A guide to the seaweed industry

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Cover photograph: *Durvillaea potatorum* on wave-swept rocks, Australia. Bruce Fuhrer.

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by
Dennis J. McHugh
School of Chemistry, University College
University of New South Wales
and
Australian Defence Force Academy
Canberra
Australia

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PREPARATION OF THIS DOCUMENT

This Technical Paper is written for those who know little about the seaweed industry, but wish to know more. It has been written with a minimum of technical language and is designed to help those who are asked to make decisions concerning the seaweed industry when they have little background information to assist them. Such decisions may be about regulation of the various sectors of the industry, about assistance to it, or financial investment in it. This may involve people in bodies such as government agencies, development banks, national and international aid and development organizations, NGOs and financial institutions.

It may also be of value to marine scientists, or students of marine science, who wish to extend their knowledge of the macro-algae and their application in the food, hydrocolloid and other industries.

Then there are those people, many of whom the author has encountered over the last twenty years, who observe the vast quantities of seaweeds on coasts and in seas around the world and ask "What can be done with it and how could they profit by utilizing this natural resource?" This paper is a useful starting point for such entrepreneurs.

The first section – Introduction to commercial seaweeds – is recommended to all readers, especially those who need a brief overview of the industry. Readers with more specific interests can then move to the other sections, which deal with particular sectors of the seaweed industry. Here, sufficient detail is provided for the average reader, but for those requiring more information on particular topics, lists of useful references are given in the text.

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ABSTRACT

Seaweed is a very versatile product widely used for food in direct human consumption. It is also an ingredient for the global food and cosmetics industries and is used as fertilizer and as an animal feed additive. Total annual value of production is estimated at almost US$ 6 billion of which food products for human consumption represent US$ 5 billion. Total annual use by the global seaweed industry is about 8 million tonnes of wet seaweed.

Seaweed can be collected from the wild but is now increasingly cultivated. It falls into three broad groups based on pigmentation; brown, red and green seaweed.

Use of seaweed as food has strong roots in Asian countries such as China, Japan and the Republic of Korea, but demand for seaweed as food has now also spread to North America, South America and Europe. China is by far the largest seaweed producer followed by the Republic of Korea and Japan but seaweeds are today produced in all continents.

Red and brown seaweeds are also used to produce hydrocolloids; alginate, agar and carrageenan, which are used as thickening and gelling agents. Today, approximately 1 million tonnes of wet seaweed are harvested and extracted to produce about 55 000 tonnes of hydrocolloids, valued at almost US$ 600 million.

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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.

2. Seaweeds used as a source of agar

2.1 GENERA AND SPECIES USED

Most agar is extracted from species of *Gelidium* (Figure 1) and *Gracilaria* (Figure 2). Closely related to *Gelidium* are species of *Pterocladia*, and small quantities of these are collected, mainly in the Azores (Portugal) and New Zealand. *Gelidiella* acerosa is the main source of agar in India. *Ahnfeltia* species have been used in both Russia and Japan, one source being the island of Sakhalin (Russia).

2.2 NATURAL HABITATS

First, a discussion is necessary of the terms used to describe where seaweeds grow. The vertical dimension of the shore is divided into zones. Common terms used to describe these are the intertidal zone and the subtidal zone. People are familiar with tides and readily understand these terms. The intertidal zone is the part of the shore that lies between the high and low tide levels, the subtidal zone is everything below the low tide level. Sometimes

FIGURE 1
Gelidium, **rehydrated from dried material purchased by an agar producer.**
The coin diameter is 20 mm.

FIGURE 2
Gracilaria**, rehydrated from dried material purchased by an agar producer.**
The coin diameter is 20 mm.

the intertidal zone is called the littoral zone. However, it has been found that, from a biologist's point of view, it is better to use terms that define the zones by what usually grows in them. So a line is drawn, and above this line is a zone where organisms receive irregular wetting and this is called the eulittoral zone. Below this line, organisms are immersed in water except on rare occasions (e.g. extremely low tides); this is called the sublittoral zone. These zones do not necessarily depend on tide levels; the upper limit of the eulittoral zone is set by the upper limit of barnacles, where they occur, and the lower limit is the highest point where the large brown algae can be found growing. Above the edge of the eulittoral zone, beyond the barnacles, is a zone that is only reached by spray water and this is called the littoral fringe.

Gelidium grows best where there is rapid water movement, which is in the eulittoral and sublittoral zones. Depending on the species, it can be found in water from 2 to 20 m in depth. *Gelidium* prefers rocky areas with steep slopes, and is rarely found on muddy or sandy bottoms (compare *Gracilaria* below). It prefers partial shade and may be bleached by full intensity light in tropical latitudes. It usually grows best at 15–20°C, but can tolerate higher temperatures. It can survive in low nutrient conditions and some species adapt to low or high salinity.

For further detail see Santelices (1991).

Large beds of *Gracilaria* usually grow in the eulittoral zone, or just below it in the beginning of the sublittoral, on sandy or muddy sediments that are protected from waves. Sometimes it can be found free-floating in tidal lakes of salt or brackish water. It can adapt to large variations in growing conditions, such as freshwater dilution, increase in fertilizer concentration from runoff, and raised temperatures. Seawater temperatures of 20°C or higher are needed for at least three months of the year. It grows in a wide range of latitudes. It can survive being covered in sediment – growing again when water motion uncovers it.

2.3 SOURCES OF AGAROPHYTES

The harvests of *Gelidium* are spread over a wide geographical area. Large quantities are harvested on the north coast of Spain, the middle to southern end of the coast of Portugal, and the west coast of Morocco. Smaller amounts are found on the Bay of Biscay coast in the southwest of France. Prior to the Second World War, the *Gelidium* of Japan was the main source of the world's agar, but industrialization has led to depletion of the natural stocks, and today Japan harvests similar quantities to countries like Spain and Morocco. The Republic of Korea harvests commercial quantities for its local industry, in an area around the southern port of Pusan. In Mexico, *Gelidium* is harvested on the Pacific coast of Baja California. Warm-water species are collected from natural beds on the south coast of Java, Sumatra and many of the islands of Indonesia that lie between Java and Timor. Less significant contributors to the total harvest of *Gelidium* are Chile, China, France and South Africa.

For further details see McHugh (1991), and for an update on individual countries see Critchley and Ohno (1998).

Gracilaria is also distributed widely, with some species adapted to tropical countries like Indonesia, others to colder waters such as southern Chile and the Atlantic coast of Canada. Chileans pioneered the commercial cultivation of *Gracilaria*, using *Gracilaria chilensis*, native to its southern coast and containing a high quality agar. There are also large beds of wild Gracilaria in Chile, and it was the fear of depletion of these beds by overharvesting that led to the development of cultivation. Wild *Gracilaria* is also harvested in Argentina and Brazil, although the quantity is decreasing in Brazil because the quality does not compare well with the Chilean product.

China produces significant quantities of *Gracilaria*, mainly in the southern provinces of Guangxi and Hainan, where it is cultivated in ponds and estuaries; it is also cultivated in Taiwan Province of China. In Indonesia, wild seaweed is collected and some is cultivated in ponds. A more concerted effort appears to have been made in Viet Nam in recent years, with a variety of species being grown in lagoons and ponds in both the north and south. Beach-wash *Gracilaria* has been collected near Luderitz (Namibia) for a number of years, and, more recently, successful cultivation has been achieved in Luderitz Bay. Since the Second World War, wild seaweed has been collected from Saldanha Bay on the west coast of South Africa, but the yearly harvest has shown wide fluctuations. In southern Thailand, a source of income for women is the collection of free floating *Gracilaria* from tidal lakes and lagoons (Figure 3).

2.4 HARVESTING METHODS FOR WILD AGAROPHYTES

For *Gelidium*, the harvesting methods used in Spain and Portugal are typical of the industry. A high percentage of the harvest comes from the gathering of storm-cast seaweed. This is often done by two people dragging a net to capture the seaweed; for cast material that has settled to the bottom in shallow bays, boats may be used to drag the nets. Sometimes significant quantities of cast seaweed collect in depressions in the sea floor and this is collected using a suction tube, put in place by a diver, to draw the material up and into a boat.

The harvesting of material that is still attached to the rock is often done by divers, who pluck off the seaweed and stow it in net bags or baskets, which are hauled into the service boat when full. However, plucking can lead to complete removal of the plant, and then regeneration of the beds is slower. The seaweed is held onto the rock by a holdfast, a structure that often consists of many finger-like pieces that are called rhizoids. It is important for some rhizoids to be left on the rock so the *Gelidium* can regrow. Machines, held by divers, for cutting or mowing the seaweed bed have been devised, usually with an attachment that sucks the cut weed up and into a boat. While the machines are expensive, they have the advantage of not damaging the holdfast and rhizoids, allowing faster recovery of the beds, which also show an increased mass of seaweed when they regrow. In several countries, such as Chile and Indonesia, most of the harvest is from attached weed that is picked by hand either at low tide or by snorkelling in shallow waters.

For *Gracilaria* that is growing on the bottom, as the plant enlarges it provides more resistance to water movement and may eventually break off, leaving some of the plant in the sediment or sand to grow again. The broken pieces drift and may be collected by nets or are picked up after they wash onto the shore. Raking the beds from a boat is also practised, but care is needed or the sea bottom may be damaged, leaving little residual plant to grow again. A harvesting strategy is needed to preserve *Gracilaria* beds, and this should take into consideration the

FIGURE 3
Negotiating a price for dried *Gracilaria*. Women derive an income from *Gracilaria* collection in southern Thailand.

best time or season to harvest, the harvesting frequency, the method used (such as dragging or plucking), the harvesting tools and the need to leave some material unharvested so that regrowth can occur. The farmgate price (price paid to the collectors) of *Gracilaria* varies with demand and collectors usually respond with heightened activity and a tendency to overharvest when the price is high, so there is a need to have an enforceable harvesting policy to preserve the natural beds. In Argentina, *Gracilaria* is gathered from large quantities brought ashore by storms; it is not harvested from attached material.

2.5 CULTIVATION OF AGAROPHYTES

Gelidium species are small, slow growing plants, and while cultivation in ponds and tanks is possible, to date it has not been economically viable. The only exception appears to be in the case of a Canadian company based near Vancouver, Marine Bioproducts International Corp. It claims to be growing a consistent, high quality *Gelidium* from which it produces speciality high grade agar and agarose products that presumably can be sold at a premium price to offset the costs of cultivation (details at www.marbio.com).

Gracilaria cultivation is widespread, and several methods are used. It can be grown vegetatively (i) in open waters on the bottom of bays, estuaries or reef flats; (ii) on lines, ropes or nets; (iii) in ponds; or (iv) in tanks. It has also been grown from spores, involving an alternation of generations and the need for nursery tanks to allow the germlings to grow before planting them out into the sea. The first three methods, (i) to (iii), are the most widely used ones.

Where the open-water bottom is a soft sediment, such as an intertidal mudflat or an estuary outlet, pieces of seaweed are forced into the sediment using a “y”-shaped fork planting tool, either by a diver or from a boat using a long wooden handle with the fork on the end. The buried portion of the plant grows laterally, anchoring the plant, and it also produces vertical shoots that develop into mature plants. When the bottom is sandy, forked pieces loosen before they can become established by growing new lateral shoots, so to overcome this a different method is used. Tubular plastic bags, about 1 m long by 30–40 cm diameter, are filled with sand, and pieces of seaweed are wound around the tube or fixed to it with an elastic band. The tubes are then placed on the sea bottom and the plant is held in place as it forms new horizontal shoots. Eventually the plastic bag disintegrates, but by then the plant is firmly attached to the bottom. However, the accumulation of large quantities of disintegrated plastic tubes, washed up on nearby shores, can be a problem. Other methods have included fixing pieces of seaweed to rocks using rubber bands or nylon mesh to hold it in place on the rock, and then placing the rocks on the sea bottom.

