

Review

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Seaweed cultivation and utilization of Korea

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Tribute to This paper is dedicated to the memory of Professor Chul Hyun Sohn (1943~2019)

Mariculture is regarded as the only option to supply the increasing demands for seaweeds as human food, feeds, fodder, and phycocolloids in a sustainable manner. Technologies for culturing a range of seaweed species have been developed successively in Korea since the 1970s. In 2017, Korean marine farms produced 1,761,526 t of seaweed. The key focus of the industry is on the production of *Pyropia* (523,648 t), *Undaria* (622,613 t), and *Saccharina* (542,285 t). *Pyropia* is economically the most important species in Korea, accounting for up to 68% of total production value. As the top exporter of *Pyropia* in the world, Korea exported up to US \$525 million of *Pyropia* products to 110 countries in 2018. Other economically important genera include *Sargassum*, *Ulva*, *Capsosiphon*, *Codium*, and *Gracilariopsis*, all of which are used for food, and *Gelidium*, *Pachymeniopsis*, and *Ecklonia* which are used as raw material for phycocolloid extraction. Significant work has gone into developing more productive strains of key seaweed species, and in 2012 the Korean government began to certify seaweed varieties. To date, 19 seaweed cultivars have been registered including 13 *Pyropia*, 5 *Undaria*, and 1 *Saccharina*. The industry is now seeking not only to increase productivity but also to add value through processing. Convenience foods and snacks have been developed that target health-conscious consumers and utilize the nutritional properties of seaweeds. The industry is also seeking to promote the sustainability of seaweed farming. One seaweed company in Korea obtained the world's first ASC-MSC (Aquaculture Stewardship Council-Marine Stewardship Council) certification in 2019 and more are expected to follow their lead. With continued research support, the Korean seaweed industry plans to continue to expand to meet new market demands at a sustainable pace.

Key Words: breeding; cultivation; seaweeds; utilization

INTRODUCTION

Human societies face the enormous challenge of having to provide food and livelihoods to a population well over 9 billion people by the middle of the twenty-first century while addressing the disproportionate impacts of climate change and environmental degradation of the resource base (Food and Agriculture Organization of the United Nations 2018). Mariculture will play a vital role in

sustainably meeting these increasing demands. Seaweed production will play a critical role in this development, providing not only food sources for humans but also animal fodder and chemical extracts. Furthermore, seaweed production is a carbon extractive activity, increasing its value as a sustainable development activity. Currently, world seaweed production is over 30 million tonnes fresh



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weight (Food and Agriculture Organization of the United Nations 2017), and production continues to increase.

In 2017, Korea was the world's third-largest seaweed producer behind China and Indonesia, with an annual harvest of 1,761,526 t (Food and Agriculture Organization of the United Nations 2017). Korean seaweed production (1,761,526 t) in 2017 consisted of 523,648 t of *Pyropia*, 622,613 t of *Undaria* and 542,285 t of *Saccharina* primarily harvest as food. *Pyropia* ('Gim' in Korean) is economically the most important species accounting for 71% of the total production value (Table 1) (Ministry of Oceans and Fisheries 2018). As the top exporter of *Pyropia* in the world, Korea exported US \$525 million of *Pyropia* products to 110 countries in 2018 (Table 2) (Korea Customs Service 2019).

Consumption of seaweed in Korea is changing qualitatively rather than quantitatively. It is diversifying from food-based products to functional health foods, beauty

products, and bio-therapeutics. Although over 30 species of seaweeds have traditionally been used as food by Koreans (Sohn 1998), the main species harvested are *Sargassum*, *Ulva*, *Capsosiphon*, *Codium*, and *Gracilariopsis* (Table 3). In addition to harvesting for food, harvesting of *Gelidium*, *Pachymeniopsis*, and *Ecklonia* occurs to provide the raw material for phycocolloid extraction and *Sargassum* and *Ecklonia* are used in the construction of artificial reef habitats. Research on seaweed cultivation techniques in Korea is focusing on maximizing natural productivity through selective breeding and reducing labor costs through automation.

In this review, we provide an overview of the history of Korean seaweed cultivation and introduce the cultivation technologies, breeding strategies, and processing used by industry. To help guide the future direction of the Korean seaweed cultivation industry, we also identify some of the necessary activities required to support the Korean industry in the future.

