Review

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Seaweed resources of Korea

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Abstract: Korea has a long history of utilizing seaweeds, as the country has a high biodiversity of seaweeds. The abundance and composition of seaweed species have changed over the past decades due to climate change and anthropogenic influences. Some species showed a significant extension of their distribution range to the north while some species declined. Some areas have even become barren ground. Korea has put extensive effort into restoring the seaweed resources in these deforested areas. Korea is one of the most advanced countries in the World in terms of seaweed aquaculture. However, the aquacultured species are mostly limited to three genera, *Saccharina*, *Undaria* and *Pyropia/Porphyra*, which represent 96% of the entire seaweed production in the country. Korea has developed highly advanced cultivation technologies as well as various cultivars using breeding and hybridization technologies for these species. There has also been considerable effort in developing environmentally sustainable aquaculture systems using seaweed cultivation (e. g. integrated multi-trophic aquaculture, nutrient bioextraction and biofloc). This study discusses the current status and challenges of the above mentioned topics in detail. In addition, the present study encourages South and North Korean scientists to collaborate in the study of seaweed resources at the border of these two countries.

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1 Introduction

Seaweed has been and continues to be a very important resource for Korean people. For example, when a woman gives birth, it is very common for the new mother to eat seaweed (*Undaria*) soup (called miyeok-guk in Korean) for every meal during the 3–4 week postpartum resting period. It is also traditional to eat miyeok-guk as a birthday meal. Korea has a long history of seaweed utilization. Old literature, such as the *Memorabilia of the Three Kingdoms* stated that seaweed (*Pyropia* spp., Gim in Korean) was used for part of their dowries during the Shilla Dynasty (57 BC–935 AD; Iryeon 1281). Korean people consumed chopped and dried *Pyropia* even before 1425 (Bae 1991; Sohn 1998). The oldest seaweed aquaculture first occurred nearly 400 years ago (Bae 1991; Chung 1937; Sohn 1996).

Korean aquaculture production is dominated by seaweeds, with 1.71 million metric tons (MT), followed by shellfish, 430,000 MT, and finfish, 86,000 MT (FAO 2020). Although Korea has an abundant and diverse seaweed flora, only three genera, the brown seaweeds, *Saccharina* and *Undaria*, and the red seaweeds *Pyropia/Porphyra*, represent 96% of the entire seaweed production in the country (Table 1). Recently however, *Sargassum* has been cultivated intensively in some regions. Other species such as *Ulva* (*U. prolifera*, *U. compressa*, *U. intestinalis*, *U. linza*, *U. clathrata*), *Capsosiphon fulvescens*, *Codium fragile*, *Ecklonia cava*, *Ecklonia stolonifera* and *Gracilariopsis chorda*, have also been cultivated (Figure 1), but the production is very low.

The present study provides information relating to the seaweed resources, seaweed flora, and seaweed forest restoration efforts in Korea. In addition, this study discusses the history and cultivar development using breeding and hybridization technologies, and the progress in using environmentally sustainable aquaculture systems (open water and land based). Finally, encouragement for

Table 1: Production and value of farmed seaweed species in Korea in 2018.

Species	Production (MT, FW)	Value (US\$1000)
<i>Saccharina japonica</i>	572,595 (33.5%)	90,608 (10.8%)
<i>Pyropia</i> spp.	567,827 (33.2%)	572,864 (68.2%)
<i>Undaria pinnatifida</i>	515,666 (30.1%)	135,923 (16.2%)
<i>Sargassum fusiforme</i>	36,170 (2.1%)	17,833 (2.1%)
Others	18,226 (1.12%)	22,700 (2.74%)
Sum	1,710,484	839,928

Data from Ministry of Oceans and Fisheries, Korea, available at <http://portal.fips.go.kr>.

MT, metric tons; FW, fresh weight.

Figure 1: Farmed seaweed species in Korea. (A) *Pyropia* sp., (B) *Undaria pinnatifida*, (C) *Saccharina japonica*, (D) *Sargassum fusiforme*, (E) *Sargassum fulvellum*, (F) *Ulva* sp., (G) *Codium fragile*, (H) *Capsosiphonia fulvescens* and (I) *Gracilariopsis chorda*.

the unification of South and North Korea using seaweed research is introduced.

