1. Introduction to commercial seaweeds

1.1 SCOPE OF THE SEAWEED INDUSTRY

The seaweed industry provides a wide variety of products that have an estimated total annual value of US$ 5.5–6 billion. Food products for human consumption contribute about US$ 5 billion of this. Substances that are extracted from seaweeds – hydrocolloids – account for a large part of the remaining billion dollars, while smaller, miscellaneous uses, such as fertilizers and animal feed additives, make up the rest. The industry uses 7.5–8 million tonnes[1] of wet seaweed annually. This is harvested either from naturally growing (wild) seaweed or from cultivated (farmed) crops. The farming of seaweed has expanded rapidly as demand has outstripped the supply available from natural resources. Commercial harvesting occurs in about 35 countries, spread between the Northern and Southern Hemispheres, in waters ranging from cold, through temperate, to tropical.

1.2 CLASSIFICATION OF SEAWEEDS

Seaweeds can be classified into three broad groups based on pigmentation: brown, red and green. Botanists refer to these broad groups as Phaeophyceae, Rhodophyceae and Chlorophyceae, respectively. Brown seaweeds are usually large, and range from the giant kelp that is often 20 m long, to thick, leather-like seaweeds from 2–4 m long, to smaller species 30–60 cm long. Red seaweeds are usually smaller, generally ranging from a few centimetres to about a metre in length; however, red seaweeds are not always red: they are sometimes purple, even brownish red, but they are still classified by botanists as Rhodophyceae because of other characteristics. Green seaweeds are also small, with a similar size range to the red seaweeds.

Seaweeds are also called macro-algae. This distinguishes them from micro-algae (Cyanophyceae), which are microscopic in size, often unicellular, and are best known by the blue-green algae that sometimes bloom and contaminate rivers and streams.

Naturally growing seaweeds are often referred to as wild seaweeds, in contrast to seaweeds that are cultivated or farmed.

1.3 USES OF SEAWEEDS – AN OVERVIEW

The use of seaweed as food has been traced back to the fourth century in Japan and the sixth century in China. Today those two countries and the Republic of Korea are the largest consumers of seaweed as food. However, as nationals from these countries have migrated to other parts of the world, the demand for seaweed for food has followed them, as, for example, in some parts of the United States of America and South America. Increasing demand over the last fifty years outstripped the ability to supply requirements from natural (wild) stocks. Research into the life cycles of these seaweeds has led to the development of cultivation industries that now produce more than 90 percent of the market's demand. In Ireland, Iceland and Nova Scotia (Canada), a different type of seaweed has traditionally been eaten, and this market is being developed. Some government and commercial organizations in France have been promoting seaweeds for restaurant and domestic use, with some success. An informal market exists among coastal dwellers in some developing countries where there has been a tradition of using fresh seaweeds as vegetables and in salads.

---

[1] Note: All units are metric (SI) unless otherwise indicated. 1 tonne = 1 000 kg

China is the largest producer of edible seaweeds, harvesting about 5 million wet tonnes. The greater part of this is for *kombu*, produced from hundreds of hectares of the brown seaweed, *Laminaria japonica*, that is grown on suspended ropes in the ocean. The Republic of Korea grows about 800 000 wet tonnes of three different species, and about 50 percent of this is for *wakame*, produced from a different brown seaweed, *Undaria pinnatifida*, grown in a similar fashion to *Laminaria* in China. Japanese production is around 600 000 wet tonnes and 75 percent of this is for *nori*, the thin dark seaweed wrapped around a rice ball in sushi. Nori is produced from a red seaweed – a species of *Porphyra*. It is a high value product, about US$ 16 000/dry tonne, compared to kombu at US$ 2 800/dry tonne and wakame at US$ 6 900/dry tonne.

Various red and brown seaweeds are used to produce three hydrocolloids: agar, alginate and carrageenan. A hydrocolloid is a non-crystalline substance with very large molecules and which dissolves in water to give a thickened (viscous) solution. Alginate, agar and carrageenan are water-soluble carbohydrates that are used to thicken (increase the viscosity of) aqueous solutions, to form gels (jellies) of varying degrees of firmness, to form water-soluble films, and to stabilize some products, such as ice cream (they inhibit the formation of large ice crystals so that the ice cream can retain a smooth texture).