For further detail, Buschmann, Westermeier and Retamales (1995) give a summary of experiences with sea-bottom farming in Chile; see also the more general references at the end of this section.

Line or rope farming was pioneered in China in the 1950s for the cultivation of brown seaweeds, and the method has been adapted to several other genera, including *Gracilaria*. Pieces of *Gracilaria* are fixed to a rope or monofilament line such as nylon. The rope needs to be stable when exposed to sunlight and salt water for long periods; polypropylene rope is often used. The seaweed can be attached by untwisting the rope to open the lay, inserting the plant and then allowing the rope to twist back to its natural position. Or the plant may be tied to a monofilament line, or a rope, with another piece of “string” – often a plastic raffia is used. The line is then stretched in the water between two stakes driven into the bottom. Success depends on the selection of farm site (suitable water flow, nutrient availability and water temperature) and positioning of the line in relation to water depth and light intensity. These are general guidelines, and adjustments must be made for each site. Nets can be used in place of ropes, but people generally find ropes are more convenient. Sometimes the ropes or nets are fixed to frames made from bamboo, giving a raft type structure (see Figure 42) that is anchored to the sea bottom and held at a fixed depth with floats.

Pond cultivation of *Gracilaria* is less labour intensive than rope farming (no need to fix many pieces to a rope or net) and has been quite successful, originally in China in Guandong, Hainan and Taiwan Province of China, now also in Indonesia, Viet Nam and in experimental trials in Malaysia. One disadvantage of *Gracilaria* from ponds is that the agar extracted from it is often of low gel strength and so only attracts the lower price of a food grade agar. Ponds are usually no larger than a hectare, preferably 0.5–1.0 ha. Pieces of fresh seaweed, either gathered from natural beds or nearby ponds, are broadcast evenly over the pond surface and allowed to sink to the bottom. Because the *Gracilaria* is not fixed in any way, any wind motion of the water will drive the plants to one side of the pond. This even occurs in small ponds, so an area that is not exposed to strong winds is preferable. Ponds need access to both salt and freshwater so that the salinity can be adjusted and so that the water can be changed every 2–3 days. Water change is usually made using tidal flows, with gates to control the water flow in and out.

Frequently, old shrimp or fish ponds are used (Figure 4). The pH of the pond water is important, and newly constructed ponds are often too acidic and must be left to rest until the pH is just slightly alkaline (pH 8). Pond depths are usually 60–70 cm, but the water level may be varied according to the air temperature. The preferred water temperature is 15–30°C so, for example, in the summer of Taiwan Province of China, if the air temperature rises above 30°C, the water depth is increased to 50–60 cm to protect the seaweed from hot surface temperatures. In the colder winter months, the water level may be reduced to 20–30 cm to allow warm water to reach the bottom.

Harvesting is possible every 35–45 days depending on the seasonal growth rate. About half the seaweed is harvested, usually by people wading through the pond, scooping it off the bottom into nets and placing it on a wooden raft or floating basket (Figure 5). The plants remaining form seed material for the next crop, and are broken into smaller pieces and broadcast over the pond. The harvested material is often laid around the banks of the pond to dry in the sun for 2–3 days (Figure 4), although a cleaner product is obtained by drying away from the ground (Figure 6).

An epiphyte is a plant that grows on another plant but is not parasitic on it. Epiphytes can be a problem in all seaweed cultivation since they contaminate the crop unless they are removed. In the pond cultivation of *Gracilaria*, epiphytes can be a particular problem because the growing seaweed is not readily accessible to the farmer, as it lies on the bottom of the pond. Contrast this with cultivation on lines, where the farmer can periodically move along the lines and physically remove epiphytes at an early stage of contamination. Sometimes *Gracilaria* is grown in ponds with other marine species, such as tilapia or milkfish, that will control the epiphytes by grazing on them. This and other types of polyculture are discussed in more detail in a later section (Section 9.6).

FIGURE 4
Pond used for *Gracilaria* cultivation, Sulawesi, Indonesia.

FIGURE 5
Harvesting *Gracilaria* from pond cultivation, Sulawesi, Indonesia

FIGURE 6
Drying *Gracilaria*, off the ground, Pattani, southern Thailand.

For further detail on epiphytism, see a review of epiphytism and its control in *Gracilaria* farming in Fletcher (1995).

Tank cultivation of *Gracilaria* has been studied by several groups. Because other methods of cultivation are relatively labour intensive, in developed countries it was thought that tank cultivation of unattached plants might be the answer to their high labour costs. However, it has not been adopted on a commercial scale because of the costs involved. The method is very energy intensive because of the need for aeration and large amounts of flowing seawater. Nutrients must also be added, and sometimes the temperature needs to be controlled, particularly in hot climates. Commercial scale production also brings a requirement for large areas of coastal land, and this can be very expensive in developed countries.

For further details

The cultivation of *Gracilaria* has been the subject of some very good reviews that give details of the processes involved and useful explanatory diagrams. See Ohno and Critchley (1993), Santelices and Doty (1989), Oliveira, Alveal and Anderson (2000), and Buschmann et al. (2001).

In addition, the June 1995 issue of the Journal of Applied Phycology is devoted to 10 papers given at a workshop on *Gracilaria* and its cultivation; each of the following papers is useful for the particular topic, which can be found in its title (see list of References): Buschmann, Westermeier and Retamales (1995); Dawes (1995); Friedlander and Levy (1995); and Fletcher (1995).

2.6 QUANTITIES HARVESTED

For *Gracilaria*, Chile is the largest supplier, although the harvest of wild seaweed has fluctuated over the last 5 years, from 121 000 wet tonnes in 1996 down to 73 000 tonnes in 1998, and back up to 137 000 wet tonnes in 2000. Cultivation has yielded about 33 000 wet tonnes for the last two years for which figures are available (1999 and 2000). China, Indonesia, Namibia and Viet Nam all supply between 12 000 and 18 000 wet tonnes each, in most cases from a mixture of wild and cultivated material. In Argentina, between 1985 and 1995, the harvest of dried *Gracilaria* varied from 1 700 to 3 100 tonnes. In India, harvests of wild *Gracilaria* and *Gelidiella* on the Tamil Nadu coast have varied between 750 and 1 300 dry tonnes from 1996 to 1999.

For *Gelidium*, the main suppliers in Europe are Spain and Portugal; in Africa, it is mainly from Morocco, with some from Namibia and South Africa. The principal contributors from Asia-Pacific are Japan, the Republic of Korea and Indonesia, while from the Americas it is Mexico.

Quantities harvested from the principal source areas are shown in Table 1.

TABLE 1

Agarophyte resources harvested in 2001 (tonnes dry weight)

Gracilaria	
Europe	200
Africa	300
Americas	25 000
Asia-Pacific	11 500
Subtotal	37 000
Gelidium	
Europe	6 600
Africa	7 200
Americas	500
Asia-Pacific	4 300
Subtotal	18 600
Pterocladia	
Europe	50
Total	55 650

Source: H. Porse, CP Kelco ApS, 2002, *pers. comm.*

2.7 MARKETS

Gelidium is sold to agar producers. In Japan, Mexico, Morocco, Portugal and Spain, the harvests are sold to local agar companies. *Gelidium* is such an excellent source of high quality agar that there is always a strong demand from any agar producer in the country of origin. However, price is always a determining factor and, for example, Spain has imported *Gelidium* from South Africa and Chile when the local price was too high. Indonesian *Gelidium* is used by local agar producers and some is also exported, mainly to Japan. Chile and South Africa both sell *Gelidium* to the producers in Europe and Japan; according to official statistics, *Gelidium* is not extracted in Chile and there are no agar producers in South Africa.

Chile has six exporters of *Gelidium*, listed by ProChile, but two of these dominate the trade: Industria Pesquera Costa Azul S.A., Vina del Mar; and Midesa S.A.C., Santiago.

A South African exporter is Taurus Products (Pty) Ltd, Johannesburg.

The numbers and names of Indonesian exporters of *Gelidium* fluctuate and current information is best obtained from the Indonesian Seaweed Industry Association (APBIRI) (See Section 3.2).

Gracilaria is sold to agar producers and some is used as food. For food consumption, the seaweed is usually gathered and sold fresh, locally. It is most common in South-East Asian countries such as Indonesia, Malaysia, the Philippines and southern Thailand, mainly in coastal communities. It is also popular with most ethnic groups in Hawaii, and is sold fresh in Honolulu markets as limu manauea or limu ogo.

Agar producers usually buy dried *Gracilaria*, but some buyers, particularly from Japan, are now requiring alkali-treated, dried seaweed. Historically, Japan produced agar by extracting the seaweed, *Gelidium*, with hot water and then freezing the extract by placing it outside in the winter sub-zero temperatures. Consequently several agar producers are located in mountainous districts of Japan, where it is becoming increasingly difficult to dispose of waste waters. To obtain a good quality agar from *Gracilaria*, it is necessary to treat it with alkali before the hot water extraction (more details in Section 3), and it is the disposal of these alkaline waste waters that is posing environmental problems. Buying *Gracilaria* that has already been treated with alkali overcomes this problem for Japanese producers. However, it means that some exporters now have to set up alkali treatment facilities in their own countries. Japan imports *Gracilaria* mainly from Chile, Indonesia, Namibia, the Philippines and South Africa. Other importers are Argentina, the Republic of Korea and Spain. Chile is the largest exporter of Gracilaria, but also uses appreciable quantities itself; in the case of Indonesia and Viet Nam, each uses about one-third of its production, exporting the remainder. Other exporters include Namibia and South Africa.

Chile lists 21 exporters of *Gracilaria*, the largest ones being Algas Vallenar S.A., Vallenar; Algas, Cultivos, Exportaciones – Acex S.A., Santiago; Alimentos Multiexport S.A., Santiago; and Midesa S.A.C., Santiago. For up-to-date information on Chilean exporters, consult the latest annual Export Directory, published by ProChile, Santiago.

A South African/Namibian exporter is Taurus Products (Pty) Ltd, Johannesburg.

The numbers and names of Indonesian exporters of *Gracilaria* fluctuates and current information is best obtained from the Indonesian Seaweed Industry Association (APBIRI) (See Section 3.2).

2.8 FUTURE PROSPECTS

Sales depend on the prosperity of the agar industry, and since it has a stable market with limited prospects of expansion, agarophytes in general are in a similar position. However, the market for *Gelidium* and *Pterocladia* will always be competitive because they provide the best quality agar and are only available from limited natural resources. Since the cultivation of *Gracilaria* has been so successful, this means that any expansion that does occur in the agar market can be readily serviced by growing more *Gracilaria*. At present the producers and collectors of *Gracilaria* are therefore likely to face a buyers market, bringing pressure to reduce prices.

3. Agar

3.1 AGAR PRODUCTION METHODS

3.1.1 Food grade agar

A short and simplified description of the extraction of agar from seaweeds is that the seaweed is washed to remove foreign matter and then heated with water for several hours. The agar dissolves in the water and the mixture is filtered to remove the residual seaweed. The hot filtrate is cooled and forms a gel (jelly) which contains about 1 percent agar. The gel is broken into pieces, and sometimes washed to remove soluble salts, and, if necessary, it can be treated with bleach to reduce the colour. Then the water is removed from the gel, either by a freeze-thaw process or by squeezing it out using pressure. After this treatment, the remaining water is removed by drying in a hot-air oven. The product is then milled to a suitable and uniform particle size.

However, for a better understanding of the process, some of the details and difficulties need to be described.

