULTIVATION TECHNOLOGIES AND CHALLENGES IN MAJOR AQUACULTURED SPECIES

Pyropia / *Porphyra* ('nori' or 'gim')

Pyropia / *Porphyra* has been cultivated for the past several hundred years in Japan and has become one of the most successful aquaculture industries in Japan, Korea, and China (Mumford and Miura 1988, Pereira and Yarish 2008). Its current annual value is nearly $0.95 billion (FAO 2017). *Pyropia* / *Porphyra* has the highest commercial value per unit mass ($523 per wet metric ton) in comparison to other aquacultured species, kelp, $141 per wet ton; *Gracilaria*, $273 per wet ton; *Kappaphycus* / *Eucheuma*, $172 per wet ton; and *Sargassum*, $460 per wet ton (FAO 2017). Although total 138 species of *Pyropia* and *Porphyr*a are currently accepted taxonomically (Guiry and Guiry 2016), only 3 major species (*Py*. *yezoensis*, *Py*. *tenera*, and *Py*. *haitanensis*) have been commercially cultivated, mostly in China, Korea, and Japan (99.99% of total production) (FAO 2017). The culture methods of *Pyropia* / *Porphyra* in these three countries are basically similar, with minor modifications (see Sahoo and Yarish 2005, Pereira and Yarish 2008, 2010, Pereira et al. 2013 for more details). For example, some farmers use free-living conchocelis for seeding while others use conchocelis on oyster shells (He and Yarish 2006, He et al. 2008). Seedlings may be outplanted in the open water farms using one of three cultivation methods: fixed pole, semifloating raft, or floating raft (see Sahoo and Yarish 2005 for details). The epiphyte control techniques are also different based on the cultivation techniques. Most Chinese farms, and some Korean and Japanese farms use desiccation control methods by exposing the *Pyropia* / *Porphyra* nets to the air to kill epiphytes and competing organisms (e.g., *Ulva* spp.), while most Korean and Japanese farmers prefer to use a pH control method by applying organic acids onto the nets (Pereira and Yarish 2010, Kim et al. 2014*a*) but this is a costly approach. There are no additional (or minimal) costs using the desiccation method and this method may even increase the protein content in tissue (Kim et al. 2013*b*). However, the desiccation method is not as efficient as the pH control method. Uncontrolled fouling organisms reduce the quality of production. Recent reports even suggest that the source of the world largest macroalgal blooms originated from *Ulva* grown on the rafts of *Pyropia* farms in the Southern Yellow Sea of China (Liu et al. 2009, Hu et al. 2010, Zhang et al. 2014, 2016, Huo et al. 2016).

Pyropia / *Porphyra* has been cultivated in the western countries since 1980s; however, production has had limited success. In 1994, the first commercial attempt to cultivate *Pyropia yezoensis* ('*Porphyra*') in open water in the State of Maine (Chopin et al. 1999, McVey et al. 2002) was unsuccessfully attempted by Coastal Plantations International (later incorporated into PhycoGen, Inc., Portland, ME, USA). The aquaculture site had insufficient nutrients to support vigorous growth of *Py. yezoensis*. In 1996, this company moved its nori nets adjacent to an Atlantic salmon (*Salmo salar*) farm at the Connors Aquaculture Inc. facilities (Deep Cove, Eastport, ME, USA). This open water cultivation was successful and ultimately lead to the development of Integrated Multi-Trophic Aquaculture (IMTA). However, PhycoGen, Inc., went bankrupt due to the downturn in the investment environment. More recently, *Porphyra umbilicalis* cultivation is in process in Maine by Brawley and her colleagues (Blouin et al. 2011, Brawley, University of Maine, personal communication). A cultivation manual has also been published for seedstock production of *Pyropia* / *Porphyra* in the United States (Redmond et al. 2014*a*) with accompanying videos in English and Spanish. These efforts reflect that the western countries are interested in *Pyropia* / *Porphyra* cultivation. However, *Pyropia* / *Porphyra* cultivation is still in its nascent stage in the western countries, and there currently are no commercial *Pyropia* / *Porphyra* growers in the United States. Therefore, it is critical to develop local cultivars and cultivation techniques suitable for the local environments and boutique markets. Selective (intra-specific and inter-specific) breeding of cultivated *Pyropia* / *Porphyra* has been intensively studied in Asia (Miura 1984, Shin 1999, 2003, Niwa et al. 2009). Genetic improvement has developed superior strains with higher growth capacity, better flavor, darker color and higher tolerance to diseases (Chen et al. 2015).