Seaweeds as a source of these hydrocolloids dates back to 1658, when the gelling properties of agar, extracted with hot water from a red seaweed, were first discovered in Japan. Extracts of Irish Moss, another red seaweed, contain carrageenan and were popular as thickening agents in the nineteenth century. It was not until the 1930s that extracts of brown seaweeds, containing alginate, were produced commercially and sold as thickening and gelling agents. Industrial uses of seaweed extracts expanded rapidly after the Second World War, but were sometimes limited by the availability of raw materials. Once again, research into life cycles has led to the development of cultivation industries that now supply a high proportion of the raw material for some hydrocolloids.

Today, approximately 1 million tonnes of wet seaweed are harvested and extracted to produce the above three hydrocolloids. Total hydrocolloid production is about 55 000 tonnes, with a value of US$ 585 million.

Alginate production (US$ 213 million) is by extraction from brown seaweeds, all of which are harvested from the wild; cultivation of brown seaweeds is too expensive to provide raw material for industrial uses.

Agar production (US$ 132 million) is principally from two types of red seaweed, one of which has been cultivated since the 1960–70s, but on a much larger scale since 1990, and this has allowed the expansion of the agar industry.

Carrageenan production (US$ 240 million) was originally dependent on wild seaweeds, especially Irish Moss, a small seaweed growing in cold waters, with a limited resource base. However, since the early 1970s the industry has expanded rapidly because of the availability of other carrageenan-containing seaweeds that have been successfully cultivated in warm-water countries with low labour costs. Today, most of the seaweed used for carrageenan production comes from cultivation, although there is still some demand for Irish Moss and some other wild species from South America.

Seaweed meal, used an additive to animal feed, has been produced in Norway, where its production was pioneered in the 1960s. It is made from brown seaweeds that are collected, dried and milled. Drying is usually by oil-fired furnaces, so costs are affected by crude oil prices. Approximately 50 000 tonnes of wet seaweed are harvested annually to yield 10 000 tonnes of seaweed meal, which is sold for US$ 5 million.

Fertilizer uses of seaweed date back at least to the nineteenth century. Early usage was by coastal dwellers, who collected storm-cast seaweed, usually large brown seaweeds, and dug it into local soils. The high fibre content of the seaweed acts as a soil conditioner and assists moisture retention, while the mineral content is a useful fertilizer and source of trace elements. In the early twentieth century, a small industry developed based on the drying and milling of mainly storm-cast material, but it dwindled with the advent of

synthetic chemical fertilizers. Today, with the rising popularity of organic farming, there has been some revival of the industry, but not yet on a large scale; the combined costs of drying and transportation have confined usage to sunnier climates where the buyers are not too distant from the coast.

The growth area in seaweed fertilizers is in the production of liquid seaweed extracts. These can be produced in concentrated form for dilution by the user. Several can be applied directly onto plants or they can watered in, around the root areas. There have been several scientific studies that prove these products can be effective. In 1991, it was estimated that about 10 000 tonnes of wet seaweed were used to make 1 000 tonnes of seaweed extracts with a value of US$ 5 million. However, the market has probably doubled in the last decade because of the wider recognition of the usefulness of the products and the increasing popularity of organic farming, where they are especially effective in the growing of vegetables and some fruits.

Cosmetic products, such as creams and lotions, sometimes show on their labels that the contents include "marine extract", "extract of alga", "seaweed extract" or similar. Usually this means that one of the hydrocolloids extracted from seaweed has been added. Alginate or carrageenan could improve the skin moisture retention properties of the product. Pastes of seaweed, made by cold grinding or freeze crushing, are used in thalassotherapy, where they are applied to the person's body and then warmed under infrared radiation. This treatment, in conjunction with seawater hydrotherapy, is said to provide relief for rheumatism and osteoporosis.

Over the last twenty years there have been some large projects that investigated the possible use of seaweeds as an indirect source of fuel. The idea was to grow large quantities of seaweed in the ocean and then ferment this biomass to generate methane gas for use as a fuel. The results showed the need for more research and development, that it is a long-term project and is not economic at present.