There are some differences in the treatment of the seaweed prior to extraction, depending on the genus used. *Gelidium* is simply washed to remove sand, salts, shells and other foreign matter and is then placed in tanks for extraction with hot water. *Gracilaria* is also washed, but it must be treated with alkali before extraction; this alkaline pre-treatment causes a chemical change in the agar from *Gracilaria*, resulting in an agar with an increased gel strength. Without this alkaline pre-treatment, most *Gracilaria* species yield an agar with a gel strength that is too low for commercial use. For the alkali treatment, the seaweed is heated in 2–5 percent sodium hydroxide at 85–90°C for 1 hour; the strength of the alkali varies with the species and is determined by testing on a small scale. After removal of the alkali, the seaweed is washed with water, and sometimes with very weak acid to neutralize any residual alkali.

For the hot-water extraction, *Gelidium* is more resistant and extraction under pressure (105–110°C for 2–4 hours) is faster and gives higher yields. *Gracilaria* is usually treated with water at 95–100°C for 2–4 hours. The remainder of the process is the same for both types of raw material. The hot extract is given a coarse filtration to remove the seaweed residue, filter aid is added and the extract is pumped through a filter press equipped with a fine filter cloth. The extract is thick and will gel if allowed to cool, so it must be kept hot during the filtration processes.

The filtrate is now cooled to form a gel, which is broken into pieces (Figures 7 and 8). This gel contains about 1 percent agar. The remaining 99 percent is water that may contain salts, colouring matter and soluble carbohydrates. The gel may be treated with bleach to reduce any colour, washed to remove the bleach, and allowed to soak in water so that most of the salts can be removed by osmosis. The wash waters are drained and the remainder of the process is concerned with the removal of the 99 percent water in the gel. Either of two methods can be used for this.

The original method of water removal is the freeze-thaw process. The gel is slowly frozen so that large ice crystals form. The structure of the gel is broken down by the freezing so that when the material is thawed most of the water drains away, leaving a concentrated gel that now contains about 10–12 percent agar (this means about 90 percent of the original water content has been removed, and with it went a high proportion of any salts, soluble carbohydrates and soluble proteins that may have been present in the gel). Sometimes this gel is placed between porous filter cloths and squeezed in a hydraulic press to remove more water. However, this is a slow process, and usually the thawed material is simply

FIGURE 7
Hot agar solution is fed, from the T-shaped PVC pipe, as a thin layer onto a stainless steel belt where it is cooled and forms a gel.

FIGURE 8
Pieces of gel breaking up as they fall off the end of the stainless steel cooling belt. A cutting device, consisting of a stainless steel screw and thin wire, is at the bottom of the ramp.

drained and placed in a hot-air dryer. After drying it is milled to the required particle size, usually about 80–100 mesh size. Because of the refrigeration costs, this freeze-thaw process is relatively expensive, compared to the alternative described next.

Sometimes the thawing is accelerated by washing the frozen blocks of gel with large quantities of water (Figure 9), but this adds to the already large water consumption of the process.

The alternative process relies on synaeresis. This is the term used to describe the separation of liquid from a gel. A common example is that of a partly used jar of jam or preserves that is left standing for several days: pools of liquid can often be seen at the surface. However, for the agar gel, pressure is used to force the separation of the liquid. The equipment used is based on the following. Two grooved metal plates are covered with porous cloth and the 1 percent agar gel is placed between the cloths, like a sandwich with metal plates on the outside, then the layers of cloth, with the gel in the middle. Pressure is applied to the metal plates and very slowly increased over about 24 hours, forcing liquid out of the gel, through the cloths, down the grooves of the metal plate and away to a drain. The piece of equipment contains about fifty of these sandwich-type units, all in a vertical plane, all being placed under pressure by one hydraulic ram (Figure 10). At the end of the time, the pressure is released, the metal plates are separated and the remaining gel, now containing about 20 percent agar, is peeled off the porous cloth (Figure 11). It is shredded and dried in a hot-air oven before being milled to the required particle size, usually about 80–100 mesh size. With no refrigeration required, the energy consumption is obviously much lower than

FIGURE 9
Thawing frozen slabs of agar by hosing with water.

FIGURE 10
Dewatering machine used to squeeze water from agar gel.

FIGURE 11
A sheet of agar gel after squeezing in the dewatering machine.

for the freeze-thaw method, and, since more water has been removed, less soluble matter remains, so the agar is more pure. Less energy is also needed in the drying process since less water is being removed. This process based on synaeresis has been widely adopted by large agar producers who can afford the higher capital costs for this equipment.

FIGURE 12
Agar blocks (left) and agar strips (right).

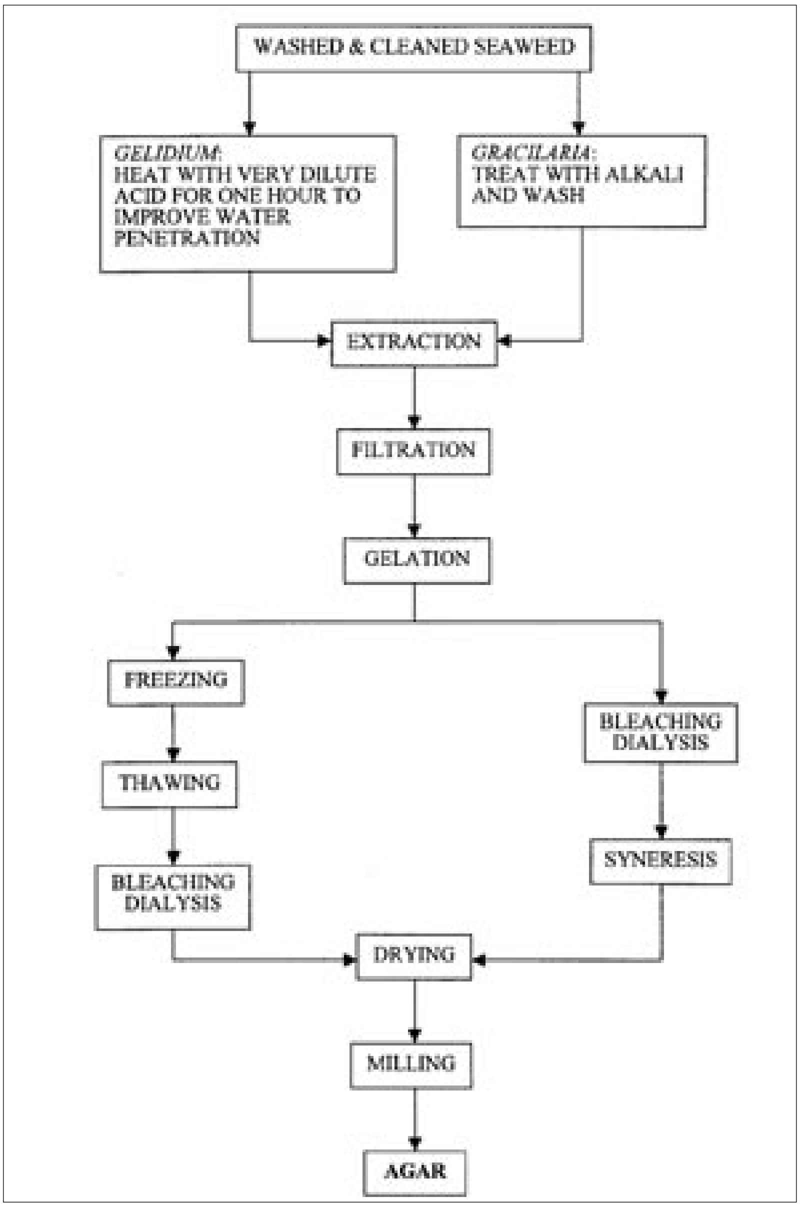

FIGURE 13
Flow chart for the production of agar (after Armisen and Galatas, 1987).

Figure 13 summarizes the production processes for agar.

A large and reliable freshwater supply is a requirement for an agar factory. Water consumption is high and the processing of *Gracilaria* requires more than for *Gelidium*. Higher water consumption also means larger quantities for waste disposal, so recycling of water is becoming more necessary, depending on the location of the factory.

For further details

Detailed information on the commercial extraction process is not easily available. There are several short publications on the results from laboratory-scale extractions, but commercial agar producers are generally secretive about the details of their processes. Armisen and Galatas (1987) is one of the few publications that gives some details, but there are still many gaps, particularly in the conditions of the alkali treatment and the subsequent hot water extraction; nevertheless, it is the best starting point. The original print version may not be readily available but it can be read and downloaded from the FAO Web site (see References 2 – Internet sources). A later book chapter by the same authors, Armisen and Galatas (2000) gives a useful comparison of the freeze-thaw and synaeresis methods for removing water from the agar gel. Nussinovitch (1997: 4–5) also has a few useful details about extraction.

3.1.2 Agar strips

Agar for use in food is sold in two forms: strip agar and agar powder. The powder is produced by the method previously described. Agar strip, sometimes called natural agar, is produced on a small scale in China, Japan and the Republic of Korea by the old, traditional method. *Gelidium* must be used; it was the only raw material used before the Second World War. It is boiled for several hours in water, acidified by the addition of either vinegar or dilute mineral acid. The hot extract is filtered through cotton cloth, then poured into wooden trays to cool and form a gel. The gel is extruded to produce spaghetti-type strips about 30 cm long. The strips are placed outside at night to freeze and allowed to thaw in the day, so water is released and runs off, leaving a more concentrated gel. This process can be repeated, or modern refrigeration can be substituted. The strips are dried in the sun, which also bleaches the strips. Strips are assembled into bundles and sold for domestic use (Figure 12). Prior soaking makes them easier to dissolve in boiling water.

3.1.3 Bacteriological agar

This can only be made from species of *Gelidium* because the resulting agar has a low gelling temperature (34–36°C) that allows the addition of other materials to the agar with a minimum risk of heat damage. *Gracilaria* and *Gelidiella* give agars that gel at 41°C or higher. "Bacto" agars must not contain anything that might inhibit the growth of bacteria, such as trace metals, soluble carbohydrates or proteins, nor should they contain any bacterial spores. They must not interact with any materials that must be added as nutrients for the bacteria under study. The gels must be strong and have good clarity. Manufacturers of bacteriological agar keep all processing details confidential. However, recently Kim et al. (2000) published details [in Korean] of a pilot-scale preparation that they claim gave a product that is superior to commercial bacteriological agar. Armisen and Galatas (1987) and Armisen (1997) discuss the necessary specifications for bacteriological agar.

3.1.4 Agarose

Agar can be divided into two principal components: agarose and agaropectin. Agarose is the gelling component; agaropectin has only a low gelling ability. There are several methods of producing agarose; many rely on removing the agaropectin from the agar. There are only a small number of processors who produce purified, high quality agarose for a small but growing market, mainly in biotechnology applications. These processors use good quality agar as their starting material rather than seaweed, and are often not in the seaweed processing business. Armisen and Galatas (1987) summarize the methods that have been used to isolate agarose from agar, and discuss the specifications expected for a high quality agarose.

3.2 AGAR PRODUCERS

A summary of the capacity of agar producers according to their broad geographical location is given in Table 2.

The principal agar producers are listed below.

TABLE 2

Agar processors. Capacity in tonnes (2001)

Europe	780	10 percent
Africa	1 050	14 percent
Americas	3 000	39 percent
Asia-Pacific	2 800	37 percent
Total	7 630	

Source: H. Porse, CP Kelco ApS, 2002, *pers. comm.*

Spain

Hispanagar, S.A.
Avenida López Bravo, 98
Polígono de Villalonquejar
Apartado Postal 392
08080 Burgos
Tel: [INT+34] + 947 298 519
Fax: [INT+34] +947 298 518
Website: www.hispanagar.net
This is the largest Spanish phycocolloid factory, which produces food and bacteriological grade agars, Purified Bacteriological Agars (for use with specially sensitive bacteria and in bacterial metabolism assays as well as in biochemistry). They also produce many different types of agarose for biochemistry and molecular biology, being the world's largest producer of agaroses.