Table 1. Production and value of farmed seaweed species in Korea in 2017

Species	Production (M/T, FW)	Value (1,000 US\$)
<i>Undaria pinnatifida</i>	622,613	101,076
<i>Saccharina japonica</i>	542,285	88,320
<i>Pyropia</i> spp.	523,648	617,507
<i>Sargassum fusiforme</i>	54,624	28,724
<i>Capsosiphon fulvescens</i>	6,276	19,340
<i>Ulva</i> spp.	6,159	6,188
<i>Codium fragile</i>	3,980	2,048
<i>Gracilariopsis</i> spp.	1,634	457
<i>Sargassum fulvellum</i>	301	695
Other species	6	4
Total	1,761,526	864,409

Data from Ministry of Oceans and Fisheries, Korea (2018), available from <http://portal.fips.go.kr>. FW, fresh weight.

SEAWEED CULTIVATION

History

The history of cultivating seaweeds in Korea began with *Pyropia*. Records before 1425 indicate that *Pyropia* was being processed by chopping and drying (Bae 1991, Sohn 1998) and cultivation of *Pyropia* started between 1623 and 1649 (Chung 1937, Bae 1991, Sohn 1996). The first cultivation of *Pyropia* was undertaken around Taein Island, southwestern coast of Korea where a fisherman found some floating bamboo twigs with *Pyropia* attached to them and began to cultivate *Pyropia* by planting bamboo twigs along the seashore (Kang and Koh

Table 2. Seaweed export and import of Korea in 2018

Species	Export		Species	Import	
	Production (M/T, FW)	Value (1,000 US\$)		Production (M/T, FW)	Value (1,000 US\$)
<i>Pyropia</i>	22,097	525,527	Cottoni & Spinosum	7,916	12,846
<i>Undaria</i>	15,615	36,945	<i>Undaria</i>	4,417	6,408
<i>Sargassum fusiforme</i>	1,665	20,848	<i>Gelidium</i>	1,157	5,940
<i>Saccharina</i>	923	5,587	<i>Pyropia</i>	40	945
<i>Gelidium</i>	292	3,379	<i>Sargassum fusiforme</i>	105	798
<i>Ulva</i>	91	1,535	<i>Gigartina</i>	134	481
Others	1,351	7,185	<i>Chondrus</i>	218	367
			Others	355	377
Total	42,033	601,006	Total	14,341	28,161

Data from the Korea Customs Service (2019), available at <http://www.customs.go.kr>. FW, fresh weight.

1977). Use of the bamboo twig cultivation method continued until 1986 around Taein Island and its vicinity on the south coast, but this method is no longer used (Sohn 1998). Development of a horizontal net system for *Pyropia* cultivation in 1928 (Kang and Koh 1977) was refined and popularized through the use of synthetic nets in the 1960s (Yoo 1964). This facilitated the rapid expansion of seaweed farming in Korea in the 1970s. The initial rapid growth of the industry resulted in low-quality seaweed products, genetic degradation, poor adaptation to the environment, and increased incidence of disease. These challenges emphasized the needs for research to support the industry, and a particular emphasis was placed on breeding cultivars that performed well on farms and delivered high-quality products. Research on breeding *Pyropia* began in the 1980s (Hong et al. 1989, Shin et al. 1997, Kim 2001, Hwang et al. 2010, Park and Hwang 2014,

2015), and genetic analysis became available as a tool to support development in the early 2000s (Choi et al. 2000, 2013, Jin et al. 2000, Shin 2003, Hwang et al. 2005, Kim et al. 2011).

To maximize production, research on seaweed farming has not been limited to local species. Transplantation of Japanese varieties of *S. japonica* into Korea occurred in the 1960s (Chang and Geon 1970), and selective breeding to extend cultivation periods has recently been undertaken (Hwang et al. 2017). Newly introduced species into Korean seaweed cultivation include three green seaweeds, *Codium* (Hwang et al. 2008b), *Capsosiphon* (Sohn 1998, Hwang et al. 2003), and *Ulva* (Yoon et al. 2003, Park and Hwang 2011); five brown seaweeds, *Ecklonia* (Hwang et al. 2013), *Eisenia*, *Costaria*, *Undariopsis* (Hwang et al. 2011), and *Sargassum* (Sohn 1998, Hwang et al. 2007); and one red seaweed, *Gracilariopsis* (Sohn 2009).