2 Marine environment along Korean coasts

The Korean Peninsula is surrounded by three different Seas: the Yellow Sea (or West Sea), South Sea, and East Sea (Figure 2). For different seas, environmental conditions vary. The Yellow Sea has an average depth of 44 m with 4–9 m of tidal range. It also has a large area of mud flats, resulting in high turbidity. The tidal amplitudes of the South Sea range from 1.4 to 3.9 m. Many seaweed aquaculture farms are located in the South Sea. These farms are surrounded by several thousand islands. The East Sea starts from the east coast of Busan and continues northwards with an average depth of 1684 m. The tidal

amplitude of the East Sea ranges between 0.2 and 0.6 m. Seawater temperature in the East Sea ranges from 24 to 29 °C in the summer and 10–14 °C during the winter. Summer water temperatures in the South Sea are about 28–29 °C and 13 °C in winter. In the Yellow Sea, summer temperatures are 24–29 °C and range from 2 to 8 °C in winter from north to south.

Korea is influenced by two main ocean currents: the Kuroshio Warm Current, which branches partially from the Kuroshio Main Current, and the North Korean Cold Current (Figure 2). The Kuroshio Warm Current is divided into two; the Tsushima Warm Current passing through the Korea Strait and the Yellow Sea Warm Current passing around the coast of Jeju Island. The Tsushima Warm Current is further subdivided into the East Korea Warm Current along the east coast of Korea. In the northern part of the East Sea, the North Korean Cold Current flows southwards along the east coast of Korea (Figure 2).

3 Seaweed flora of Korea

Over 908 species of seaweeds have been reported in Korea, including 123 greens, 193 browns, and 592 reds (Kim et al. 2013). Over 520 species are found in Jeju Island including 85 endemic species (Lee 2008). The Korean Peninsula has 34 endemic species, including three greens, two browns, and 29 reds (Nam et al. 2018). Among these endemic species, two green algae (*Codium spinulosum*, *C. tapetum*), one brown alga (*Undaria crenata*) and several red seaweeds (*Pyropia koreana*, *Gelidium coreanum*, *G. eucorneum*, *G. jejuensis*, *G. nimum*, *G. prostratum*) have been used as resources in the seaweed industry in Korea.

Some species showed a significant extension in their distribution to the north due in part to climate change while some species decreased or even became extinct. For example, *Undaria peterseniana* and *Caulerpa okamurae*

Figure 2: Map of seas around Korea indicating main ocean currents during summer and winter.

have expanded their geographical distribution on the coast of Korea. *Undaria peterseniana* was previously only found on the Udo coast of Jeju Island (Hwang et al. 2010a), but recently was found subtidally (20–30 m deep) at Ulleung Island, East Sea, Korea (Yoon 2015). One of the climate change indicators, *C. okamurae*, was originally reported along the coast of Jeju Island and in some coastal areas of the South Sea (Gao et al. 2019). Recently, this species has significantly expanded its geographical distribution to the north (Gao et al. 2019), most likely due to the increased seawater temperature.

A red seaweed, *Meristotheca papulosa* has been found subtidally on the coast of Jeju Island. This species was harvested by women divers (called Haenyeo in Korean) from natural populations (Kim et al. 2016). The harvested amount of *M. papulosa* has continuously declined from 161 tons in 1990 to 11 tons in 2004. No production was recorded after 2007 (Kim et al. 2019). A brown seaweed *Silvetia siliquosa* grew in a wide geographical range in the mid to lower intertidal zones (Han et al. 2016; Hwang et al. 2015). However, the population of this species has declined from the mid-1990s onward (Lee et al. 1997; Song et al. 1996). Now this alga can be found only along the rocky shores of the offshore islands of southern Korea (Gao et al. 2017). Although the causes of population decline for these two species, *M. papulosa* and *S. siliquosa* are not fully understood, overharvesting and environmental changes have been suggested as the main reasons. To overcome this issue, there have been recent efforts by Korean scientists to restore these species (Gao et al. 2017; Kim et al. 2019).