Industrias Roko, S.A.
Rua os Regos 27
Oleiros,
La Coruña 15173
Tel: [INT+34] +981 631 159
Situated near Oviedo, it produces food grade agar and some types of bacteriological agar.

Algas de Asturias, S.A.
LG Bria - Posadas de Llanes
Llanes - Asturias
A smaller factory that produces food grade agar and some types of bacteriological agar.

Portugal

Iberagar S.A.
Estrada Nacional 10, Km. 18, Coina
Tel: [INT+35] +(121) 210 9252
Fax: [INT+35] + (121) 210 9255
Website: www.iberagar.com
Produces food and bacteriological grade agars.

Morocco

SETEXAM, S.A
Km 7 Route de Tanger,
B.P. 210
14000, Kenitra
Tel: [INT+212] + 7 378 496
Fax: [INT+212] + 7 378 448

Marokagar, S.A.
44 Rue Abou Baker Wahrani
B.P. 2121
Casablanca 05
Tel: [INT+212] + 2 623 611
Fax: [INT+212] + 2 614 895

Chile

Algas Marinas S.A. (Algamar)
Fidel Oteiza 1956 Piso 14
Providencia, Santiago
Tel: [INT+56] + (2) 205 5086
Fax: [INT+56] + (2) 205 5184

Prodoctora de Agar S.A. (Proagar S.A.)
Av. Vicente Perez Rosales 800
Llanquihue
Tel: [INT+56] + (65) 242 635
Fax: [INT+56] + (65) 243 312
In 2000, this Japanese controlled company claimed to be the world's second-largest agar producer, exporting about 450 tonne/year.

Agar del Pacifico S.A.
Av. Federico Schwager 1112 -
Parque Industriel Coronel
Coronel
Tel: (56-41) 75 1286
Fax: (56-41) 75 1143

Cobra Chile S.A.
Av. Andres Bello 1051 Of. 2501
Providencia, Santiago
Tel: [INT+56] + (2) 236 1582
Fax: [INT+56] + (2) 236 0276

Japan
Ina Food Industry Co., Ltd.
574 Tsurumakicho, Waseda
Shijuku
Tokyo 162
Tel: [INT+81] + (3) 3235 8861
Fax: [INT+81] + (3) 3235 8863

Matsuki Agar-Agar Industrial Co., Ltd
2638 Miyagawa
Chino City
Nagano-Pref
Tel: [INT+81] + (266) 724 121

The Republic of Korea
Myeong Shin Chemical Ind. Co., Ltd.
2191-3 Songbaek Sannae
Milyang, Kyeongnam
Tel: [INT+82] + (55) 352 0547
Fax: [INT+82] + (55) 352 0548
Website: www.miryangagaragar.com
(agar factory)

Myeong Shin Chemical Ind. Co., Ltd.
439-13, Soju-Ri, Ungsang-Up,
Yangsan-gun, Kyeong-Nam,
Tel: [INT+82] + (55) 389 1001
Fax: [INT+82] + (55) 389 0478
(Head Office and carrageenan factory)

Indonesia
P.T. Agarindo Bogatama
Jl. Gajah Mada No. 3
Komplex Duta Merlin Blok E No.34-35
Jakarta 10130

For further details about Indonesia and other Indonesian companies contact the Indonesian Seaweed Industry Association (APBIRI)
Asosiasi Pengusaha Budidaya dan Industri Rumput Laut Indonesia (APBIRI)
BPPT Lt. 13
Jl. MH Thamrin No. 8
Jakarta Pusat 10340
Tel: [INT+62] + 21 322430

Mexico
Agarmex S.A.
Ensenada

New Zealand
Coast Biologicals Ltd
Factory Road
Opotiki
Tel: [INT+64] + 7 315 7663
Fax: [INT+64] + 7 315 8002
Produces only bacteriological agar from Pterocladia.

France
SOBIGEL S. A.
Rue de L'industrie B.P. 304
64703 Hendaye
Tel: [INT+33] + (55) 9201844
Fax: [INT+33] + (55) 9202362
Owned by Hispanagar, S.A.

Argentina
Soriano S.A.
9 de Julio 745
9100 Trelew
PCIA Chubut

3.3 AGAR USES

The uses of agar centre around its ability to form gels, and the unique properties of these gels. Agar dissolves in boiling water and when cooled it forms a gel between 32° and 43°C, depending on the seaweed source of the agar. In contrast to gelatin gels, that melt around 37°C, agar gels do not melt until heated to 85°C or higher. In food applications, this means there is no requirement to keep them refrigerated in hot climates. At the same time, they have a mouth feel different from gelatin since they do not melt or dissolve in the mouth, as gelatin does. This large difference between the temperature at which a gel is formed and the temperature at which it melts is unusual, and unique to agar. Many of its applications take advantage of this difference.

For details on the chemistry of why and how agar forms gels see Nussinovitch (1997) or Armisen and Galatas (2000).

3.3.1 Food

About 90 percent of the agar produced is for food applications, the remaining 10 percent being for bacteriological and other biotechnology uses. Agar has been classified as GRAS (Generally Recognized As Safe) by the United States of America Food and Drug Administration, which has set maximum usage levels depending on the application. In the baked goods industry, the ability of agar gels to withstand high temperatures means agar can be used as a stabilizer and thickener in pie fillings, icings and meringues. Cakes, buns, etc., are often pre-packed in various kinds of modern wrapping materials and often stick to them, especially in hot weather; by reducing the quantity of water and adding some agar, a more stable, smoother, non-stick icing is obtained.

Some agars, especially those extracted from *Gracilaria chilensis*, can be used in confectionery with a very high sugar content, such as fruit candies. These agars are said to be "sugar reactive" because the sugar (sucrose) increases the strength of the gel. Because agar is tasteless, it does not interfere with the flavours of foodstuffs; this is in contrast to some of its competitive gums that require the addition of calcium or potassium salts to form gels. In Asian countries, it is a popular component of jellies; this has its origin in the early practice of boiling seaweed, straining it and adding flavours to the liquid before it cooled and formed a jelly. A popular Japanese sweet dish is *mitsumame*; this consists of cubes of agar gel containing fruit and added colours. It can be canned and sterilized without the cubes melting. Agar is also used in gelled meat and fish products, and is preferred to gelatin because of its higher melting temperature and gel strength.

In combination with other gums, agar has been used to stabilize sherbets and ices. It improves the texture of dairy products like cream cheese and yoghurt. It has been used to clarify wines, especially plum wine, which is difficult to clarify by traditional methods. Unlike starch, agar is not readily digested and so adds little calorific value to food. It is used in vegetarian foods such as meat substitutes.

3.3.2 Other uses

In the pharmaceutical industry agar has been used for many years as a smooth laxative.

In orchid nurseries, agar gels containing appropriate nutrients are used as the growth substrate to obtain clones or copies of particular plants. Meristems – the part of the plant with actively dividing cells, usually the stem tips – are grown in the gel until there has been sufficient root development and growth for them to be transplanted. An advantage of this system is that the plants can be cultured in a sterile environment.

3.3.3 Microbiological agar

Bacteriological agar is used in testing for the presence of bacteria. It is specially purified to ensure that it does not contain anything that might modify bacterial growth. It is therefore more expensive, frequently at least twice the price of food grade agar. A hot agar solution (1–1.5 percent) is prepared and as it cools, nutrients or other chemicals specific for the type of bacteria being tested are added. When the solution has cooled below its gel point, the sample suspected of containing bacteria is spread on the surface of the gel, which is then covered and stored at a temperature suitable for bacterial growth. The agar gel should be as clear as possible so that any bacterial growth can be easily seen.

For further details

Further information about the uses of agar can be found in Glicksman (1983) and Armisen and Galatas (1987, 2000). Armisen and Galatas (2000) also contains some interesting recipes for yokan (traditional Japanese), sweet potato dessert (traditional Argentinian) and sugar icings, all of which illustrate typical methods for using agar in foods. Armisen (1997) lists eleven important advantages enjoyed by agar in food applications. Armisen (1995) is a paper about the use and importance of *Gracilaria*, but it also has useful discussions about natural and industrial agars, compares the characteristics of agars from *Gelidium* and from *Gracilaria*, and is useful background reading for those wishing to learn more about the agarophyte and agar industries.

3.4 MARKETS AND MARKETING OF AGAR

A summary of the agar markets is shown in Table 3. It does not include production from *Gelidiella acerosa* and *Gracilaria* species in India, where 800–1 300 dry tonnes of seaweed are used to produce 100–160 tonnes/year of agar.

All the companies previously listed as agar producers sell directly to agar users. However, there are other companies that buy from producers and re-sell the agar, either alone or in admixture with other hydrocolloids, to users. These companies specialize in supplying food ingredients, usually defined as food additives that improve the quality, texture, stability or presentation of a food product. Because they are more active in the carrageenan and alginate industries, further discussion about them can be found later, in the relevant sections.

TABLE 3
Agar markets (2001)

Markets by application		
Application	**tonnes**	**percent**
Food	6 930	91
Bacteriological	700	9
Total	7 630	
Markets by grade and source		
Grade / seaweed	**tonnes**	**percent**
Powder / ***Gracilaria***	4 100	54
Powder / ***Gelidium***	2 305	30
Square / ***Gracilaria***	250	3
Strips / ***Gracilaria***	275	4
Bacto / ***Gelidium***	700	9
Total	7 630	

NOTE: The total market has a value of about US$ 137 million.
Source: H. Porse, CP Kelco ApS, 2002, *pers. comm*.

Some future prospects for the red seaweed industry and its hydrocolloid products are considered by Kapraun (1999).

3.5 FUTURE PROSPECTS

The market for food grade agar is stable and not likely to expand very much in the near future, unless new uses are developed, and this does not seem likely at present. During the last 30–40 years agar has gradually been replaced in some of its traditional uses by other hydrocolloids that either gave a better result in particular applications or are cheaper. Uses now are restricted to those that depend on the unique gelling properties of agar. There are many producers, some endeavouring to capture market share with low price or low quality material, so it is becoming a very tight market. The bacteriological agar market is also stable, but present prospects are that it is unlikely to show much expansion in the next five years. The market for agarose will expand during the next five years as its uses in biotechnology increase and probably diversify as new techniques are developed. However, it is a specialized and relatively small market; users often purchase in lots of 100 g, with a total worldwide consumption of about 50 tonne/year.

4. Seaweeds used as a source of alginate

4.1 GENERA AND SPECIES USED

Alginate, sometimes shortened to “algin”, is present in the cell walls of brown seaweeds, and it is partly responsible for the flexibility of the seaweed. Consequently, brown seaweeds that grow in more turbulent conditions usually have a higher alginate content than those in calmer waters. While any brown seaweed could be used as a source of alginate, the actual chemical structure of the alginate varies from one genus to another, and similar variability is found in the properties of the alginate that is extracted from the seaweed. Since the main applications of alginate are in thickening aqueous solutions and forming gels, its quality is judged on how well it performs in these uses.

A high quality alginate forms strong gels and gives thick aqueous solutions. A good raw material for alginate extraction should also give a high yield of alginate.

Brown seaweeds that fulfil the above criteria are species of *Ascophyllum*, *Durvillaea*, *Ecklonia*, *Laminaria*, *Lessonia*, *Macrocystis* and *Sargassum,* although the last, *Sargassum*, is only used when nothing else is available: its alginate is usually borderline quality and the yield usually low.

4.2 NATURAL HABITATS

Ascophyllum (Figures 14 and 15) is found in cold waters of the Northern Hemisphere. It grows in the eulittoral zone (see Section 2.2 for definition), forming distinct bands of dark brown, branched plants 1–4 m long. It prefers somewhat sheltered areas and disappears where there is strong wave action.