Table 3. Seaweeds used as food in Korea

Species name	Korean name	Preparation	Cooking method	Remark
Chlorophyceae				
<i>Monostroma</i> complex	Hotparae	f, d	Various seasoning by soy sauce	<i>M. grevillea</i> , <i>M. nitidum</i>
<i>Ulva</i> complex	Parae	f, d	Sesame oil, sometimes vinegar	<i>U. prolifera</i> , <i>U. compressa</i> , <i>U. intestinalis</i> , <i>E. linza</i> , <i>U. clathrata</i>
<i>Capsosiphon fulvescens</i>	Maesaengi	f	Boiled soup with oyster	-
<i>Codium fragile</i>	Cheonggak	f, d	Seasoning by soy sauce and vinegar, mix to kimchi	-
Phaeophyceae				
<i>Scytosiphon lomentaria</i>	Korimae	f	Various seasoning soup, fried in oil	-
<i>Ecklonia stolonifera</i>	Kompi	f, d	Fresh salad	-
<i>Undaria pinnatifida</i>	Miyok	f, d, s	Fried in oil, boiled soup, soaked with vinegar, soy sauce and sugar in water	-
<i>U. peterseniana</i>	Nolmiyok	f, d, s	Fried in oil, boiled soup, soaked with vinegar, soy sauce and sugar in water	-
<i>Saccharina japonica</i>	Dasima	f, d	Fried in oil, soup	-
<i>Pelvetia siliquosa</i>	Thumbugi	f, d	Steamed salad	-
<i>Sargassum fusiforme</i>	Tot	f, d	Various seasoning	-
<i>S. fulvellum</i>	Mojaban	f, d	Various seasoning	-
<i>S. horneri</i>	Kwaengsaegi-mojaban	f, d	Various seasoning	-
Rhodophyceae				
<i>Pyropia</i> complex	Gim	f, d	Toasted, seasoning, rolled with rice	<i>P. yessoensis</i> , <i>P. seriata</i> , <i>P. dentata</i>
<i>Nemalion vermiculare</i>	Chamguksunamul	f	Salad	-
<i>Gelidium amansii</i>	Umutkasari	d	Extracted agar	-
<i>Pterocladia capillacea</i>	Kaeumu	d	Extracted agar	-
<i>Gloiopeltis furcata</i>	Bultunggasari	f, d	Mixed soup, seasoning	-
<i>G. tenax</i>	Pulgasari	f, d	Mixed soup, seasoning	-
<i>G. complanata</i>	Aekipulgasari	f, d	Mixed soup, seasoning	-
<i>Grateloupia asiatica</i>	Jinaejinuari	f, d	Salad	-
<i>G. subpectinata</i>	Bitsaldobak	f, d	Salad	-
<i>Gracilariopsis chorda</i>	Gaekkosshiraegi	f	Various seasoning	-
<i>Chondria crassicaulis</i>	Gaeseoshil	f, d	Various seasoning	-

Modified from the Table 2 of Sohn (1998).

f, fresh; d, dried; s, salted.

Cultivation technology

The largest concentration of seaweed culture grounds in Korea is located on the southwestern coast, where nearly 90% of total seaweed production occurs (Sohn 1996, 1998). The dominant aquaculture species include *Pyropia* spp., *Undaria pinnatifida*, and *Saccharina japonica* which collectively accounts for 96% of the total production (Table 1).

Pyropia. The main species in cultivation have change from *Pyropia yezoensis*, *P. tenera*, and *P. kuniedae* in the 1970s to *P. yezoensis*, *P. seriata*, and *P. dentata* today (Kang 1972, Sohn 1996, 1998). *Pyropia* cultivation technology improved significantly in the 1960s (Sohn 1998) following the introduction of an artificial seeding method based on the culture of conchocelis in oyster shells. Further development in the early 1980s, saw the fixed-pole system replaced by a floating production system and an increase in the use of frozen seeded nets. The annual production of *Pyropia* has increased even more markedly since the 1980s due to the artificial seeding, introduction of new species, and expansion of the culture grounds.

The *Pyropia* cultivation process begins with settling the free-living conchocelis stage of the algae onto shells in March (Fig. 1A). Oyster shells are used as the substrate as these can be obtained cheaply and easily from oyster farmers. The conchocelis filaments grow densely within these shells (Fig. 1B). The seeded oyster shells are cultured by horizontal or vertical culture method. In the horizontal culture method, oyster shells with conchocelis filaments are laid and cultured on the floor of shallow concrete tanks or wooden boxes which are covered with polyethylene film (Fig. 1C). This horizontal culture method is normally used for outdoor seeding. In the vertical culture method, oyster shells are tied into string in sets of 20 and dangled from rods and suspended in seawater tanks (Fig. 1D). This method can culture 3-4 times more shells than the horizontal method but has the disadvantage of uneven growth from top to bottom. From late September to early October, the conchocelis mature in the oyster shells and release conchospores. At this time, cultivation nets are placed in the culture tanks and become seeded with conchospores. During this period, the seawater temperature begins to drop below 22°C. The temperature during this period is variable depending on where the cultivation grounds are located.