The effects of climate change may be an incentive to do more research in genetic manipulations. Recently, National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) reported the year 2016 ranks as Earth's warmest since 1880. The 17 warmest years on record, with the exception of 1998, have occurred since 2000. Since 1880, Earth's average surface temperature has risen by about 1.1°C and the majority of that warming has occurred in the past three decades (NASA 2017). Therefore, development of new strains with high thermo-tolerances will be a must for the development of a sustainable seaweed aquaculture industry.

Gracilaria / Gracilariopsis

The red algae *Gracilaria* / *Gracilariopsis* are two of the world's most cultivated seaweeds with over 3.8 million tons of annual production and worth annually about US $1 billion (FAO 2017). *Gracilaria* / *Gracilariopsis* have been mostly cultivated in two Asian countries (China 70% and Indonesia 28% of global production). In the Americas, Chile is the most productive country, producing more than 12.8 tons per year with an annual value of US $29 million (FAO 2017). Most of the biomass is used in the phycocolloid industry as the main source of food grade agar (Pereira and Yarish 2008) and as an animal feed (Qi et al. 2010, Johnson et al. 2014). *Gracilaria* / *Gracilariopsis* contribute approximately 66% of the total agar production (Pereira and Yarish 2008). Currently 185 *Gracilaria* and 24 *Gracilariopsis* species are accepted taxonomically (Guiry and Guiry 2016). *Gracilaria* / *Gracilariopsis* include warm temperate to subtropical eurythermal species. These species are easy to propagate (asexually and sexually), and have relatively high growth rates (Abreu et al. 2011*a*, Kim and Yarish 2014, Kim et al. 2015*c*, 2016, Wu et al. 2015, Gorman et al. 2017). *Gracilaria* / *Gracilariopsis* are also euryhaline species, which can tolerate a wide range of salinities, from about 10-40 psu, though they grow best in ranges of 25-33 psu (Yokoya et al. 1999, Weinberger et al. 2008, Kim et al. 2016, Gorman et al. 2017). They can survive temperature ranges from 0-35°C but have an optimal range of 20-28°C (Yokoya et al. 1999, Raikar et al. 2001, Abreu et al. 2011*a*, Kim et al. 2016).

Gracilaria / *Gracilariopsis* have been cultivated mainly in four different ways, including open water rope cultivation, near shore bottom cultivation, pond culture and tank cultures (see Oliveira et al. 2000, Sahoo and Yarish 2005, Pereira and Yarish 2008 for more details). In any of these methods, providing sustainable seedstock is critical. Currently, most *Gracilaria* / *Gracilariopsis* seedstock has been supplied from the wild (either collection of healthy branches of *Gracilaria* / *Gracilariopsis* from natural stock or selection of reproductive plants to collect spores (either carpospores or tetraspores) for seeding (Buschmann et al. 2008*a*). Dependence on natural stocks may cause some serious problems including physiological variations (e.g., growth, agar content, etc.) in the seedstock. Adequate measures should be taken to protect natural stocks of *Gracilaria* / *Gracilariopsis* from over-exploitation of donor populations. Another methodology that could be used is nursery (tank culture) systems to provide sufficient seedstock through vegetative propagation (Hanisak 1987, Abreu et al. 2011*a*, 2011*b*, Kim and Yarish 2014). One important advantage of tank cultivation is the ease of controlling the culture system (Abreu et al. 2011*b*, Pereira et al. 2013). This ensures that production meets high quality standards and biosafety for human consumption and other high value production applications for the cosmeceutical and pharmaceutical industries. A limitation for tank culture, however, is high management costs (Hanisak and Ryther 1984, Caines et al. 2014). Recently, Abreu et al. (2011*b*) have used tank cultivation to mitigate fish effluent, therefore reducing the production costs. Kim and Yarish (2014) has also suggested other cost efficient resources, such as injecting CO_2 and using commercial fertilizers. The use of LED lighting could further reduce tank cultivation costs (Kim et al. 2015*c*). There was an intensive study on genetics, mutation, selective breeding and even genetic engineering in *Gracilaria* / *Gracilariopsis* by van der Meer and his collaborators a few dacades ago (see Patwary and van der Meer 1992 and references therein). More recently in Chile, strains of *Gracilaria chilensis* were established and maintained without sexual reproduction. These strains are homogeneous clonal cultures (Buschmann et al. 2008*a*, Guillemin et al. 2008, Robinson et al. 2013), which can be more susceptible to diseases outbreaks and environmental changes. The quality of wild *Gracilaria* / *Gracilariopsis* in recent years has been diminished due to declines in the cultivation environments and increase in diseases (Alamsjah 2010). Using asexually derived branches may lead to a reduction in genetic variability but more work needs to be done on the population genetics of these taxa.