Durvillaea (Figures 16 and 17) is found only in the Southern Hemisphere, and grows best in rough water, near the top of the sublittoral zone, on rocky shores or offshore reefs. Plants are smaller where summer water temperatures rise to 19°C, but grow best where the temperature does not rise above 15°C. Plants of 5 m length are not uncommon, but 2–3 m is more usual.

Ecklonia species are found in both Northern and Southern Hemispheres, in warm temperate waters, usually on rocky substrates of the upper sublittoral zone (Figure 18).

FIGURE 14
Ascophyllum nodosum **(Specimen from National Herbarium, Royal Botanic Gardens, Sydney. Collectors: Alan J.K. Millar and Jacob Larsen.)**

FIGURE 15
***Ascophyllum nodosum* at low tide**

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FIGURE 16
***Durvillaea potatorum* on wave-swept rocks, Australia**

BRUCE FUHRER

FIGURE 17
***Durvillaea potatorum* suspended on poles. being transferred to 5-metre high air-drying racks, King Island, Australia.**

Laminaria harvests rely on mainly three species: *L. digitata*, *L. hyperborea* and *L. saccharina*. All three grow in cold temperate water, 10°–15°C, and are harvested in the Northern Hemisphere. *L. japonica* is sometimes used in China, but it is mainly cultivated there for use as a food, and only surplus production is used in the alginate industry. The cultivation of *L. japonica* is discussed in Section 8.4.

Laminaria digitata grows in the upper sublittoral zone in rocky, wave-exposed localities and it is well adapted to this because of its flexible stipe (stem) and divided blades (Figures 19 and 20).

FIGURE 18
***Ecklonia* species (Cheju Island, the Republic of Korea).**

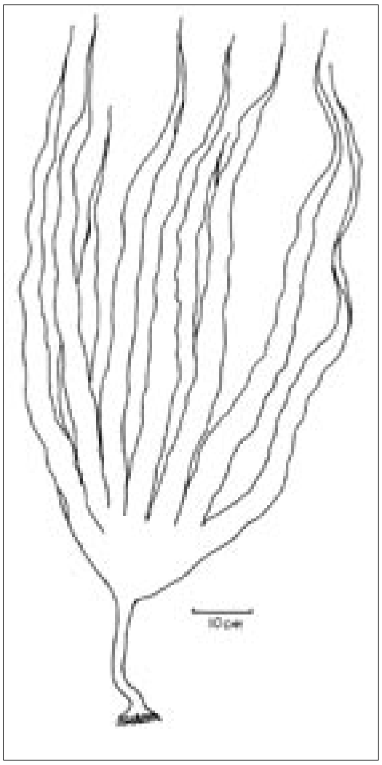

FIGURE 19
***Laminaria digitata* (after Lüning, 1990).**

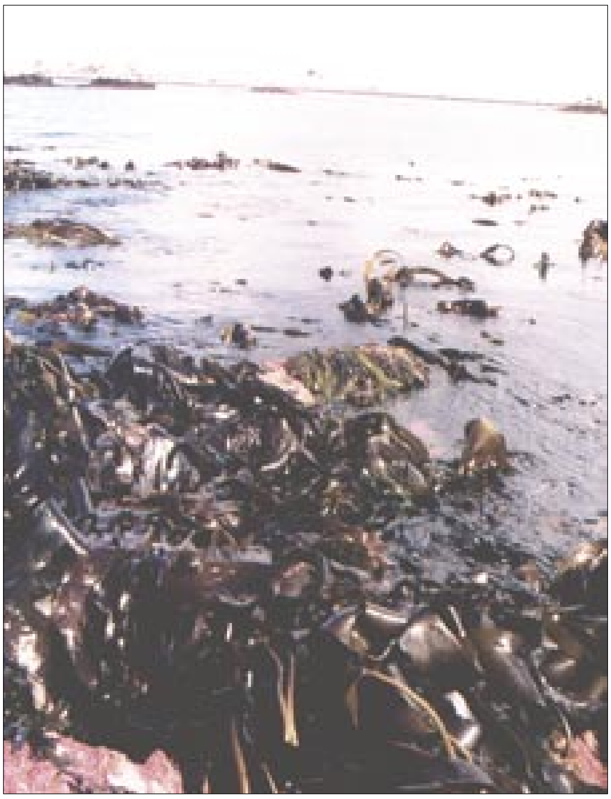

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FIGURE 20
Laminaria digitata

Laminaria saccharina also grows in the upper sublittoral, usually below *L. digitata,* but requires more sheltered conditions because of its undivided and mechanically less tolerant blade (Figure 21).

Laminaria hyperborea (Figures 22 and 23) grows on rocky bottoms of the mid-sublittoral zone, in depths of 2–10 m, but in clear water it can be 15–25 m: the limiting factor being sufficient light for growth. It has a strong stipe and the plant stands upright in the water and forms "laminarian forests". They can survive for up to 15 years, in contrast to the *Laminaria* in the upper sublittoral, which have a life of about 3 years.

Lessonia has two species that are collected in Chile for alginate extraction. They are collected from the northern and central coasts, but the harvests are sometimes disrupted by an El Niño event. This causes the El Niño Current to develop, which flows from north to south with water temperatures as high as 23°–27°C and has been known to destroy almost the entire *Lessonia* population.

Lessonia nigrescens grows in thick belts in the rocky lower eulittoral zone, where its massive holdfast allows it to survive the rough waters in which it thrives (Figure 24).

Lessonia trabeculata (Figure 25) grows in the sublittoral, 1–20 m depth. It also has a very thick holdfast and stands up underwater, rather like *Laminaria hyperborea.*

Macrocystis pyrifera grows best in calm, deep waters in temperatures of 15°C or less. It is sensitive to water temperature and does not withstand a rise above 20°C. It grows on rocky

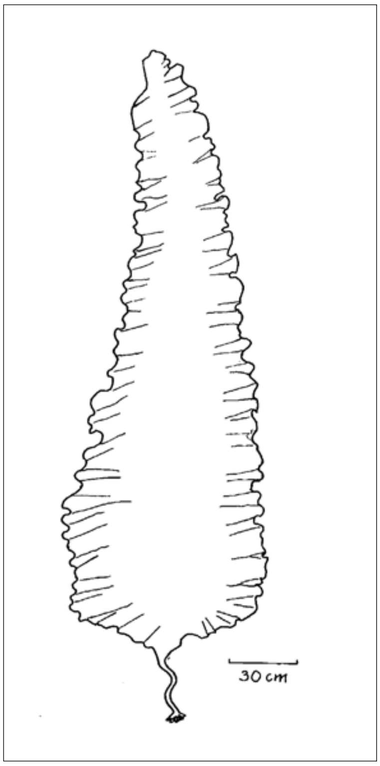

FIGURE 21
Laminaria saccharina **(after Lüning, 1990).**

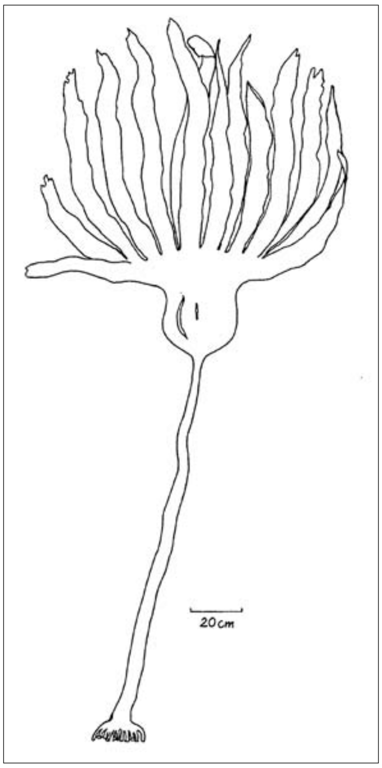

FIGURE 22
Laminaria hyperborea **(after Chapman and Chapman, 1980).**

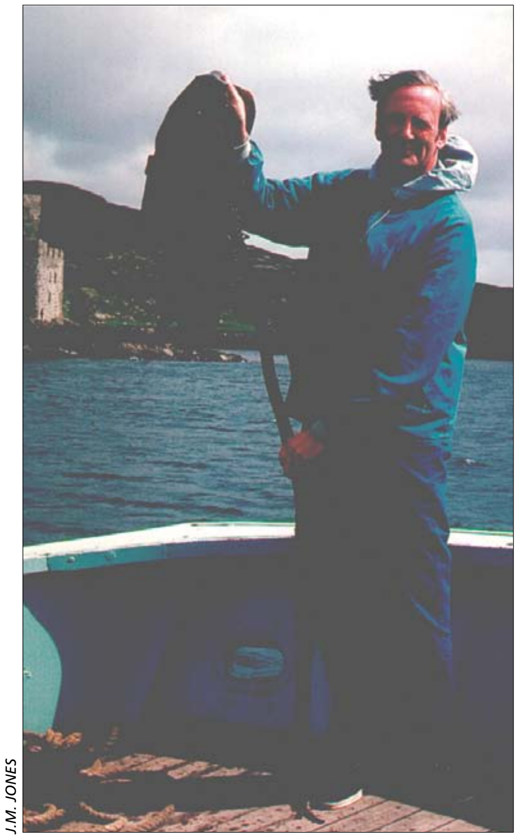

FIGURE 23
Laminaria hyperborea, **held upright, as it stands on the ocean floor, by Norman Jones.**

R.H. MCPEAK

FIGURE 24
***Lessonia nigrescens*, held by John Sanderson, Kelco Co.**

R.H. MCPEAK

FIGURE 25
***Lessonia trabeculata*, held by John Sanderson, Kelco Co.**

FIGURE 26
***Macrocystis pyrifera*, fixed to the bottom in 10 m depth of water, grows up to and then along the surface, kept afloat by gas-filled bladders (Tasmania, Australia).**

bottoms where its holdfast can become established, and can be found as large underwater forests, with plants rising to and growing along the surface, at times up to 20 m in length (Figure 26).

Sargassum species are found worldwide in warm temperate and tropical water-temperature regions. They are found in both the eulittoral and upper sublittoral zones. They exhibit a wide variety in shape and form (Figures 27 and 28). The alginate content is usually low compared to the previously listed genera, and the quality of the alginate poor, although there are exceptions. For alginate extraction, they are regarded as the raw material of last resort.

FIGURE 27
***Sargassum* species (Specimen from National Herbarium, Royal Botanic Gardens, Sydney. Collector: S. Skinner).**

FIGURE 28
***Sargassum flavicans* (after a specimen from National Herbarium, Royal Botanic Gardens, Sydney. Collector: Australian Museum).**

4.3 SOURCES OF ALGINOPHYTES

Ascophyllum, also known as rockweed, is widely distributed in cold waters of the Northern Hemisphere. Material for alginate extraction comes from the west coast of Ireland; the Outer Hebrides, off the west coast of Scotland (United Kingdom); Iceland; the west coast of Norway; and, until recently, the coasts of Nova Scotia and New Brunswick (Canada). However, it is no longer harvested for alginate extraction in Canada because of government harvesting restrictions that made it uneconomic. In France, it can only be cut by hand, with some used in the alginate industry and some as a powdered additive to cattle feed. It is also harvested in Iceland.

Durvillaea is collected as beach wash on the west coast of King Island, which lies between Tasmania and the mainland of Australia. Small quantities are also collected in southern Chile.

Ecklonia species are found in both Northern and Southern Hemispheres, but are currently only collected in South Africa. Some of it is exported and some used internally to produce fertilizer. There is no alginate industry in the country. Some ten years ago it was harvested by divers on the coast of Cheju Island (the Republic of Korea), and used in an alginate factory located there. However, the factory has since been closed and sold to real estate developers. Experimental cultivation of *Ecklonia* in South Africa has been successful, with growth of young plants on rafts.