Twelve kelp species have been found along the coasts of Korea, including *Saccharina* (*S. japonica*, *S. sculpera*, and *S. religiosa*), *Ecklonia* (*E. cava*, *E. stolonifera*, and *E. kurome*), *Undaria* (*U. pinnatifida*, *U. crenata*, and *U. peterseniana*), *Agarum clathratum*, *Costaria costata*, and *Eisenia bicyclis*. *Saccharina japonica* and *Undaria pinnatifida* grow on all of the coasts in Korea, while other kelp species grow regionally. The geographical distribution of *U. crenata* is restricted to Jeju Island, but *U. peterseniana* is found from Jeju Island to Ulleung Island, East Sea, Korea (Yoon 2015). *Ecklonia cava* is distributed from Jeju to Samcheok, Gangwon Province, and *E. stolonifera* and *Ecklonia kurome* inhabit the South Sea of Korea. *Saccharina sculpera*, *Saccharina religiosa*, *A. clathratum*, *C. costata*, and *E. bicyclis* have mainly been found in the East Sea, but recently the natural population of *S. sculpera* has disappeared from the area. Some kelp species such as *U. pinnatifida*, *C. costata*, and *S. japonica* are thoroughly cultivated for human consumption and abalone feed. In addition, cultivation techniques for specific perennial kelp species, including *E. cava*, *E. stolonifera* and *E. bicyclis*,

have been fully developed and are used in kelp forest restoration in barren grounds.

4 Restoration of deforested areas

Marine kelp forests have sharply declined in Korea, resulting in a serious reduction of marine fisheries resources and species diversity, and contributing to a decrease in spawning and nursery grounds for various species of finfish and invertebrates (Choi et al. 2019; Gao et al. 2016; Lindstrom 2009). Seaweed deforested areas have become barren grounds covered by crustose coralline algae. These barrens have continuously extended along most Korean coasts (Kim et al. 2007). The Korea Fisheries Resources Agency (FIRA) has recently developed tools to estimate rock surface areas and barren ground areas using a hyper-spectral imaging method. The barren ground was on average of 36.4% of rock surfaces on the Korean coasts, with the highest (51.2%) in the East Sea (Table 2). The causes of this destruction of kelp forests are known to differ from region to region, such as overgrazing by sea urchins in the East Sea, sedimentation in the South Sea, and climate change in Jeju Island.

To restore barren grounds and to enhance coastal productivity, species diversity and fisheries resources, FIRA has constructed seaweed forests artificially using kelp or *Sargassum* spp. *E. cava*, a perennial kelp found from Jeju Island to Samcheok, Gangwon Province, has mainly been utilized to construct the artificial seaweed forests, and it makes up about 56% of the artificial forests, followed by *Sargassum fulvellum* (31%), *E. bicyclis* (7%) and *E. stolonifera* (6%). To date, marine seaweed forests have been created using various techniques such as anchoring bags containing mature seaweeds (called spore bags) to supply spores, transplanting ropes with juvenile plants attached on artificial seaweed reefs, and removing seaweed-feeding grazers (Kim et al. 2013b).

Table 2: Areas of barren grounds and rock surface along Korean coasts surveyed by hyper-spectral image method from 2016 to 2018.

Region (year)	Rock surface (ha)	Barren grounds (ha)	Barren percentage (%)
Jeju (2016)	15,828	5,574	35.2
East Sea (2017)	12,372	6,339	51.2
South Sea (2018)	7,171	961	13.4
Total	35,371	12,874	36.4

Yellow Sea was not included because high seawater turbidity interfered the analysis (Korea Fisheries Resources Agency 2019).

To restore deforested areas, the Korean government has invested over US\$280 million from 2009 to 2019 (Table 3). Thirty-five and 51 percent of barren grounds have been restored in Jeju Island and the East Sea, respectively. The seaweed forests constructed to date are over 7600 ha in Jeju and 8300 ha in the East Sea. Over 11 years, a total of 21,500 ha of seaweed forests have been restored in Korea (Table 3).

5 History of seaweed aquaculture in Korea

Seaweed cultivation began with *Pyropia* sp. in Korea. Cultivation of *Pyropia* appears to have begun between 1623 and 1649 (Bae 1991; Chung 1937; Sohn 1996). The first cultivation of *Pyropia* was conducted around Taein Island, Jeonnam Province. A fisherman found some floating bamboo twigs with *Pyropia* attached and began his own cultivation by planting bamboo twigs along the seashore (Kang and Ko 1977). This bamboo twig cultivation method was used around Taein Island and its vicinity on the south coast until 1986, but it no longer occurs (Sohn 1998). A horizontal net system was devised in 1928 (Kang and Ko 1977), and the use of a spread synthetic net began in the 1960s (Yoo 1964). Seaweed farming in Korea expanded rapidly in the 1970s. This expansion resulted in low-quality seaweed products, genetic degradation, failure to adapt environmentally, and an increase in the incidence of disease. Therefore, breeding studies were critical to maintain the sustainability of the seaweed aquaculture industry.