The seeding of *Pyropia* is undertaken using either the outdoor seeding or the indoor seeding method. For outdoor seeding, farmers hang vertical or horizontal bags of slender mosquito net containing crushed oyster

shell, at regular intervals on the cultivation nets. The nets are placed in a large plastic envelope and moved to the sea for seeding (Fig. 1E). Although the outdoor seeding method can be conducted in any culture ground, this method is highly affected by weather and requires high labor inputs and time. The indoor seeding method uses a big wheel (>5 m in diameter) that rotates the cultivation nets through the spore tank. The bottom part of the wheel is immersed in seawater to allow the conchospores to attach on the net (Fig. 1F). This indoor seeding method ensures that only the desired cultivar is seeded onto the nets and allows conchospore density to be adjusted as needed. However, outdoor seeding method still more common in Korea because it does not require a large investment in infrastructure.

During the growing season, *Pyropia* nets supported on poles (Fig. 1G) or on a floating system (Fig. 1H & I). With the floating system, it is necessary to periodically expose *Pyropia* nets to the air to improve growth and reduce epiphytes. Farmers use a tidal cycle to flip over the nets automatically; a unique method of *Pyropia* cultivation in Korea (Oohusa 1993, Sohn 1998).

Undaria and Saccharina. The Korean seaweed industry produced more than 622,613 tons of *U. pinnatifida* in 2017 (Table 1, Fig. 2A), accounting for 35% of Korean seaweed production. The first artificial seeding of *Undaria* occurred in 1967 (Sohn 1998). The seeding method involves winding special seed string around a PVC frame (ca. 45 × 55 cm) (Fig. 2B). The frame is then used as a zoospore collector. These collectors are hung vertically in a concrete tank containing reproductive sporophyte blades. Seawater in the culture tank is changed once a month and does not have additional nutrients added. The tanks are exposed to ambient sunlight that is filtered through windows. The initial seawater temperature is approximately 17°C, but if the temperature exceeds 25°C during the summer, window shades are used to lower the light level to about 10 μmol photons m⁻² s⁻¹ (Sohn and Kain 1989, Sohn 1998). From September to October, when the seawater temperature falls below 23°C, the seed frames are taken to intermediate culture grounds to allow the young sporophytes to adapt to open seawater conditions (Fig. 2C). Once the young fronds have grown to 0.5-1 cm in length, the seed strings are removed from the seed frame and attached to a culture rope in one of several ways. One popular method is to cut the string into ca. 3-4 cm lengths (Fig. 2D) and then insert these short strings through the lay of the culture rope (Fig. 2E) or a thinner intermediate rope at 30 cm intervals. If an intermediate rope is used, it is then attached to or wound



Fig. 1. Artificial seeding and cultivation of *Pyropia* in Korea. (A) Free-living conchocelis culture of *Pyropia*. (B) *Pyropia* conchocelis in oyster shells. (C) Oyster shell bearing conchocelis filaments culture in horizontal culture tank. (D) Oyster shell bearing conchocelis filaments culture in vertical concrete tank. (E) Outdoor seeding of *Pyropia* showing the slender mosquito net bags (arrows, included oyster shell pieces to facilitate the release of the inner conchosporos) with seeding nets on sea surface. (F) Seeding wheel with cultivation nets, immersed seawater tank containing oyster shell bearing conchocelis filaments. (G) Fixing pole system of *Pyropia*. (H & I) Floating system of *Pyropia*. Cultivation nets are submerged under sea surface (H) and exposure to the air (I).



Fig. 2. Artificial seeding and cultivation of *Undaria* and *Saccharina* in Korea. (A) Cultivation ground of *Undaria pinnatifida*. (B) Tank culture of seedling of kelp. (C) Young sporophytes of kelp after nursery culture. (D) Nursery culture of kelp. (E) Cultivation rope inserted seed fibers. (F) Automatic sewing machine for insertion of seed fibers to cultivation rope. (G) Harvesting ship of *Saccharina japonica*.

around the main culture rope. Recently, a sewing machine (Fig. 2F) for this process has been developed that inserts seed string pieces into the rope automatically, therefore reducing labor and increasing efficiency.