Therefore, the technology development combining hybridization, genetic material establishment while maintaining genetic diversity will become very important in

Gracilaria / *Gracilariopsis* aquaculture. Another challenge in *Gracilaria* / *Gracilariopsis* aquaculture is to develop technologies and strategies to reduce fouling problems. Fouling organisms (e.g., epiphytes, tunicates, hydroids, etc.) have been observed at *Gracilaria* farms in Long Island Sound (CT), Bronx River estuary (NY), and Waquoit Bay (MA) (Kim et al. 2014*b*, Lindell et al. 2015). A few successful solutions to these problems include fresh water rinses, the use of tank grown fresh *Gracilaria* seedstock, determination of optimal stocking density and photon fluence levels. However, more studies are needed for sustainable production and to understand the genetic variability of the seedstocks.

Kappaphycus and *Eucheuma*

The red algae *Kappaphycus* and *Eucheuma*, major sources of carrageenan, account for over 80% of world's carrageenan production (Pereira and Yarish 2008, Hayashi et al. 2010). Approximately 10.75 million tons of these species were produced worth over US $1.9 billion in 2014 (FAO 2017). *Kappaphycus* and *Eucheuma* have been cultivated mostly in Indonesia (over 9.0 million tons, over 83% of global production, mostly *Eucheuma*), followed by the Philippines (nearly 1.4 million tons, 13% of global production, mostly *Kappaphycus*). Approximately 340,000 tons of these carrageenophytes were also cultivated in Malaysia, Cambodia / Vietnam, China, Tanzania / Madagascar, Belize and Brazil (Valderrama et al. 2015, Bjerregaard et al. 2016, FAO 2017).

Of six species taxonomically accepted as *Kappaphycus* and 30 *Eucheuma* species, *Kappaphycus alvarezii* and *Eucheuma denticulatum* are most often cultivated. Both of these taxa are cultivated using the same methodologies including the fixed, off-bottom line method, the floating raft method and basket method (see Ask and Azanza 2002, Pereira and Yarish 2008, Hayashi et al. 2010 for more details). The steps in the farming of these genera include 1) site selection, 2) selection of cultivation methodology, 3) farm maintenance, and 4) harvesting and drying. Among these steps, site selection is most important due to the herbivory of siganids (rabbitfish) and puffers. Turtles are also problematic because they take large bites and also crawl through a farm, causing physical damage to the farm systems. Long-spined sea urchins may also be a pest and can cause injuries to the farmers as they try to remove them. There is no simple solution except moving to another site where these animals are not prevalent. Diseases are also a challenge. The most common disease of the euchemoid spp. is called "ice-ice" because the appearance of white segments on the thalli, causing them to break (Largo et al. 1995, Ask and Azana 2002, Vairappan et al. 2009). It is still unknown what vector causes this disease, but a bacterial or viral infection, and / or physical stresses have been suggested as the potential sources (Vairappan et al. 2009). Farmers also need to remove epiphytes 2-3 times each and every week, which requires intensive labor (Hurtado et al. 2006). Therefore, it is extremely important to develop new strains that are light and thermally tolerant and disease resistant. More efficient epiphyte control also needs to be developed. In addition, storm damage due to typhoons is problematic in tropical regions where cultivation occurs. The simplest solution to minimize storm damage is the removal of all cultivation systems prior to the typhoon season (~3 months per year). Development of more robust and cost efficient farm systems are needed especially in the offshore environment.

Kelp (*Saccharina* and *Undaria*)

Over 8.0 million tons of kelp were cultivated and harvested in 2014 with a value of about US $1.4 billion annual values (FAO 2017). Nearly all kelp production occurred in Asia: China 88.3%; Korea (south) 6.6%; and Korea (north) 4.4% (FAO 2017). Kelp has been utilized mostly for human consumption, but recently, it also has been increasingly utilized as abalone feed due to low production costs (Hwang et al. 2012, 2013). Since the early part of this decade, *Undaria* and *Saccharina* production have continuously increased due to demand for abalone feeds in Korea (Hwang et al. 2012). Over 60% of total production of *Saccharina* and *Undaria* was used in the abalone industry in 2012 (Hwang et al. 2012).