There are potential uses for seaweed in wastewater treatment. Some seaweeds are able to absorb heavy metal ions such as zinc and cadmium from polluted water. The effluent water from fish farms usually contains high levels of waste that can cause problems to other aquatic life in adjacent waters. Seaweeds can often use much of this waste material as nutrient, so trials have been undertaken to farm seaweed in areas adjacent to fish farms.

1.4 SOURCES OF SEAWEED

1.4.1 Brown seaweeds

The main uses of brown seaweeds are as foods and as the raw material for the extraction of the hydrocolloid, alginate. The more useful brown seaweeds grow in cold waters in both the Northern and Southern Hemispheres. They thrive best in waters up to about 20°C. Brown seaweeds are found in warmer waters, but these are less suitable for alginate production and rarely used as food.

Brown seaweeds as food

Food from brown seaweeds comes mostly from the genera *Laminaria*, *Undaria* and *Hizikia*. Originally, harvests of wild seaweeds were the only source, but since the mid-twentieth century demand has gradually outstripped the supply from natural resources and methods for cultivation have been developed. Today, seaweed for food comes mainly from farming rather than natural sources.

Species of the genus *Laminaria* are eaten in Japan and China, and to a lesser extent in the Republic of Korea. *Laminaria* was native to Japan and the Republic of Korea, and was introduced accidentally to China, in 1927 at the northern city of Dalian (formerly Dairen), probably by shipping. Prior to that, China had imported its needs from the naturally growing resources in Japan and the Republic of Korea. In the 1950s, China developed a way of cultivating *Laminaria* on long ropes suspended in the ocean, and this became a widespread source of income for large numbers of coastal families. By 1981, they were

producing 1 200 000 wet tonnes annually of seaweed. In the late 1980s, production fell as some farmers switched to the more lucrative but risky farming of shrimp. By the mid-1990s, production had started to rise and the reported harvest in 1999 was 4 500 000 wet tonnes. China is now self-sufficient in *Laminaria* and has a good export market.

Laminaria was in plentiful supply in Japan, mainly from the northern island of Hokkaido, where several naturally growing species were available. However, as Japan increasingly prospered after the Second World War, demand grew, and by the 1970s cultivation became necessary. They now draw their supply from a mixture of natural and cultivated harvests. In the Republic of Korea, the demand for *Laminaria* is much lower and most is now provided from cultivation.

Undaria has been harvested from natural resources for many years in the Republic of Korea, China and Japan. The Republic of Korea has the highest consumption of the three countries. Cultivation commenced in the Republic of Korea and Japan in the 1960s, but not until the mid-1980s in China. By 1999, the Republic of Korea was producing about 5 000 wet tonnes of wild seaweed and about 250 000 wet tonnes by cultivation. Some of this was exported to Japan, where production was only 3 000 wet tonnes of wild harvest and 77 000 wet tonnes by cultivation. *Laminaria* is more popular than *Undaria* in China, and by the mid-1990s China was harvesting about 100 000 wet tonnes of *Undaria* from cultivation, small by comparison with the 3 million wet tonnes of *Laminaria* at that time.

Hizikia is popular in Japan and the Republic of Korea. It has been harvested from natural beds, up to 20 000 wet tonnes in the Republic of Korea in 1984, when cultivation was commenced. Since then cultivation, on the southwest coast of the Republic of Korea, has steadily increased so that by 1994 about 32 000 wet tonnes were farmed and only 6 000 wet tonnes harvested from the wild. A large proportion of the Republic of Korea production is exported to Japan, where there is little activity in cultivation of this species.

Alginate-containing seaweeds

These are called alginophytes – needing only one word instead of three to describe the seaweed.

These are nearly all harvested from natural resources. A wide variety of species are used, harvested in both the Northern and Southern Hemispheres. Countries include Argentina, Australia, Canada, Chile, Ireland, Norway, Mexico, South Africa, United Kingdom (Scotland and Northern Ireland) and United States of America. More details of the species harvested are given in a later section, dealing with the alginate industry. Cultivation of brown seaweeds like *Laminaria* and *Undaria* go through the sexual reproduction cycle, a time consuming and labour intensive process that is expensive, even in low-labour-cost countries. Cultivated raw material is normally too expensive for alginate production. While much of the *Laminaria* that is cultivated in China is used for food, when there is surplus production this can be used in the alginate industry, probably provided at a lower price that is subsidized by the high price obtained on the food market.