The first *S. japonica* (Fig. 2G) farm was established in Ulsan in 1968. Following the introduction of the mature thalli from Hokkaido, Japan in 1969, and commercial cultivation began in the Jumunjin region, Gangwon Province on the central eastern coast in 1971 (Sohn 1998). Following the successful transfer of plants from the east coast and the development of suitable culture technologies, the *S. japonica* culture grounds have expanded to the south coast. The seeding and cultivation method of *S. japonica* is similar to that used for *U. pinnatifida*. The seeding process for *S. japonica* commences in September, once the seed production of *U. pinnatifida* ends. The shared use of resources for seeding the two species allows the use of production facilities to be maximized.

S. japonica seeding begins when the seawater temperature begins to drop below 19°C. The lower temperature allows for natural seawater to be used without the need for facilities to cool the water. After 1 month in the hatchery tanks and one month in nursery culture in the field, the main production period *S. japonica* commences. Production lines are seeded with seed fibers by insertion of fibers through the lines or winding of seed fibers around them. The choice of technique depends on whether the kelp will be used for human food or abalone feed. Edible kelp is grown into large and thick thalli by regularly thinning-out and harvesting to leave ten individuals per bundle. If the kelp is used for abalone feed, the lines are harvested all at once. Kelp seedling producers sell seedlings from November to March, and so abalone farmers can purchase kelp every month depending on the farms feed requirements.

Sargassum. Two *Sargassum* species are cultivated in Korea, *S. fusiforme* and *S. fulvellum*. Nearly 90% of *S. fusiforme* production is exported to Japan, and *S. fulvellum* is mainly used domestically for food or seedlings for marine forest restoration.

S. fusiforme has been cultured since 1984 around Wando, Jeonnam Province in the western region of the Korean south coast (Sohn 1998). However, cultivation of this species now also occurs in other regions in Jeonnam. The young fronds of *S. fusiforme* (5-10 cm in length) are collected from the natural beds, and about 3-4 young fronds are inserted into the seeding rope at a 5-10 cm interval. The seeding rope is then attached to the main cultivation rope using a second-hand fishing net (Fig. 3A). The cultivation period of *S. fusiforme* runs from November to

May. There is no biological and / or cultural significance to starting the cultivation in November. The only reason for doing so is to avoid the busiest period for *Undaria* cultivation. After transplanting the seed plants onto the main culture ropes, *S. fusiforme* flourishes and reaches full growth between May and June (Fig. 3B). Artificial seeding has described by Hwang et al. (1994a, 1994b, 1999) and is based on the reproduction patterns of this species. Recently culture methods have been used to regenerate seedlings from holdfasts by leaving the holdfast on the culture rope after harvesting in June. The holdfasts left on the culture rope are cut with a knife, leaving a layer 5-8 mm thick (Fig. 3C). The following year, young fronds grow densely from the holdfasts and can be thinned out and transplanted on to new culture ropes. Each “holdfast” rope produces enough seedlings to stock 5-6 culture ropes.

S. fulvellum (Fig. 3D) has recently been introduced to the seaweed aquaculture industry in Korea. Artificial seeding and tank culture methods of this species followed the method described by Hwang et al. (2007). After the seeding of embryos of *S. fulvellum*, seedlings are reared in a culture tank for 60 days until they grow 5 mm in length. The young thalli of *S. fulvellum* can be significantly impacted by grazing during the period of nursery culture. However, plants that grow rapidly can out-compete the grazing animals. It is therefore important to understand the optimal growth conditions for this species (Hwang et al. 2007). The growth at each cultivation stage of *S. fulvellum* is controlled by managing the depth of the cultivation rope to maintain the optimal irradiance for growth.

Recently developed cultivation species. In Korea, an *Ulva* complex of mixed *U. prolifera*, *U. compressa*, *U. intestinalis*, *E. linza*, *U. clathrata* (Fig. 3E), *Capsosiphon fulvescens* (Fig. 3F), and *Codium fragile* (Fig. 3G) is also cultivated but production levels are currently very low. In 2017, the cultured production of *Ulva* complex, *C. fulvescens* and *C. fragile* was 6,159, 6,276, and 3,980 tons-fresh wt., respectively (Table 2). The production of *Ulva* spp. was 6,159 tons-fresh wt. (Table 1). Although there is a commercial demand for these species and there have been significant efforts to harvest it on an industrial scale, there are few places in Korea where *U. prolifera* production in the wild is sufficient to allow for commercial exploitation. This has led to the investigation of the opportunity for increasing production through stock enhancement (Yoon et al. 2003). As part of an investigation into increasing the yield of *U. prolifera* harvested from mudflats, Park and Hwang (2011) reported that the spa-