In Western countries, kelp species (primarily the sugar kelp, *Saccharina latissima* and winged kelp, *Alaria esculenta*) have been cultivated during the last two decades in the North Atlantic Ocean (e.g., the United States, Canada, Iceland, Norway, Scotland, Ireland, Sweden, and Germany, etc.) (Buck and Buchholz 2004, Barrington et al. 2009, Broch et al. 2013, Kraemer et al. 2014, Kim et al. 2015*b*, Marinho et al. 2015) and *Macrocystis*, *Saccharina latissima*, and *Alaria esculenta* in the eastern Pacific Ocean (e.g., Chile: Buschmann et al. 2008*b*, 2014, Camus et al. 2016, Correa et al. 2016, Valero et al. 2017; Alaska: Stekoll and Peeples 2016). The kelp aquaculture industry in the western countries has become one of the fastest growing industries (Cottier-Cook et al. 2016).

For both *Saccharina* and *Undaria*, cultivation begins with zoospores (meiospores) for seeding. The seeding methods are a bit different between Asia (use of seed frames) and the West (use of seedspools) (Pereria and Yarish 2008, Redmond et al. 2014*a*) mainly due to the nursery capacities and the scale of operations of the open water farms. However, the open water cultivation techniques using longlines are very similar. Once the seedstring is outplanted at open water farms the kelp thalli will grow up to 2-5 m in length, but sometimes may grow up to 10 m (see Pereira and Yarish 2008, Redmond et al. 2014*a*, SINTEF 2014 for details).

Dealing with climate change will be a challenge for cultivation of cool temperate species of kelp (Park et al. 2017). Efforts to develop strains of kelp with traits of fast growth, disease resistance and high temperature tolerance are needed. Selective breeding and intensive selection of kelp strains in Asia, however, have reduced the genetic diversity and narrowed the germplasm base of the varieties in cultivation (Kawashima and Tokuda 1993, Li et al. 2007, 2016, Robinson et al. 2013), therefore jeopardizing the industry expansion in Asia.

In the United States, Canada and Europe, strain development will be a challenge. Meiospore "seeds" (zoospores) have relied mostly on natural populations. Development of "seedbanks" for the kelp species will provide a sustainable and reliable source of seedstock without impacting the natural beds of the kelp. Having the seaweeds with desirable morphological and physiological traits will also enhance production capacity of the seaweed industry. Another challenge in these countries is permitting and the social syndrome known as NIMBY ("Not In My Back Yard") reactions. For example, in the United States at least 120 federal laws were identified that affect aquaculture either directly (50 laws) or indirectly (70 laws) and more than 1,200 state statutes regulate aquaculture in 32 states (Getchis et al. 2008). Regulatory complexity is further increased when towns or counties are given jurisdiction over local waters. Social resistance has also been major factor limiting the growth of aquaculture in the United States (Getchis et al. 2008). The nearshore waters of the United States are heavily used, having both recreational (boating, fishing, swimming) and aesthetic (ocean and bay views from waterfront homes) values. Due to this reason, offshore cultivation has been suggested as an alternative to avoid stakeholder conflicts (Langan and Horton 2005, Rensel et al. 2011).

Recently, the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) has expressed interest in offshore seaweed aquaculture for the production of feeds, fuels and chemicals. The potential species discussed include *Saccharina* in the Northeast (Western Atlantic Ocean), Northwest (eastern Pacific Ocean of Washington and Alaska) and *Sargassum* spp. in the Gulf of Mexico and Caribbean. To achieve success in these ventures, technology development will be required, including breeding for suitable strain development, cultivation, harvesting, transport, storage, processing, ecosystem services and product opportunities for long-term financial viability of a United States-based macroalgae industry on the path to biofuels. The nutrients for the growth of seaweeds may also be limited in the offshore environment. To resolve this issue, site selection for cultivation will be critical, such as in upwelling areas. The offshore seaweed farms are unlikely to experience conflicts with other economic and recreational uses, which may result in fewer restrictions on farm size and greater economies of scale. Considering current cultivation techniques, the kelp will be most the appropriate species to cultivate offshore due to its low requirement for maintenance and harvest in comparison to other aquacultured species. For example, an endemic kelp phenotype, known as *Saccharina latissima* forma *angustissima* (F. S. Collins) A. Mathieson could be an ideal candidate for the offshore cultivation. This endemic form grows only at wave-impacted locations in Maine (Mathieson et al. 2008, Augyte et al. in press). Unlike the common *Saccharina latissima* plants, this endermic form grows very narrow (2-5 cm) and long (~5 m), which is probably induced by hydrodynamic forces and mechanical stress from breaking waves and strong currents (Fowler-Walker et al. 2006, Koehl et al. 2008). These features will make *Saccharina latissima* forma *angustissima* more suiatable for the offshore cultivation.