6 Cultivar development

Korea joined the UPOV (International Union for the Protection of New Varieties of Plants) in 2002. The plant variety

protection system was extended to seaweeds in 2012 (Park et al. 2016). This system, implemented in 74 countries, recognizes intellectual property rights that legally guarantee ownership of new plant varieties. In 2012, the Korean government began to certify seaweed varieties. To date, 19 seaweed varieties have been registered including 13 *Pyropia*, five *Undaria* and one *Saccharina* species (Table 4). The development of these varieties has contributed directly to industrial development and it has significantly increased seaweed production in Korea.

A *Pyropia* breeding study began in the 1980s (Hong et al. 1989; Hwang et al. 2010b; Kim 2001; Park and Hwang 2014, 2015; Shin et al. 1997), and genetic analysis commenced in the early 2000s (Choi et al. 2000, 2013; Hwang et al. 2005; Kim et al. 2000, 2011; Shin 2003). The goal of the *Pyropia* breeding project is to develop fast growing and temperature-tolerant cultivars, which are also rich in highly functional substances (antioxidants, amino acids, vitamins, etc.). Three basic methods, selection, hybridization and mutation were used for *Pyropia* breeding. The objective for all three methods is to establish genetically pure cell lines. A pure line is created by first isolating a single cell from a young gametophytic blade of a selected strain (Hwang et al. 2010b). A pure line can be a new variety if it demonstrates increased performance in production. These pure lines can also be used in hybridization or mutation breeding programs. In order to make a pure line of *Pyropia*, an archeospore with a unique haplotype needs to be extracted, then self-fertilized. Park and Hwang (2014) isolated *P. yezoensis*-AP1, and this specific variety is highly resistant to the pathogen causing red dot disease, *Pythium porphyrae*. Among 13 *Pyropia* cultivars registered for plant variety protection in Korea, 12 (Jeonsu No. 1 is the only exception) have been grown commercially in Korea. In addition, 12 additional applications are being examined for registration (Hwang et al. 2019).

Undaria pinnatifida occurs throughout eastern Asia (Kang 1966) and it is widely cultivated in Korea. *Saccharina japonica* was introduced from Japan in 1968 and is now

Table 3: Areas of seaweed forest restored in different seas around Korea, and the budget to build artificial seaweed reefs from 2009 to 2019 (Korea Fisheries Resources Agency 2019).

Region	Year											Total
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	
Jeju Island (ha)	20	50	312	262	496	1,121	1,088	1,086	1,188	1,098	969	7,689
East Sea (ha)	75	60	282	416	491	725	1,126	1,634	1,050	1,360	1,081	8,300
South Sea (ha)	25	130	106	112	300	529	672	294	640	640	480	3,928
Yellow Sea (ha)	1	10	15	70	101	200	350	50	165	10	599	1,571
Total (ha)	121	250	715	860	1,388	2,575	3,236	3,064	3,043	3,108	3,129	21,489
Budget (US\$1,000)	9,500	15,000	12,974	15,894	18,300	32,760	35,750	34,770	35,193	35,173	35,173	280,487

Table 4: List of registered seaweed cultivars in Korea (2012–2019).

Genera	Species	Registration no.	Selected (S), hybrid (H) or mutation (M)	Name of cultivar	Year
<i>Pyropia</i>	<i>P. yezoensis</i>	APVP-1	S	Pulmunoeul	2014
		APVP-6	S	Haepoong No. 1	2015
		APVP-7	S	Pulmuhaesim	2015
		APVP-8	S	Sugwawon No. 104	2015
		APVP-11	S	Sugwawon No. 105	2017
		APVP-13	M	Jeonsu No. 1	2017
		APVP-15	S	Sugwawon No. 108	2018
		APVP-16	S	Haepoong No. 2	2019
		APVP-17	S	Sugwawon No. 106	2019
		APVP-18	S	Sugwawon No. 109	2019
		APVP-19	S	Sugwawon No.110	2019
	<i>P. seriata</i>	APVP-12	S	Haemodol No. 1	2017
		APVP-14	S	Shinpoong No. 1	2018
<i>Undaria</i>	<i>U. pinnatifida</i>	APVP-2	S	Sugwawon haeorum	2014
		APVP-3	S	Sugwawon bibari	2014
		APVP-4	S	Sugwawon cheonghae	2014
		APVP-9	S	Sugwawon No. 201	2015
		APVP-10	H	Sugwawon No. 202	2016
<i>Saccharina</i>	<i>S. japonica</i>	APVP-5	S	Jeongwan No. 1	2014