Fig. 3. Cultivation of *Sargassum*, *Ulva*, *Caposiphon*, *Codium*, *Ecklonia*, and *Gracilariopsis* in Korea. (A) Insertion of young fronds of *Sargassum fusiforme*. (B) Harvest of *S. fusiforme*. (C) After harvesting, holdfast of *S. fusiforme* remained on the culture rope without any epiphytes. (D) Cultivation rope of *S. fulvellum*. (E) Cultivation net of *Ulva* spp. (F) Cultivation net of *Caposiphon fulvescens*. (G) Cultivation rope of *Ecklonia stolonifera*. (H) Cultivation rope of *Codium fragile*. (I) Cultivation rope of *E. cava*. (J) Cultivation rope of *Gracilariopsis chorda*.

tial differences in abundance observed in the field were related to the ratio of sand to silt on the Muan mudflats, South Korea. The study has demonstrated that attachment and survival of zoospores of *U. prolifera* is dependent on particle size. By analyzing the quality of sediment in the intertidal flats, it should therefore be possible to estimate the potential for successful stock enhancement of this species with in a given estuary.

With its unique flavor and soft texture, *C. fulvescens* is traditionally used for soup in Korea (Sohn 1998). Large-scale cultivation of this alga has succeeded both in laboratory and field experiments (Hwang et al. 2003). Currently, large-scale farming occurs out around Wando, on the southwestern coast of Korea. Hwang et al. (2008a) reported that the alga has the potential to be further exploited as human food and as an ingredient in formulated food. *C. fragile* is often produced by the settlement of wild zygotes onto culture lines. However, Hwang et al. (2008b) reported that using the regeneration capability of this alga could be a more reliable method for producing seed stock and have published methods for the artificial seed production and nursery culture for this species. The use of these medullary filament seeding methods increased production from less than 1 kg-fresh wt. to ca. 7 kg-fresh wt. per 1 m culture rope. *Ecklonia* spp. are also cultivated in Korea. However, production levels are very low and consequently are not recorded in the national statistics. *E. stolonifera* (Fig. 3H) is used as food, feed, and seedlings for sea forest construction. *E. cava* (Fig. 3I) is also used as seedlings for the restoration of sea forest. The increasing demand for fresh algae from the abalone industry has provided the opportunity to investigate the culture of these species further. These algae are perennial and continue to grow and produce valuable biomass for abalone feed during the summer when other species of brown seaweed are not abundant (Hwang et al. 2013). *Gracilariopsis chorda* is cultured as human food and is mainly eaten in a steamed salad. Asexual propagation (regeneration) and spore seeding methods have been tried for the cultivation of this species (Sohn 2009), and 1,634 tons-fresh wt. were produced in 2017 (Table 1, Fig. 3J).

Processing industry

Traditionally Korean people used seaweeds in their raw or sun-dried forms for food. Since the 1980s many different seaweed food products have been developed, e.g., machine-dried *Pyropia* (Fig. 4A), toasted *Pyropia*, seasoning *Saccharina* jam, salted or cut *Undaria*, sun-

dried *Undaria* (Fig. 4B) and *S. fusiforme* (Fig. 4C), etc. Recently several processed fast foods and various packaged goods (seaweed soup, seaweed powders for rice, seaweed noodles, etc.) also have been manufactured. Almost all harvested *Pyropia* is machine processed to form dried sheets. The number of similar seaweed processing companies rapidly increased during the 2010s, and the production of dried *Pyropia* amounted to ca. 200 million sheets (21 cm × 19 cm, 2.5 g-dry wt.) in 2017. Thus the export of *Pyropia* is now the second most valuable marine product exported from Korea, with a value of approximately US\$ 525 million in 2017.

Salted *Undaria* was one of the most important processed seaweed products in Korea between the 1970s and 1990s and was manufactured mainly on the southwest coast of Korea. A decrease in the export of salted *Undaria* to Japan has led to a change in production from salted to dried *Undaria*. Dried *Undaria* has become a common product in Korea and is included in many processed foods, snacks, and well-being products that utilize the nutritional properties of *Undaria*.

Boiled and sun-dried *S. fusiforme* is also a commercially important product for export to Japan. Sun-dried *S. fusiforme* is used as a raw material for secondary products such as seasoning. Some of the pigments of *S. fusiforme* are lost during the heat treatment for secondary products, and the fronds are dyed to maintain their appearance using pigments extracted from *Ecklonia cava* (Sohn 1998). *S. japonica* is mainly sold as chopped dried products. Auctions (Fig. 4D) of dried *S. japonica* are held in June and July in Wando, southwestern coast of Korea.