Laminaria digitata in France is the main raw material for the alginate industry. *Laminaria saccharina* often grows in close association with *L. digitata,* and is sometimes harvested at the same time. In Norway, *L. digitata* grows in masses at the lower end of the eulittoral zone and was previously an important source for the Norwegian industry. In France, it is in the upper sublittoral and is harvested around the coast of Brittany and adjacent islands. Iceland is also a source of *L. digitata* for the alginate industry in Scotland (United Kingdom).

Laminaria hyperborea is found on the west coast of Ireland; and the Outer Hebrides and the Orkney Islands, Scotland (United Kingdom). On the west coast of Norway, it forms dense forests, 1–2 m high. There are estimates of large quantities growing around the coast of Brittany (France), but commercial harvesting has not yet occurred.

Lessonia species are found in both Northern and Southern Hemispheres, but it is only collected in northern Chile (Regions II, III and IV). Here it grows, especially *L. trabeculata*, on offshore shoals and is torn off in rough weather.

Macrocystis pyrifera, sometimes called the giant kelp, is harvested from offshore beds that stretch from Monterey in California (United States of America), to Bahia Asuncion in Baja California Sur (Mexico). Smaller quantities are also collected in northern Chile. Collections from large beds in southern Argentina ceased a few years ago. *Macrocystis angustifolia* has been cultivated on an experimental scale in South Africa with a view to eventually growing it for alginate production or abalone feed.

Sargassum is collected on the south coast of Java (Indonesia) and in the Philippines. In the former country it is used for alginate production while in the latter there are pilot studies for its use in alginate production, but its present use is to produce seaweed meal for animal feed.

4.4 HARVESTING METHODS FOR WILD SEAWEEDS

Ascophyllum

In Ireland, this is cut by hand, leaving about 25 cm for regrowth; it is floated in nets to a point on the shore where it can be loaded on to trucks for transport to premises for drying and milling. In Norway, it was traditionally cut using a sickle, and this is still done in some places. However, most is now mechanically harvested using a flat-bottom vessel specifically designed for the purpose. It operates at high tide and because of the shallow depth, a water jet instead of a propeller is used for manoeuvring. A steel pipe fitted with rotating cutters extends beyond the bow of the vessel and can be lowered onto the seaweed. As the seaweed is cut, it is sucked up through the pipe and into a net on the boat. When the net is full it is thrown overboard (the seaweed floats) and nets are collected by another boat and taken to the factory. The Norwegian vessels were also used in Nova Scotia (Canada), but government restrictions on harvesting led to the alginate company ceasing activity. *Ascophyllum* is a very dark seaweed, black rather than brown when dried, and alginate extracted from it is dark and must be strongly bleached. Because of this, alginate producers often prefer other seaweeds.

Durvillaea

This is collected only from storm-cast material on King Island (Australia), and it is illegal to harvest the seaweed by cutting it from the rocks. Collection is restricted to 50 percent of the cast kelp, for unsubstantiated environmental reasons. The seaweed is hung on large racks to air dry for several days, then it is broken up, dried in a hot-air oven and milled to a powder that is freighted to Scotland (United Kingdom). The unusually high alginate content of the dried seaweed (40 percent) allows the whole operation to be economic.

Ecklonia

This is collected from beach-cast seaweed on the west coast of South Africa, mainly from beaches south of St Helena Bay.

Laminaria digitata

This was harvested in Norway by hand from the lower eulittoral, but with the advent of mechanical harvesting of *L. hyperborea* and *Ascophyllum*, the use of *L. digitata* has ceased. It is one of the major raw materials for the French alginate industry and it is harvested very efficiently using a mechanical device, the *scoubidou*, mounted on a boat.

FIGURE 29
Scoubidou boats harvesting *Laminaria digitata* off the coast of Brittany, France

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FIGURE 30
Harvesting *Laminaria hyperborea* in Norway. The crane has just lifted aboard the rake and its load of seaweed. Prongs of the rake are visible on the right-hand end.

FMC BIOPOLYMER

The scoubidou is a curved iron hook which is suspended from a hydraulic arm mounted on the boat. The scoubidou is lowered into the *L. digitata* bed and rotated. The blades of the seaweed are wound around the rotating scoubidou and the hydraulic arm pulls them out of the sea (Figure 29). Short blades are missed by the device and form the next year's crop. The scoubidou boats operate from May to October, and during the winter are used to collect scallops. Restrictions are placed on the number of boats and their daily harvest to prevent overharvesting of the beds, since demand in France well exceeds its supply of *L. digitata*.

Laminaria hyperborea

Beach-cast material has been collected for several decades in Ireland, and in the United Kingdom from the Outer Hebrides and Orkney Islands. The stipes (stems) of this species are thick, strong and have a high content of a good quality alginate and usually it is just the stipes that are collected and dried. In Norway the alginate industry originally used *L. digitata* but as the company expanded its market, it became necessary to exploit the

L. hyperborea “forests”. A harvesting vessel was designed specifically for this purpose. The harvesting is done by dragging a large rake-like device through the seaweed bed where it cuts the plant near the holdfast. It is fixed to a crane on the boat and after about two minutes of dragging the crane lifts the rake and its catch (about 2 tonne) into the boat (Figure 30). A boat can carry up to 130 tonne, and when full it takes its load to a storage silo where it is chopped and stored in a formalin solution. When more raw material is required by the factory, it is then taken there by a larger ship. The harvesting areas are divided into five parts and harvesting is by rotation every fifth year, allowing the beds to recover. A study has found that while harvesting by this method removed all the adult kelp plants, small kelp plants were left undisturbed and, with the improved light conditions, they grew to a height of at least 1 m within 2-3 years.

Macrocystis pyrifera

Macrocystis pyrifera grows in relatively deep water (8–25 m) and is harvested by “mowing” it. A vessel is equipped at the front or rear with reciprocating cutters, reaching across the width of the vessel and about 2 m vertically on each side, in a “U” shape. Mounted behind the cutters is a sloping wire mesh belt (Figure 31). As the vessel approaches the seaweed bed, the entire assembly of cutters and wire mesh belt is lowered about one metre into the water. The normal habit of *Macrocystis* is to grow to the surface and as it continues to grow it floats along the surface (Figure 26). The cutters cut the stipe (stalk) about one metre below the surface and the forward motion of the vessel forces the seaweed onto the moving belt. This transports the seaweed up and into an open hold that runs for most of the length of the vessel. A mechanically driven rake is used to spread the seaweed evenly over the hold. The vessels in California are large and capable of carrying several hundred tonnes of seaweed per trip.

4.5 CULTIVATION OF SEAWEEDS

None of the usual seaweeds for alginate production are cultivated. They cannot be grown by vegetative means, but must go through a reproductive cycle involving an alternation

FIGURE 31

Cutters mounted on the front of a vessel for harvesting *Macrocystis pyrifera*. When harvesting, the reciprocating cutters and conveyor belt are lowered one metre below the surface and the cut seaweed is forced onto the belt by the forward motion of the vessel.

of generations, as outlined in Section 1.5. For alginate production, this makes cultivated brown seaweeds too expensive when compared to the costs of harvesting and transporting wild seaweeds. The only exception is for *Laminaria japonica*, which is cultivated in China for food but sometimes surplus material is diverted to the alginate industry in China.

4.6 QUANTITIES HARVESTED

The statistics in the following paragraph have been taken mainly from Critchley and Ohno (1998). Many of the values refer to 1995 or 1996 harvests; those for Chile are for 1999. Note that, unless otherwise stated, all the values are in wet tonnes. There are three exceptions, and they are clearly marked as being dry tonnes.

Ascophyllum: Ireland – 32 000; Norway – 25 000; France – 14 000 but used for animal feed as well as alginate extraction; United Kingdom – 8 000; Iceland – see under *L. digitata*.

Durvillaea: Australia – 4 000 dry tonnes; Chile – 2 000.

Ecklonia: South Africa – 500 dry tonnes.

Laminaria digitata: France – 60 000; Iceland harvests both *L. digitata* and *Ascophyllum* and uses geothermal hot water to produce a combined 6 000 tonnes of dried seaweed.

Laminaria hyperborea: Norway – 170 000; United Kingdom – 5 000; Ireland – 2 500; France – 1 000.

Lessonia: Chile – 110 000.

Macrocystis pyrifera: United States of America – 80 000; Mexico – 30 000; Chile – 6 000.

Sargassum/Turbinaria: India – 1 900–3 800 dry tonnes; Indonesia has an alginate factory with a capacity of 300 tonne requiring an input of about 3 000 dry tonnes of *Sargassum,* but the actual harvest is not available.

Table 4 shows estimates of harvests of alginophyte, all in dry tonnes, grouped into broad geographical regions.

TABLE 4
Alginophyte resources (tonnes dry weight; 2001)

	Ascophyllum	
Europe	20 000	16 percent
	Durvillaea	
Asia-Pacific	4 500	3.5 percent
	Ecklonia	
Africa	3 000	2.5 percent
	Lessonia	
Americas	20 500	16 percent
	Laminaria	
Europe	30 500	34 percent
Asia-Pacific	13 000	
	Macrocystis	
Americas	35 000	28 percent
Total	126 500	

Source: H. Porse, CP Kelco ApS, *pers. comm.,* 2002

4.7 MARKETS

The alginate industry is concentrated into fewer producers than the agar industry so the number of buyers of alginophytes is quite small compared to the market for agarophytes. Nevertheless the alginate producers are still competitive in their buying. They need to secure their sources and like to draw their supplies from a variety of geographic areas so that if one is affected by climatic conditions (e.g. El Niño) there are alternative supplies available. Following recent mergers and acquisitions in the industry, there are now four major alginate producers in Europe and the United States of America; two in Japan; and a smaller one in each of Chile and Indonesia. There are about 20 producers in China, though many are of the cottage industry type; they use mostly *Laminaria japonica* cultivated in China, but the larger processors also buy seaweed from Chile.

The large alginate producers need to ensure continuity of supply of raw material. The original factories were established where the seaweed was available and any sources located near each producer are usually contracted to that producer. Thus the seaweeds in Ireland and Scotland go to the factory in Scotland; the Norwegian *Laminarias* go to the Norwegian factory in Haugesund; and the giant kelp, *Macrocystis*, on the coast of California, United States of America, goes to the factory in San Diego. The brown seaweeds in Chile are the main source available to any buyer, and there are limited supplies of *Ecklonia maxima* available from South Africa. There are many exporters listed in the Export Directory of ProChile under two items that include both red and brown seaweeds.

The following export brown seaweeds; there may be others in the ProChile lists.

Chile	**South Africa**
Alimentos Multiexport S.A., Santiago.	Taurus Products (Pty) Ltd, Johannesburg
Comercial Cisandina Chile Ltda., Santiago.	
Algas Chile Ltda., Tocopilla.	
Algas Vallenar S.A., Vallenar.	
Seaweeds Chile Lcsa, Chiguayante.	

Alginates from different species of seaweed often have variations in their chemical structure, resulting in different physical properties. For example, some may yield an alginate that gives a strong gel, another a weaker gel; one may readily give a cream/white alginate, another may give that only with difficulty and is best used for technical applications where colour does not matter. There are more reasons why alginate producers prefer to buy a mixture of species of seaweeds, this allows them to blend their products to give properties to suit particular uses. So, price permitting, normally there is a market for any brown seaweed that will yield an alginate of medium to high viscosity or high gel strength. Price must include the cost of transport to the processor's factory and that rules out some rich natural beds, such as those found in the Falkland Islands, Chatham Island (New Zealand) and the Kerguelen Islands.