Data from Aquatic Plant Variety Center, National Institute of Fisheries Science (2019) available at <http://nifs.go.kr/apvc/index.ap>.

grown extensively for human consumption and abalone feed in Korea (Hwang et al. 2019). The expanding abalone industry in Korea is closely associated with the growth of the seaweed aquaculture industry (Hwang et al. 2009). *Undaria* and *Saccharina* have been used as live feed on abalone farms. However, these species are not farmed during the summer months. Therefore, no live feeds are available for abalones in this period. One goal of breeding studies in these species is to develop high-temperature resistant varieties to supply raw kelp to abalones, especially during the summer months.

Hybrids of *U. peterseniana* (male) and *U. pinnatifida* (female) were made to produce a cultivar growing from April to June when *U. pinnatifida* is not available (Hwang et al. 2012). This new cultivar achieved a maximum blade length much greater than its parental plants. This hybrid can grow even after the growth of *U. pinnatifida* cease in April and therefore, can provide biomass to abalones for a longer period of time.

Driven by an increasing demand for kelp in the abalone industry, *S. japonica* farming areas have increased by 671% from 2001 to 2015, and the cultivation area is now over 9100 ha (Hwang et al. 2019). The rapid growth of the kelp aquaculture industry has been supported by advances in seedling-rearing and ‘autumn sporeling-rearing’ technologies (Sohn 1998). Consecutive selection for three generations (F_3) in *S. japonica* targeted a cultivar with an extended cultivation period (Hwang et al. 2017). A new cultivar ‘Sugwawon No. 301’ that can grow during the

summer months has been developed and there are plans to distribute this to fishermen after registration. Hwang et al. (2018) compared the growth performance of ‘Sugwawon No. 301’ with the cultivars from China, and demonstrated that cultivars displayed different morphological traits, temperature tolerance, and resistance to wave action when they grew in different environments (Hwang et al. 2017, 2018). Therefore, it is necessary to develop unique cultivars for specific habitats.

6.1 Seaweed cultivation as part of an integrated multi-trophic aquaculture (IMTA)

Most aquafarms (finfish, shellfish and seaweed) in Korea are located on the southern coast of the country, where many bays and island archipelagos are able to protect the farms from severe storms. Interestingly, most finfish and shellfish aquaculture is being conducted in Gyeongnam Province, southeast of Korea, while most seaweed cultivation occurs in Jeonnam Province, southwest of the country. There is very little overlap between fish and seaweed aquaculture areas. The size and duration of harmful algal blooms (HABs) in the coastal waters of Gyeongnam Province have increased during the past several decades (Lee et al. 2013). Fish aquaculture has been considered to be one of the main sources of nutrients to fuel the growth of phytoplankton blooms (Lee et al. 2013). On