Sargassum

Sargassum is the most common brown macroalgae found in temperate, tropical, and subtropical waters worldwide. These seaweeds are adapted to many different oceanic environments with a wide variety of forms and reproductive strategies (Guiry and Guiry 2016). *Sargassum* species have traditionally been utilized for food and medicine in Asia. They continue to be wild harvested and cultivated in Japan, China, and Korea, for human consumption as sea vegetables and for use as a medicinal "seaweed herbs." Locally known as the "black vegetable" in China, *Sargassum* is valued for its high nutritional content and nutty flavor. It is added to salads, soups or vegetable dishes (Xie et al. 2013). *Sargassum* is utilized in Chinese medicine as an expectorant for bronchitis, and to treat laryngitis, hypertension, infections, fever, and goiter (Hou and Jin 2005). *Sargassum fusiforme* (formally

"*Hizikia fusiformis*") cultivation was initiated in the early 1980s. Thus, the production and economic value is still low, approximately 175,000 tons of production worth US $80 million in 2014 (FAO 2017). Nearly all *Sargassum* is produced in China. Although still low in production, its commercial value per unit mass is very high (US $460 per wet ton), which is the highest amongst the aquacultured brown seaweeds. It is even comparable to *Pyropia* / *Porphyra* (US $523 per wet ton). Currently, several *Sargassum* species are cultured in Asia, including *S. thunbergii*, *S. fulvellum*, *S. muticum*, and *S. horneri* in China (Xie et al. 2013), and *S. fusiforme* and *S. fulvellum* in Korea (Hwang et al. 2006*a*).

Traditional culture methods initially relied on the use of wild seedlings collected from natural beds. Groups of 3-4 seedlings, 5-10 cm in length, were inserted into seeding rope at intervals of 5-10 cm. This smaller seeding line was then attached to a main longline placed at depths of 2-3 m, and cultivated from November to May (Sohn 1998, Hwang et al. 2006*a*, Redmond et al. 2014*b*). This dependence on wild seedlings resulted in overharvesting natural beds, so new culture methods were developed. Holdfast-derived seeding was the first step towards developing culture techniques for *Sargassum*. This type of culture takes advantage of the perennial nature of the holdfast, allowing farmers to reuse the holdfasts from the previous year's crops (Hwang et al. 1998). While plants may still be sourced from wild beds, the attached holdfasts can be re-used for the next season's crop by over-summering in the sea after harvest until the next growing season. While this allows for reuse of existing cultured plants, the resulting harvestable biomass tends to diminish after each year. Today, *Sargassum* lines are seeded with juvenile plants obtained from reproductive adults. Obtaining seedlings through sexual reproduction allows for mass production of new plants for seeding, and results in higher biomass yields (Hwang et al. 2006*b*, Peng et al. 2013, Redmond et al. 2014*b*). Fertilized eggs are gathered from mature fronds and "seeded" onto seedstring by allowing juveniles to attach to seed lines with newly forming rhizoids. Once attached, seedlings are cultured in a nursery until ready for out-planting at sea, where they are transferred to submerged long lines until harvest. The attached holdfasts can also be re-used for multiple years without any further initiation of culture ropes. This is economically reasonable cultivation method, but fouling organisms are problematic. Technology development to reduce fouling is an urgent need for the sustainable production and the growth of the *Sargassum* aquaculture industry.