U. prolifera (Fig. 4E) is dried in the form of sheets similar to *Pyropia* and has recently been processed into salt and oil (Fig. 4F). Various processed fast foods, snacks, and instant salads also have been manufactured from *Ulva* (Fig. 4G & H). Seanol (sea polyphenol) is extracted from *E. cava* and has been commercialized for use in cosmetics, medical food, and treatment to manage human health and lifestyle (Fig. 4I). The extraction of agar-agar from *Gelidium* has historically been an important industry in Korea and has consistently been a leading export item. However, the agar processing industry has declined significantly (Sohn 1998) because most of the processing plants have moved offshore. At present, there are a few remaining agar processing plants and agar-agar exports account for only ca. US \$3 million in exports annually.

In addition to food uses, the market for health supplements such as tablets, extracts, jelly, and powder using kelp is expanding. Sales of beauty products (soaps, shampoos, body washes, bathing agents, etc.) using vari-



Fig. 4. Seaweed processing and products of Korea. (A) Processing of *Pyropia* to dried sheets (21 cm × 19 cm in size, 2.5 g-wet wt.). (B) Sun-dried *Undaria pinnatifida*. (C) Sun-dried *Sargassum fusiforme*. (D) Sun-dried *Saccharina japonica* waiting for the auction. (E) Sun-dried *Ulva prolifera*. (F) Fried with oil and salt of *Pyropia*. (G) Various products of *Pyropia*. (H) Snacks and instant salads of seaweeds. (I) Seaweed cosmetics.

ous seaweeds are also increasing, and in some districts, local governments have created thalassiotherapy using seaweed. Seaweed uses also include medicines, food additives, livestock feeds, organic fertilizers, biodegradable materials, pulp, eco-friendly building materials, bio-energy sources, and materials for seaforest restoration.

With the increasing use of seaweed products, there have been calls for risk-benefit analyses to evaluate the health risks related to seaweed consumption (Barbier et al. 2019). Analysis including microbial and chemical risk assessment of seaweed products such as bacteria and heavy metals is necessary, and food safety must be secured during both aquaculture production and processing.

BREEDING AND CULTIVARS

In 2002, Korea joined the International Union for the Protection of New Varieties of Plants (UPOV) (Park et al. 2016, Hwang et al. 2019) and started to apply the varieties protection system to seaweed since 2012. To date, 19 seaweed cultivars have been registered, including 13 *Pyropia*, 5 *Undaria*, and 1 *Saccharina* (Table 4). These cultivars have contributed directly to industrial development and increased seaweed production significantly in Korea.

Pyropia spp. are the most important seaweeds in Korea, with 20 species and two subspecies recorded (Lee

and Kang 1986, Hwang and Lee 2001, Kim and Kim 2011, Hwang et al. 2019). The goal of breeding *Pyropia* is to develop fast-growing, temperature-tolerant cultivars which are resistant to diseases and are also rich in highly desirable secondary metabolites (e.g., antioxidants, amino acids, vitamins, etc.). Three methods are used for *Pyropia* breeding; selection (Park and Hwang 2014), hybridization (Kim 2001), and mutation through mutagen induction (Lee and Choi 2018) or radiation treatment (Lee et al. 2019). Park and Hwang (2014) isolated the *P. yezoensis*-AP1 variety, which was resistant to the pathogen, *Pythium porphyrae* that caused red rot disease in cultivation. Among 13 *Pyropia* cultivars registered for plant variety protection in Korea, 12 have been grown commercially. Also, 12 additional applications are being examined for registration (Hwang et al. 2019). Completion of the mitochondrial genome sequencing in *P. yezoensis* and *P. retortata* could provide novel molecular markers for systematic study, and may help differentiate cultivars (Hwang et al. 2014b, 2018b, Kim et al. 2018).

Undaria pinnatifida occurs throughout eastern Asia (Kang 1966) and is widely cultivated in Korea. The expanding abalone industry in Korea is closely associated with the seaweed aquaculture industry (Hwang et al. 2009), and *Undaria* is used as a fresh feed for abalone. However, the natural growth period of this species is not long enough to cover the period for which fresh seaweed

Table 4. List of registration seaweed cultivars in Korea (2012-2019)

Genera	Species	Registration No.	Breeding method	Name of cultivar	Year	
<i>Pyropia</i>	<i>P. yezoensis</i>	APVP-1	S	Pulmunooul	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
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 from <http://nifs.go.kr/apvc/index.ap>. S, selected; M, mutation; H, hybrid.