the other hand, the issues in the seaweed farms in Jeonnam Province are very different from those at fish farms. Seaweeds are cultivated intensively in this region, and nutrients have limited the development of seaweed during its growing season, causing discoloration and low growth (Kim et al. 2017; Park et al. 2018; Shim et al. 2014). This nutrient limitation is most severe in the *Pyropia* farms in Korea with economic losses of over US\$25 million in 2013 (NFRDI 2014; Shim et al. 2014). In Korea, therefore, it is extremely important to develop sustainable aquaculture techniques for long-term aquaculture expansion. Farmers have suggested applying slowly dissolving fertilizers to the *Pyropia* farms. However, this approach requires new rules and regulations and may even negatively impact the environment if not properly managed. To achieve environmental and economic sustainability, integrated multi-trophic aquaculture (IMTA) has been suggested (Kim et al. 2017; Park et al. 2018). IMTA-like practices have been conducted in Korea for decades, in the co-cultivation of kelp (*U. pinnatifida* and *S. japonica*) and abalone (*Haliotis discus hannai*) (Hwang et al. 2017; Park and Kim 2013, see above). This was due to the dramatic increase of the abalone industry, and this polyculture began to meet the needs of the abalone feeds without originally considering the IMTA concept (Son et al. 2014). Therefore, the kelps were cultured near the abalone farms, so the farmers could feed the animals easily. Since this polyculture did not consider the nutrient balance between abalone and seaweed, some issues have arisen. For example, abalone retains about 80% of ingested seaweed; the rest becoming waste in the local environment (Park 2005). The feces and uneaten seaweed from these animal farms may change sediment composition, increasing organic material and biological oxygen demand, and possibly causing eutrophication, hypoxia and/or anoxia (Kim et al. 2011). Therefore, a properly designed production system is required to create a balanced ecosystem in this polyculture area.

The first pilot scale open water IMTA practice (< 0.25 ha) was conducted at an abandoned pier at Susan, Gangwon Province, Korea in 2012, growing seaweeds (*S. japonica* and *S. fulvellum*), pacific oysters (*Crassostrea gigas*) and sea cucumbers (*Stichopus japonicas*) adjacent to a finfish *Sebastes schlegeli* cage (Park et al. 2015, 2016). This first attempt was very successful, since all IMTA organisms grew faster than those in monoculture. This first attempt was to determine if aquacultured organisms of different trophic levels could grow together within an IMTA system. Following this success, a large scale IMTA system (> 2 ha) was installed at Tongyoung, Gyeongnam Province, in the southeast of Korea (Figure 3), the centre of intensive finfish and shellfish aquaculture. This large-scale system was

designed to develop a sustainable IMTA model for Korean waters and to balance the ‘fed’ and the ‘extractive’ aquaculture components. In this IMTA system, red seabream (*Pagrus major*) was cultivated as a fed aquaculture species. Two kelp species, *S. japonica* and *U. pinnatifida* (winter crops) and a red seaweed *G. chorda* (summer species) along with pacific oysters (*C. gigas*) were also cultivated near the finfish cages. Additionally, sea cucumbers (*S. japonicas*) were placed underneath the finfish cages (Kim et al. 2017; Park 2017; Park et al. 2018). As with the study at Susan, all organisms in this IMTA system grew equally well or better than those grown in monoculture farms. The extractive organisms, especially seaweeds and oysters, removed nitrogen very efficiently. Tissue nitrogen content in the kelps (~ 3.5%) and oysters (~ 0.97%) in the IMTA system were much higher than those in monoculture (e. g. 1.3% for *Saccharina* and 0.7% for oysters; Kang et al. 2011; Kim et al. 2017; Reitsma et al. 2017). These results indicate higher nutrient availability for extractive species in the IMTA system than in the monocultures. Although seaweeds removed nitrogen efficiently in this IMTA system, they did not consume nitrogen coming directly from the finfish cages. Stable isotope signatures (nitrogen, carbon and oxygen) of sea cucumbers and oysters were strongly correlated with the signatures of the finfish (feed and feces), but seaweed did not show any correlation (Kim et al. unpublished). This may be due to the seaweed taking up inorganic nutrients which were processed by microbes (Esposito et al. 2019).

Park et al. (2018) concluded that 50 MT of fish (a basic unit of a finfish farm in Korea) discharges about 7.5 tons of nitrogen per year, and approximately 4 ha of seaweed and oyster farms are required to extract 100% nitrogen from this finfish farm. *Gracilariopsis chorda* did not grow due to unusually high water temperatures during the summer months (Park et al. 2018). Therefore, taking climate change into consideration, it is critical to develop high temperature tolerant species/strains of certain seaweed.

6.2 Land-based seaweed aquaculture

Although Korea is one of the more advanced countries in seaweed aquaculture, no commercial scale land-based seaweed aquaculture has been developed. Some research has focused on physiological studies and the selection of potential species for use in land based integrated multi-trophic aquaculture and nutrient bioextraction systems (Chung et al. 2002; Kang et al. 2008, 2013, 2014; Shin et al. 2020). In the early 2000s, Chung and his colleagues at

Figure 3: Open-water Integrated Multi-Trophic Aquaculture System at Tongyoung, Gyungnam Province, Korea (Source: National Institute of Fisheries Science).