4.8 FUTURE PROSPECTS

At present, with a worldwide recession, demand for alginate is flat, but will improve as economic conditions recover, particularly in the textile industry. Because the supply of brown seaweeds from southern California–Baja California and Chile can be curtailed, sometimes severely, by El Niño events, processors are always interested in finding new sources. Well-dried brown seaweeds can also be stored for lengthy periods, so processors are willing to stockpile their raw materials. There appears to be a steady market for alginophytes, though not one that will expand very rapidly.

5. Alginate

5.1 ALGINATE PRODUCTION METHODS

5.1.1 Sodium alginate

"Alginate" is the term usually used for the salts of alginic acid, but it can also refer to all the derivatives of alginic acid and alginic acid itself; in some publications the term "algin" is used instead of alginate. Alginate is present in the cell walls of brown algae as the calcium, magnesium and sodium salts of alginic acid. The goal of the extraction process is to obtain dry, powdered, sodium alginate. The calcium and magnesium salts do not dissolve in water; the sodium salt does. The rationale behind the extraction of alginate from the seaweed is to convert all the alginate salts to the sodium salt, dissolve this in water, and remove the seaweed residue by filtration. The alginate must then be recovered from the aqueous solution. The solution is very dilute and evaporation of the water is not economic. There are two different ways of recovering the alginate.

The first is to add acid, which causes alginic acid to form; this does not dissolve in water and the solid alginic acid is separated from the water. The alginic acid separates as a soft gel and some of the water must be removed from this. After this has been done, alcohol is added to the alginic acid, followed by sodium carbonate which converts the alginic acid into sodium alginate. The sodium alginate does not dissolve in the mixture of alcohol and water, so it can be separated from the mixture, dried and milled to an appropriate particle size that depends on its particular application.

The second way of recovering the sodium alginate from the initial extraction solution is to add a calcium salt. This causes calcium alginate to form with a fibrous texture; it does not dissolve in water and can be separated from it. The separated calcium alginate is suspended in water and acid is added to convert it into alginic acid. This fibrous alginic acid is easily separated, placed in a planetary type mixer with alcohol, and sodium carbonate is gradually added to the paste until all the alginic acid is converted to sodium alginate. The paste of sodium alginate is sometimes extruded into pellets that are then dried and milled.

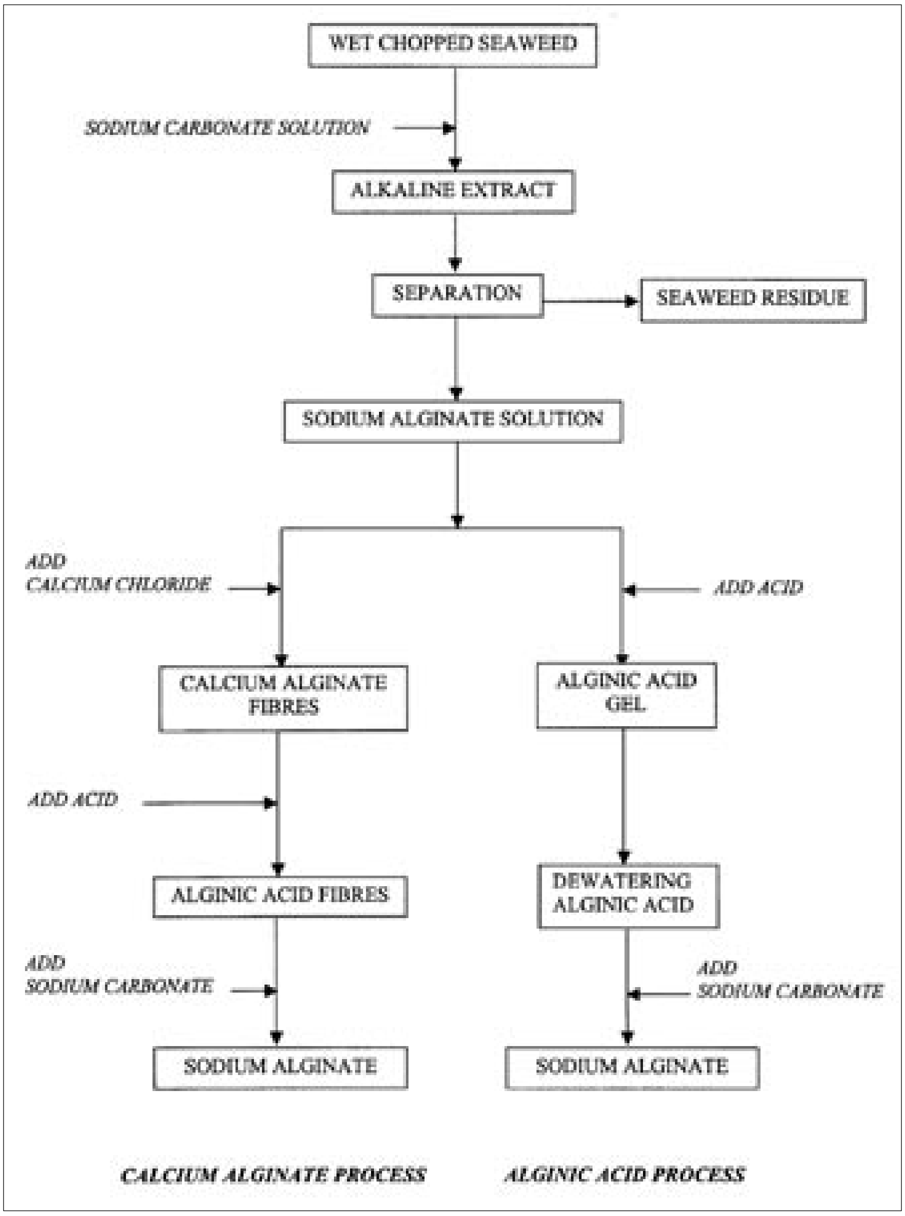
These essentials of the process are illustrated in the flow diagram in Figure 32.

The process appears to be straightforward, certainly the chemistry is simple: convert the insoluble alginate salts in the seaweed into soluble sodium alginate; precipitate either alginic acid or calcium alginate from the extract solution of sodium alginate; convert either of these back to sodium alginate, this time in a mixture of alcohol and water, in which the sodium salt does not dissolve.

The difficulties lie in handling the materials encountered in the process, and to understand these problems a little more detail of the process is required.

To extract the alginate, the seaweed is broken into pieces and stirred with a hot solution of an alkali, usually sodium carbonate. Over a period of about two hours, the alginate dissolves as sodium alginate to give a very thick slurry. This slurry also contains the part of the seaweed that does not dissolve, mainly cellulose. This insoluble residue must be removed from the solution. The solution is too thick (viscous) to be filtered and must be diluted with a very large quantity of water. After dilution, the solution is forced through a filter cloth in a filter press. However, the pieces of undissolved residue are very fine and can quickly clog the filter cloth. Therefore, before filtration is started, a filter aid, such as diatomaceous earth, must be added; this holds most of the fine particles away from the surface of the filter cloth and facilitates filtration. However, filter aid is expensive and can make a significant contribution to costs. To reduce the quantity of filter aid needed, some processors force air into the extract as it is being diluted with water (the extract and

FIGURE 32
Flow chart for the production of sodium alginate (after McHugh, 1987).



diluting water are mixed in an in-line mixer into which air is forced). Fine air bubbles attach themselves to the particles of residue. The diluted extract is left standing for several hours while the air rises to the top, taking the residue particles with it. This frothy mix of air and residue is removed from the top and the solution is withdrawn from the bottom and pumped to the filter.

The next step is precipitation of the alginate from the filtered solution, either as alginic acid or calcium alginate.

Alginic acid method

When acid is added to the filtered extract, alginic acid forms in soft, gelatinous pieces that must be separated from the water. Again flotation is often used; filtration is not possible because of the soft jelly-like nature of the solid. If an excess of sodium carbonate is used in the original extraction, this will still be present in the filtered extract so that when acid is added, carbon dioxide will form. Fine bubbles of this gas attach themselves to the pieces of alginic acid and lift them to the surface where they can be continuously scrapped away. The processor now has a jelly-like mass of alginic acid that actually contains only 1–2 percent alginic acid, with 98–99 percent water. Somehow, this water content must be reduced. It is too soft to allow the use of a screw press. Some processors place the gel in basket-type centrifuges lined with filter cloth. Centrifuging can increase the solids to 7–8 percent and this is sufficient if alcohol is to be used in the next step of converting it to sodium alginate. It is also now sufficiently firm to be squeezed in a screw press. The 7–8 percent alginic acid is place in a mixer and, allowing for the water contained in the alginic acid, enough alcohol (usually ethanol or isopropanol) is added to give a 50:50 mixture of alcohol and water. Then solid sodium carbonate is added gradually until the resulting paste reaches the desired pH. The paste of sodium alginate can be extruded as pellets, oven dried and milled.

Calcium alginate method

When a soluble calcium salt, such as calcium chloride, is added to the filtered extract, solid calcium alginate is formed. If the calcium solution and filtered extract are mixed carefully, the calcium alginate can be formed as fibres – bad mixing gives a gelatinous solid. This fibrous material can be readily separated on a metal screen (sieve) and washed with water to remove excess calcium. It is then stirred in dilute acid and converted to alginic acid, which retains the fibrous characteristics of the calcium alginate. This form of alginic acid can be easily squeezed in a screw press. A screw press with a graduated-pitch screw is usually used; the squeezing action must be applied very gradually, otherwise the material will just move backwards and out of the press. The product from the screw press looks relatively solid but still contains only 20–25 percent alginic acid. However, it is dry enough to form a paste when sodium carbonate is mixed with it to convert it to sodium alginate. Sodium carbonate is added to the alginic acid in a suitable type of mixer until the required pH is reached, then the paste is extruded as pellets, dried and milled.

The disadvantage of this second method, compared to the alginic acid method, is that an extra step is added to the process. The advantage is that the handling of the fibrous calcium alginate and alginic acid is much simpler and alcohol is not needed. Alcohol is expensive and while it is usually recovered and recycled, recovery is never 100 percent, so its use adds to the costs.

Other important factors in alginate production are colour control of the product, water supply and waste disposal.

If the original seaweed is highly coloured, e.g. *Ascophyllum*, the alkaline extract will also be highly coloured and the process will eventually yield a dark product that commands only a low price as it is limited to use in technical applications. Lighter coloured seaweeds, such as *Macrocystis*, yield a lighter coloured alginate suitable for food and other applications. Colour can be controlled by the use of bleach – sodium hypochlorite – that is added to the filtered alkaline extract or even to the paste at the final conversion stage. Care must be taken, since excessive bleach can lower the viscosity of the alginate, reducing its value. Sometimes the seaweed is soaked in a formalin solution before it is extracted with alkali. The formalin helps to bind the coloured compounds to the cellulose in the cell walls, so much of the colour is left behind in the seaweed residue when the alkaline extract is filtered.

Large quantities of water are used in the process, especially when diluting the thick (viscous) initial alkaline extract to a viscosity suitable for filtration. A plentiful and reliable water supply is a necessity for an alginate factory to survive.

Waste waters from filtration are alkaline, they contain calcium from the calcium precipitation (excess calcium gives a more fibrous calcium alginate) and acid from the acid conversion step. In some countries the waste is pumped out to sea. Where environmental concerns are greater, or when water supplies are limited, recycling is not too difficult and its costs may be partly offset by the lowering of the quantity and cost of water used by the factory. A means of disposing of solid wastes – the seaweed residue and used filter aid – must be found. There have been several positive studies reported on the use of this waste to adsorb heavy metals, such as cadmium, zinc and copper, from industrial liquid wastes (e.g. Romero-Gonzalez, Williams and Gardiner, 2001). Attempts to ferment this waste to produce ethanol from the cellulose content appear to be less promising, in economic terms (Horn, Aasen and Oestgaard, 2000).