ECOSYSTEM SERVICES

Seaweeds are valued as food in many parts of Asia and in the western countries. Seaweeds are also used to produce animal feed, chemicals, paper, fertilizer, biofuel, and other renewable, derivative products, and even to test biological toxicity for human and environmental health (Han et al. 2011, Johnson et al. 2014, Hafting et al. 2015, Kerrison et al. 2015, Park et al. 2016, Wells et al. 2016). One goal for the development of sustainable aquaculture is to ensure that commercial aquaculture has minimal adverse effects on the environment. One way to achieve this goal is through development of improved methods of waste management for land based and coastal / offshore aquaculture. IMTA combines the fed aquaculture (e.g., fish or shrimp) with the extractive aquaculture (seaweed and shellfish) to create a more balanced ecosystem. In coastal waters, high levels of these nutrients can trigger harmful algal blooms and contribute to excessive growth of nuisance or opportunistic macroalgae, which in turn have negative consequences on coastal ecosystems and economies (Neori et al. 2004, Buschamann et al. 2008*a*, Chopin et al. 2008, Pereira and Yarish 2008, Abreu et al. 2009, 2011*b*, Kim et al. 2015*a*). Nutrient bioextraction is a similar concept but without the fed aquaculture component. The concept of nutrient bioextraction can be applied to urbanized estuaries, where the excess nutrients are already problematic. In the IMTA and the nutrient bioextraction systems (whether land based, coastal or offshore) seaweed can be used as an extractive component to remove inorganic nutrients and mitigate potentially adverse environmental impacts (Neori et al. 2004, 2007, Corey et al. 2012, 2014, Kim et al. 2013*a*, 2014*b*, 2015*b*, Rose et al. 2015, Wu et al. 2017). Seaweeds take up nitrogen, phosphorus and carbon dioxide, which they use for growth and production of energy storage products. When seaweeds are harvested from the IMTA or nutrient bioextraction systems, the nutrients are also being removed from the water.

Considering the global seaweed production and tissue carbon and nitrogen contents in each species, total extractive nitrogen and carbon by seaweed aquaculture can be estimated. Considering average values of nitrogen (*Pyropia* / *Porphyra* 5.5%, *Gracilaria* 3.0%, *Kappaphycus* / *Eukeuma* 1.7%, kelp 2.0%, and *Sargassum* 4.1%) and carbon (*Pyropia* / *Porphyra* 38%, *Gracilaria* 28%, *Kappaphycus* / *Eukeuma* 29%, kelp 30%, and *Sargassum* 34%) (Asare and Harlin 1983, Gerald 1997, Schaffelke and Klumpp 1998, Gevaert et al. 2001, Schaffelke 2001, Chung et al. 2002, Rawson et al. 2002, Sahoo and Ohno

2003, Dean and Hurd 2007, Kim et al. 2007, 2014*b*, 2015*b*, Buschmann et al. 2008*b*, Abreu et al. 2009, Robertson-Andersson et al. 2009, Levine and Sahoo 2010, Broch et al. 2013), the total nitrogen and carbon removal by these five major aquaculture groups is approximately 65,000 tons of nitrogen per year and 760,000 tons of carbon per year (to 2.8 million tons of CO_2), respectively. Over 120 million tons of fertilizer was used in 2014 and approximatelty 15-30% of it entered the ocean (FAO 2015). Recently, Bjerregaard et al. (2016) reported that seaweed aquaculture could remove approximately 30% of the introduced nitrogen if seaweeds were aquacultured in 0.03% of the ocean surface area, producing 500 million tons DW. They also estimated that approximately 135 million tons of carbon could be removed by the same amount of aquacultured seaweed. This carbon removal is approximately 3.2% of the carbon input to seawater from greenhouse gas emissions annually. The ecosystem services role provided by seaweed aquaculture often falls unnoticed by coastal managers, partly because the seaweeds are hidden underwater, and partly because the services themselves are not yet accurately valued by markets (Barbier 2013, Costanza et al. 2014). The additional ecosystem benefits of seaweed aquaculture need further study and dissemination via print and social media channels.

FUTURE DIRECTIONS

Seaweed aquaculture technologies have developed dramatically over the last several decades, but there are still challenges to overcome. New strain development by advanced breeding tools is the most urgent challenge. Superior strains will allow the growers to expand growing seasons and enhance production. Considering the global climate challenges, development of thermo-tolerant strains may be needed. Also the strains with disease resistance, fast growth, high concentration of desired molecules, the reduction of fouling organisms also need to be developed. Development of advanced cultivation technologies which are more robust and cost efficient farm systems is very important. This new system will be even more critical for highly exposed, off-shore environments since most seaweed aquaculture have occurred nearshore. With offshore aquaculture, new designs and approaches to macroalgae cultivation will be required, including strain development, harvesting, transport and processing. The offshore aquaculture system may leverage new material and engineering solutions, autonomous and robotic technologies, as well as advanced sensing and monitoring capabilities.

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