Busan National University first introduced the IMTA concept to Korea (Chung et al. 2002). In addition, they conducted the first land-based seaweed cultivation in 2007 as part of a land-based IMTA system (Kang et al. 2011). They used a completely closed system with one 700-L tank for finfish (black rockfish) and three 200-L tanks (0.3 m² water surface) for seaweeds. Three seaweed species, *Ulva pertusa*, *S. japonica* and *G. chorda* were used to test nutrient bioextraction efficiency. All three showed high nitrogen and phosphorus removal capacity and therefore were deemed suitable for the IMTA system. Interestingly, *S. japonica* preferably took up nitrate over ammonium while the preference of *U. pertusa* and *G. chorda* was ammonium. This result suggests that co-culture of two seaweed species (with different nitrogen preference) may enhance the nutrient bioextraction capacity in an IMTA system (Corey et al. 2013).

Kang et al. (2013) used a seaweed-based integrated aquaculture suitability index (SASI) to identify suitable seaweed species for IMTA. This index was determined based on economic value, cultivation technology development, and growth and nutrient uptake capacity. These values were obtained from the literature, reference data, and physiological seaweed experiments to identify and prioritize the desired species. Three seaweed species including *U. pinnatifida*, *Pyropia yezoensis* and *Ulva compressa* scored the highest based on SASI for Korean IMTA systems.

Recently, Kim and his colleagues at Incheon National University and the National Institute of Fisheries Science cultivated a red seaweed, *Agarophyton vermiculophyllum* (formerly known as *Gracilaria vermiculophylla*) in biofloc effluent from flounder (*Paralichthys olivaceus*) (Figure 4; Shin et al. 2020). This was one of a few studies of the growth of macroalgae in a biofloc effluent (Brito et al. 2014, 2016). Biofloc effluent usually contains extremely high concentrations of nitrate (e. g. 3000 $\mu\text{mol L}^{-1}$) with a very high nitrogen:phosphorus ratio ($\sim 90:1$). This high concentration of nitrate can negatively affect the growth and survival of some fish larvae and juveniles, increase the number of pathogens,

and affect the immune responses of some animals (Frakes and Hoff 1982; Tucker 1998). Seaweed cultivation can be used as a solution, since nitrate concentration must be reduced in the biofloc system. However, biofloc medium has some challenges when growing seaweed, including its high turbidity and a high concentration of microbes in the medium. Shin et al. (2020) found that *A. vermiculophyllum* grew very well and efficiently removed nutrients from the biofloc medium. Cultivating seaweed with shrimp together in a biofloc system also enhanced the growth of the shrimp and reduced cyanobacterial density (Brito et al. 2014). These results suggest that some seaweed can grow in the biofloc system and reduce nitrate efficiently.

7 Using seaweed as a bridge for conflict resolution and sustainable peace between South and North Korea

When managed well, natural resources can play an important and positive role in improving economic

Figure 4: *Agarophyton vermiculophyllum* growing in high turbidity biofloc effluent from flounder (*Paralichthys olivaceus*) cultivation.

recovery and growth, and even help to build sustainable and durable peace. There are numerous cases where hostility between countries has been reduced by environmental interventions. The Cordillera Condor between Peru and Ecuador is one of the best examples of achieving peace through setting up a cross-area conservation area as a buffer zone.

Similar efforts through *Gelidium* research are being made in Korea. The annual demand for agar has increased from 250 to 700 tons, but the global harvest of *Gelidium* (a major source of agar) has decreased significantly (Callaway 2015), resulting in a substantial shortage of agar in life sciences laboratories, schools, and hospitals around the world. The wholesale price of agar rose nearly threefold, with a record high of around \$35–45 per kilogram. Amidst these concerns, North Korea was named as a potential alternative to supply *Gelidium* (Callaway 2015). Han and his colleagues at Ghent University Global Campus and 15 different institutions in Korea have proposed a ‘Korean Seaweed Peace Belt and Red Gold (*Gelidium*)’ project on the west coast between South and North Korea. Researchers from 14 different countries (Belgium, Canada, Chile, China, Germany, India, Japan, Netherlands, North Korea, Russia, South Korea, Spain, United Kingdom, and the United States) met in Incheon, Korea to support this project on March 27, 2019, in the presence of Her Majesty the Queen of Belgium, Matilde, and former UN Secretary-in-General, Ban Ki-Moon. This project expects to confirm the agreement made at the April 2018 Inter-Korean Summit, which states that the “Special Peace and Cooperation Zone in the Yellow Sea” shall be established as defined in the Joint Declaration on October 4, 2018 and the construction of a special economic zone shall be actively promoted. The launch of the South–North joint marine resources R&D project in the Yellow Sea Peace zone, including the establishment of the South–North joint fishing Zone, may serve as the basis for creating stable peace between the two Koreas and securing marine resources, thus contributing to future economic symbiosis.