is required for feeding abalone. One goal of breeding *Undaria* in Korea is therefore to develop high-temperature resistant varieties for supplying raw kelp feed, especially in the summer, so that the abalone growing season can be prolonged. Some success has been achieved by rearing hybrids of *U. peterseniana* (Kjellman) Okamura (male) and *U. pinnatifida* (female) to provide algal biomass for abalone when *U. pinnatifida* is not readily available (Hwang et al. 2011, 2012). This hybrid continued growing even after the growth of *U. pinnatifida* ceased in April (Hwang et al. 2014a). Trials showed that the hybrid not only provided an extended production period, it also provided greater biomass than *U. pinnatifida*. These hybrids are not currently fully utilized due to difficulties in mass-producing artificial seedlings for hybrids, but these issues are expected to be resolved in the near future. Among 5 *Undaria* cultivars that have been registered for plant variety protection, all were developed by selection or hybridization.

Driven by increasing demand for kelp feed from abalone farmers, the area used for farming *S. japonica* increased by 671% between 2001 to 2015, and the cultivation area is now 9,147 ha (Hwang et al. 2019). Technological advancements have supported the rapid development of the kelp farming industry for seedling-rearing and 'autumn sporeling-rearing' (Sohn 1998). Consecutive selection for three generations (F_3) in *S. japonica* targeted a cultivar with an extended cultivation period (Hwang et al. 2017). An application for registration of cultivar 'Sugwawon No. 301' has been made to the Korean government and once the registration process is completed, it will be distributed to seaweed growers. Hwang et al. (2017, 2018a) demonstrated that cultivars displayed different morphological traits, temperature tolerance, and resistance to wave action when they grew in different environments. There is, therefore, the potential to increase productivity on seaweed farms by developing unique cultivars for specific environments. To date one *Saccharina* cultivar has been registered for variety protection in Korea.

FUTURE PROSPECT OF SEAWEED CULTIVATION

Korean seaweed cultivation has continued to grow since 1970s and Korea became the world's top exporter of *Pyropia* in 2017. This growth is the result of the development of seaweed cultivation technology which has focused on reducing labor and by pursuing the efficient use of technology, large-scale farming, development

of automated harvesting and processing technologies, and increasing productivity through improved varieties and culture techniques. Looking to the future, seaweed cultivation will focus on deriving value from improved product quality and through more eco-friendly farming technologies rather than a single focus on increasing the quantity of seaweed produced. The recent and continued development of new high quality and disease-resistant varieties means that Korean seaweed cultivation has a bright future.

In addition to technological advances that lead to increased productivity from marine farms, there is a growing interest in indoor culture systems for seaweed. Development of indoor culture systems will help to secure the competitiveness of the industry and enable year-round production of seaweeds that compete with terrestrial vegetables. Locating such systems close to markets serves to meet consumer demand for fresh products while reducing the carbon emissions associated with transporting fresh materials from distant ports.

A changing climate will impact mariculture and reinforced the need to continue to develop varieties that can adapt to these new conditions. At the same time, consumer demands are changing, and the demand for functional foods and high-value seaweed extracts continues to rise. Research to support varieties that have a higher proportion of functional ingredients will increase the value of the industry without the need to increase production area or biomass. Techniques of seaweed breeding must also evolve to sustain the development of the seaweed farming industry, in response to an ever-changing environment. The Korean government has recognized the importance of seaweed breeding and has created the 'Golden Seed Project' supporting the development of seaweed cultivars to increase seaweed export earnings.

In a world where consumers are becoming increasingly aware of environmental sustainability as a key part of product quality, the industry must also meet the challenges of developing and demonstrating more eco-friendly practices. A seaweed company in Korea obtained the world's first ASC-MSC (Aquaculture Stewardship Council-Marine Stewardship Council) certification in 2019 and more are expected in the future as the Korean seaweed industry develops in line with the demands of eco-friendly and health-conscious consumers.

In summary, seven key challenges are facing that the Korean seaweed industry must meet to secure its growth:

1. Management and maintenance of the seaweed farming environment to maintain continuous productivity by understanding the environmental ca-

capacity for production.

2. Raising awareness of environmental management with seaweed farmers and developing and promoting more environmentally sustainable practices.
3. Development of seaweed varieties that will allow the industry to adapt to the challenge of climate change.
4. Continuous development of value-added functional seaweed varieties that add value to the industry without the need to increase production area.
5. Development of new processed products and fresh convenience products to meet changes in consumer habits and facilitate the expansion of export markets.
6. Development of food safety protocols that meet international standards.
7. Administrative and financial support at the national level to secure the national and international status of the seaweed cultivation industry.

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