For further detail about alginophytes, see Section 4.

1.4.2 Red seaweeds

The main uses of red seaweeds are as food and as sources of two hydrocolloids: agar and carrageenan. Useful red seaweeds are found in cold waters such as Nova Scotia (Canada) and southern Chile; in more temperate waters, such as the coasts of Morocco and Portugal; and in tropical waters, such as Indonesia and the Philippines.

Red seaweeds as food

Porphyra species are the largest source of food from red seaweeds. *Porphyra*, known by the more common names of nori and laver, is dried and processed into thin purplish-black

sheets. One of its common uses is in Japanese sushi, where it is wrapped on the outside of a small handful of soured, boiled rice topped with a piece of raw fish. *Porphyra* has been cultivated in Japan and the Republic of Korea since the seventeenth century; there are natural stocks, but even at that time they were insufficient to meet demand. Cultivation was developed intuitively, by observing the seasonal appearance of spores, but *Porphyra* has a complex life cycle that was not understood until the 1950s. Since then, cultivation has flourished, and today the supply is virtually all from cultivation, which is conducted on a large scale in Japan, China and the Republic of Korea. In 1999, the combined production from these three countries was just over 1 000 000 wet tonnes. It has the highest value of any cultivated seaweed, about US$ 1 200 per wet tonne. For comparison, the brown seaweeds used as food are valued at US$ 610/wet tonne for *Laminaria* and US$ 530/wet tonne for *Undaria*.

Dulse (*Palmaria palmata*, formerly *Rhodymenia palmata*) is another red seaweed used as food, but on a very small scale, mostly collected by coastal people from natural resources and consumed locally. It is dried and sold in whole pieces, usually eaten without cooking, or as a powder that is used as a condiment. It grows in cold waters and is collected in Ireland, Iceland and the east coast of Canada. There is a small industry in the Bay of Fundy (Canada), and a company based in Belfast, Northern Ireland (United Kingdom), is working to expand the market for dulse.

Agar-containing seaweeds (agarophytes)

Two genera, *Gelidium* and *Gracilaria*, account for most of the raw material used for the extraction of agar. Extraction of *Gelidium* species gives the higher quality agar (as measured by the gel strength: the strength of a jelly formed by a 1.5 percent solution).

All *Gelidium* used for commercial agar extraction comes from natural resources, principally from France, Indonesia, the Republic of Korea, Mexico, Morocco, Portugal and Spain. *Gelidium* is a small, slow growing plant and while efforts to cultivate it in tanks/ponds have been biologically successful, it has generally proved to be uneconomic. However, one company, Marine BioProducts International, has launched high-grade agar and agarose products that they claim are derived from their own cultivated *Gelidium*. Presumably the profit from these products at the high end of the market is sufficient to offset the costs of cultivation. Small quantities of *Gracilariopsis* are harvested in Chile and species of *Gelidiella* provide the raw material for a small agar industry in India.

Gracilaria species were once considered unsuitable for agar production because the quality of the agar was poor (gel strength too low). In the 1950s, it was found that pre-treatment of the seaweed with alkali before extraction lowered the yield but gave a good quality agar. This allowed expansion of the agar industry, previously limited by the supply of *Gelidium* available, and led to the harvesting of a variety of wild species of *Gracilaria* in countries such as Argentina, Chile, Indonesia and Namibia. Chilean *Gracilaria* was especially useful, but soon there was evidence of overharvesting of the wild crop. Cultivation methods were then developed, both in ponds and in the open waters of protected bays. These methods have spread beyond Chile to other countries, such as China, the Republic of Korea, Indonesia, Namibia, the Philippines and Viet Nam, usually using species of *Gracilaria* native to each particular country. Obviously, *Gracilaria* species can be grown in both cold and warm waters. Today the supply of *Gracilaria* still comes mainly from the wild, with the degree of cultivation depending on price fluctuations.

For further detail about agarophytes see Section 2.

Carrageenan-containing seaweeds (carrageenophytes).