‘The Korean Seaweed Peace Belt and Red Gold’ project plans to pursue (1) making an invoice of North Korean seaweed resources for biodiversity survey and standing stocks, and assessments, leading to the identification of species for potential exploitation; (2) determining *Gelidium* bed ecology and environmental physiology (e. g., phenology, seasonal growth patterns, sustainable harvesting strategies); (3) developing *Gelidium* aquaculture both in-sea (site selection, environmental conditions, engineering design) and on-shore (optimization; engineering design; sustainability, CO₂ sequestration); and (4)

industrializing agar extraction protocols: identifying other functional biomolecules (biorefinery), utilizing remaining residues (biochar, fertilizer, absorbents) or establishing AI/IoT-based zero-waste technology platforms, identifying and exploiting functional biomolecules from other seaweed species, and maximizing biomolecule production via genetic modification.

This joint project aims to achieve a seaweed bio-economy in pursuit of sustainable conservation, utilization and valorization of marine algal resources on the Korean Peninsula. Moreover, this project plans to biorefine the *Gelidium* to produce agar and other high-value materials including polyphenols, fluorescent proteins for medical imaging, dementia therapeutic substances and biochar. Additionally, this project may help to establish peace negotiations that will hopefully lead to an end of the war in the Korean peninsula, and resolve the conflict between the two Koreas. The most critical challenge is that this unification movement by phycologists is dependent on the relationship between both Korean governments. The atmosphere for this collaboration was much better when the Inter-Korean Summits occurred in 2018. The current political situation between South Korea and North Korea, however, is not as stable as it was in 2018. To overcome this difficult obstacle, strong support from international organizations such as the United Nations, Green Climate Fund, etc. may help to achieve the goals of this Inter-Korean project.

8 Conclusion

Korea has high biodiversity of seaweeds, but the number of species and their quantity has decreased due to climate change, coastal development, and intensive aquaculture practices. There have been numerous efforts to restore the seaweed forests in barren grounds and, typically, Korean people have used seaweed resources efficiently. Over the past few decades, Korea has dominated the seaweed aquaculture industry. In fact, in 2017, it was the world’s top exporter of *Pyropia*. This was due, at least in part, to the development of improved seaweed cultivation technologies. In response to the global climate change and industrial needs, new cultivars have also been developed in Korea. Since only three genera, *Saccharina*, *Undaria* and *Pyropia/Porphyra* represent over 96% of the entire seaweed production in Korea, diversifying the cultivation species is also critical. Therefore, further development of cultivation technologies for other species including *Sargassum*, *Ulva*, *Capsosiphon*, *Codium*, *Ecklonia*, *Gracilariopsis* etc. is essential for the Korean aquaculture industry to be fully sustainable.

Seaweed aquaculture has also become integrated into animal aquaculture. This technology is now called IMTA and is based upon nutrient bioextraction, which provides important ecosystem services. Although a great deal of potential was shown in some studies (Kim et al. 2015; Park et al. 2018; Wang et al. 2018), seaweed usage in these industries is either minimal or remains at the R&D stage. Therefore, it is important to diversify the application of seaweed resources in Korea.

Finally, the border between both Koreas in the Yellow Sea and its coastline may be a biological hotspot and could provide valuable seaweed resources. Therefore, it is important for South and North Korean scientists to work together to study the seaweed resources at this border. This ‘Korean Seaweed Peace Belt and Red Gold (*Gelidium*)’ project can be an important unification movement between South and North Korea’s phycologists for creating stable peace, securing marine resources, and contributing to future economic symbiosis.

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