The original source of carrageenan was the red seaweed *Chondrus crispus* (common name: Irish Moss), collected from natural resources in France, Ireland, Portugal, Spain and the east coast provinces of Canada. As the carrageenan industry expanded, the demand for raw material began to strain the supply from natural resources, although by this time

(early 1970s) *Chondrus* was being supplemented by species of Iridaea from Chile and *Gigartina* from Spain.

The introduction of cultivation of species of *Eucheuma* in the Philippines during the 1970s provided the carrageenan industry with a much enhanced supply of raw material. A further advantage of this cultivated material was that one species contained almost exclusively a particular type of carrageenan (kappa-carrageenan) while a second species contained predominantly a second type (iota-carrageenan), each type having its own particular applications. *Chondrus* contains a mixture of two types (kappa and lambda) that could not be separated during commercial extraction. Today most of the raw material comes from the two species originally cultivated in the Philippines, but their cultivation has now spread to some other warm-water countries, such as Indonesia and Tanzania. Limited quantities of wild *Chondrus* are still used; attempts to cultivate *Chondrus* in tanks have been successful biologically, but uneconomic as a raw material for carrageenan. Wild species of *Gigartina* and *Iridaea* from Chile are also being harvested and efforts are being made to find cultivation methods for these.

The two species originally cultivated in the Philippines were named *Eucheuma cottonii* and *Eucheuma spinosum*, and the industry shortened these so they are often referred to as "cottonii" and "spinosum". However, botanists have since renamed both species, so that *Eucheuma cottonii* is now *Kappaphycus alvarezii*, while *Eucheuma spinosum* is now *Eucheuma denticulatum*. Unfortunately all these names are still in use, so an awareness of them is necessary when reading about carrageenophytes.

For further detail about carrageenophytes see Section 6.

1.5 CULTIVATION METHODS – GENERAL OUTLINE

Some seaweeds can be cultivated vegetatively, others only by going through a separate reproductive cycle, involving alternation of generations.

In vegetative cultivation, small pieces of seaweed are taken and placed in an environment that will sustain their growth. When they have grown to a suitable size they are harvested, either by removing the entire plant or by removing most of it but leaving a small piece that will grow again. When the whole plant is removed, small pieces are cut from it and used as seedstock for further cultivation. The suitable environment varies among species, but must meet requirements for salinity of the water, nutrients, water movement, water temperature and light. The seaweed can be held in this environment in several ways: pieces of seaweed may be tied to long ropes suspended in the water between wooden stakes, or tied to ropes on a floating wooden framework (a raft); sometimes netting is used instead of ropes; in some cases the seaweed is simply placed on the bottom of a pond and not fixed in any way; in more open waters, one kind of seaweed is either forced into the soft sediment on the sea bottom with a fork-like tool, or held in place on a sandy bottom by attaching it to sand-filled plastic tubes.

Cultivation involving a reproductive cycle, with alternation of generations, is necessary for many seaweeds; for these, new plants cannot be grown by taking cuttings from mature ones. This is typical for many of the brown seaweeds, and *Laminaria* species are a good example; their life cycle involves alternation between a large sporophyte and a microscopic gametophyte – two generations with quite different forms. The sporophyte is what is harvested as seaweed, and to grow a new sporophyte it is necessary to go through a sexual phase involving the gametophytes. The mature sporophyte releases spores that germinate and grow into microscopic gametophytes. The gametophytes become fertile, release sperm and eggs that join to form embryonic sporophytes. These slowly develop into the large sporophytes that we harvest. The principal difficulties in this kind of cultivation lie in the management of the transitions from spore to gametophyte to embryonic sporophyte; these transitions are usually carried out in land-based facilities with careful control of water temperature, nutrients and light. The high costs involved in this can be absorbed if the

seaweed is sold as food, but the cost is normally too high for production of raw material for alginate production.

Where cultivation is used to produce seaweeds for the hydrocolloid industry (agar and carrageenan), the vegetative method is mostly used, while the principal seaweeds used as food must be taken through the alternation of generations for their cultivation.

Further details

For an overall understanding of the basic requirements for the cultivation of any type of seaweed, read Santelices (1999). More detail about cultivation methods can be found in Ohno and Critchley (1993), Kain (1991) and Schramm (1991a). Methods used for cultivating particular types of seaweed can be found in Sections 2.5, 4.5 and 6.5.