For further details

In the above descriptions of the production process, suggestions about the detail of reagent concentrations, time, temperatures, etc., have been deliberately omitted to simplify the reading of it. Commercial processors regard these details as confidential and do not publish them. However, some detail can be found in McHugh (1987) and in the results of a series of trials, run on a pilot-plant scale using *Macrocystis* as raw material, published by Hernández-Carmona *et al.* (1998), Hernández-Carmona, McHugh and López-Gutiérrez (1999), McHugh *et al.* (2001) and Hernández-Carmona *et al.* (2002).

5.1.2 Other alginate products

Sodium alginate, produced as described above, is the main form of alginate in use. Smaller quantities of alginic acid and the calcium, ammonium and potassium salts, and an ester, propylene glycol alginate, are also produced. Calcium alginate and alginic acid are made during the calcium alginate process for making sodium alginate; each can be removed at the appropriate stage and, after thorough washing, can be dried and milled to a required particle size. The other salts are made by neutralization of moist alginic acid with the appropriate alkali, usually ammonium hydroxide or potassium carbonate; sufficient water or alcohol can be added to keep the material at a workable consistency; they are processed as described for the paste-conversion method in the calcium alginate process for sodium alginate production.

Propylene glycol alginate, an ester of alginic acid, has different properties and uses from the salts such as sodium alginate. It was first patented in 1947 and has been the subject of further patents as methods for its production were improved. It is made by taking moist alginic acid (20 percent or greater solids) that has been partially reacted with sodium carbonate, and treating it with liquid propylene oxide in a pressure vessel for 2 hours at about 80°C. The product is dried and milled. Further details and references to the patents can be found in McHugh (1987).

5.2 ALGINATE PRODUCERS

The capacities of alginate producers are summarized according to their broad geographical location and given in Table 5, and the principal alginate producers are listed below.

ISP Alginates (UK) Ltd
Waterfield
Tadworth
Surrey KT20 5HQ
United Kingdom
Tel: [INT+44] + (1737) 377 000
Fax: [INT+44] + (1737) 377148
Website: www.ispcorp.com/products/alginates

FMC Biopolymer
1735 Market Street
Philadelphia PA 19103
United States of America
Tel: [INT+1] + (215) 299 6000
Fax: [INT+1] + (215) 299 5809
Websites: www.fmc.com; www.fmcbiopolymer.com

TABLE 5

Alginate processors. Capacity in tonnes (2001)

	Ca & acid process	PGA	Total	%
Europe	16 000	-	16 000	44
Africa	-	-	-	-
Americas	3 000	1 500	4 500	13
Asia-Pacific	14 000	1 600	15 600	43
Total	33 000	3 100	36 100	

Source: H. Porse, CP Kelco ApS, 2002, *pers. comm.*

Degussa Texturant Systems
Lise-Meitner-St.34
85354 Freising
Germany
Tel: [INT+49] + (8161) 548 266
Fax: [INT+49] + (8161) 548 582
Website: www.texturantsystems.com

Danisco Cultor
Edwin Rahrs Vej 38
8220 Brabrand
Denmark
Tel: [INT+45] + 89 43 50 00
Fax: [INT+45] + 86 25 06 81
Website: www.daniscocultor.com

Kimica Corporation
15-4 Uchikanda 2 - chome
Chiyoda-ku
Tokyo
Japan
Tel: [INT+81] + (3) 3252 8708
Fax: [INT+81] + (3) 3252 8704
Website: www.kimica.com

Fuji Chemical Industry Co Ltd
1570, Nakanoshima
Wakayama City
Japan
Tel: [INT+81] + (73) 423 1247
Fax: [INT+81] + (73) 431 3005
Website: www.waila.or.jp/kasei

Algisa, Compania Industrial de Alginatos S.A.
PO Box 51645
Santiago 1
Chile
Tel: [INT+56] + 2 738 7904
Fax: [INT+56] + 2 738 7038

China Seaweed Industrial Association
Room 203 - Building 18 Maizidian Street -
Chaoyang Dist. Beijing 100026
China
Tel: [INT+86] + 10 6419 5140
Fax: [INT+86] + 10 6419 5141
This seems to be sponsored by the Ministry of Fisheries and represents the alginate industry.

5.3 ALGINATE USES

The uses of alginates are based on three main properties. The first is their ability, when dissolved in water, to thicken the resulting solution (more technically described as their ability to increase the viscosity of aqueous solutions). The second is their ability to form gels; gels form when a calcium salt is added to a solution of sodium alginate in water. The gel forms by chemical reaction, the calcium displaces the sodium from the alginate, holds the long alginate molecules together and a gel is the result. No heat is required and the gels do not melt when heated. This is in contrast to the agar gels where the water must be heated to about 80°C to dissolve the agar and the gel forms when cooled below about 40°C. The third property of alginates is the ability to form films of sodium or calcium alginate and fibres of calcium alginates.

Alginate molecules are long chains that contain two different acidic components, abbreviated here for simplicity to M and G. The way in which these M and G units are arranged in the chain and the overall ratio, M/G, of the two units in a chain can vary from one species of seaweed to another. In other words all "alginates" are not necessarily the same. So some seaweeds may produce an alginate that gives a high viscosity when dissolved in water, others may yield a low viscosity alginate. The conditions of the extraction procedure can also affect viscosity, lowering it if conditions are too severe. All of this results in sellers normally offering a range of alginates with differing viscosities.

Similarly, the strength of the gel formed by the addition of calcium salts can vary from one alginate to another. Generally alginates with a higher content of G will give a stronger gel; such alginates are said to have a low M/G ratio.

Some examples: *Macrocystis* can gives a medium-viscosity alginate, or a high viscosity with a careful extraction procedure (lower temperature for the extraction). *Sargassum* usually gives a low viscosity product. *Laminaria digitata* gives a soft to medium strength gel, while *Laminaria hyperborea* and *Durvillaea* give strong gels. These are some of the reasons why alginate producers like to have a variety of seaweed sources, to match the alginate to the needs of particular applications.

5.3.1 Textile printing

In textile printing, alginates are used as thickeners for the paste containing the dye. These pastes may be applied to the fabric by either screen or roller printing equipment. Alginates became important thickeners with the advent of reactive dyes. These combine chemically with cellulose in the fabric. Many of the usual thickeners, such as starch, react with the reactive dyes, and this leads to lower colour yields and sometimes by-products that are not easily washed out. Alginates do not react with the dyes, they easily wash out of the finished textile and are the best thickeners for reactive dyes. Alginates are more expensive than starch and recently starch manufacturers have made efforts to produce modified starches that do not react with the reactive dyes, so it is becoming a more competitive market. This use of alginate represents a large market, but it is affected by economic recessions when there is often a fall in demand for clothing and textiles. The types of alginate required vary from medium-to-high viscosity with older screen printing equipment, to low viscosity if modern, high speed, roller printing is used. Textile printing accounts for about 50 percent of the global alginate market.

5.3.2 Food

The thickening property of alginate is useful in sauces and in syrups and toppings for ice cream. By thickening pie fillings with alginate, softening of the pastry by liquid from the filling is reduced. Addition of alginate can make icings non-sticky and allow the baked goods to be covered with plastic wrap. Water-in-oil emulsions such as mayonnaise and salad dressings are less likely to separate into their original oil and water phases if thickened with alginate. Sodium alginate is not useful when the emulsion is acidic, because insoluble alginic acid forms; for these applications propylene glycol alginate (PGA) is used since this is stable in mild acid conditions. Alginate improves the texture, body and sheen of yoghurt, but PGA is also used in the stabilization of milk proteins under acidic conditions, as found in some yoghurts. Some fruit drinks have fruit pulp added and it is preferable to keep this in suspension; addition of sodium alginate, or PGA in acidic conditions, can prevent sedimentation of the pulp. In chocolate milk, the cocoa can be kept in suspension by an alginate/phosphate mixture, although in this application it faces strong competition from carrageenan. Small amounts of alginate can thicken and stabilize whipped cream.

For more information about factors that affect the viscosity of alginate solutions, see King (1983: 132–141). This discusses the effects of concentration of alginate, its molecular weight, the presence of any calcium remaining in the alginate from the extraction process, pH, temperature and other salts. For a briefer discussion, see McHugh (1987) or Clare (1993).

Alginates have some applications that are not related to either their viscosity or gel properties. They act as stabilizers in ice cream; addition of alginate reduces the formation of ice crystals during freezing, giving a smooth product. This is especially important when ice cream softens between the supermarket and the home freezer; without alginate or similar stabilizer the refrozen ice cream develops large ice crystals, giving it an undesirable crunchy mouth feel. Alginate also reduces the rate at which the ice cream will melt. Beer drinkers prefer some foam on the top of a newly-poured glass, and a poor foam leads to a subjective judgement that the beer is poor quality. Addition of a very low concentration of propylene glycol alginate will provide a stable, longer lasting beer foam. A variety of agents are used in the clarification of wine and removal of unwanted colouring – wine fining – but in more difficult cases it has been found that the addition of sodium alginate can be effective.

The gelling properties of alginate were used in the first production of artificial cherries in 1946. A flavoured, coloured solution of sodium alginate was allowed to fall, in large drops, into a solution of a calcium salt. Calcium alginate immediately formed as a skin on the outside of the drop and when the drop was allowed to sit in the solution, the calcium gradually penetrated the drop converting it all into a gel that hardened with further standing. Because the cherry-flavoured gels did not melt, they became very popular in bakery products. Fruit substitutes can now be made by automated and continuous processes that are based on similar principles. Either the calcium can be applied externally, as above, or internally. In the latter case a calcium salt that does not dissolve is added to the fruit puree, together with a weak acid; the weak acid slowly attacks the calcium salt and releases water-soluble calcium that then reacts with the alginate and forms the gel.

Edible dessert jellies can be formed from alginate-calcium mixtures, often promoted as instant jellies or desserts because they are formed simply by mixing the powders with water or milk, no heat being required. Because they do not melt, alginate jellies have a different, firmer mouth feel when compared to gelatin jellies, which can be made to soften and melt at body temperature. Mixtures of calcium salts and sodium alginate can be made to set to a gel at different rates, depending on the rate at which the calcium salt dissolves. Gel formation can also be delayed even after everything is mixed together; this is done using a gel-retarder that reacts with the calcium before the alginate does, so no calcium is available to the alginate until all the retarder is used. In this way gel formation can be delayed for several minutes if desired, such as when other ingredients need to be added and mixed before the gel starts to set.

Alginate gels are used in re-structured or re-formed food products. For example, re-structured meats can be made by taking meat pieces, binding them together and shaping them to resemble usual cuts of meat, such as nuggets, roasts, meat loaves, even steaks. The binder can be a powder of sodium alginate, calcium carbonate, lactic acid and calcium lactate. When mixed with the raw meat they form a calcium alginate gel that binds the meat pieces together. This is used for meats for human consumption, such as chicken nuggets; it has become especially useful in making loaves of meat for fresh pet food; some abattoir wastes are suitable and cheap ingredients. Up to 1 percent alginate is used. Similar principles are applied to making shrimp substitutes using alginate, proteins such as soy protein concentrate, and flavours. The mixture is extruded into a calcium chloride bath to form edible fibres which are chopped, coated with sodium alginate and shaped in a mould. Restructured fish fillets have been made using minced fish and a calcium alginate gel. Onion rings are made from dried onion powder; pimento olive fillings are made using pimento pulp. In 2001, a new line of olives launched in Spain were stuffed with flavoured pastes, such as garlic, herbs, hot pepper, lemon and cheese. Each of these is made with green manzanilla olives and an alginate-based paste containing the appropriate ingredient to provide the flavour.

Calcium alginate films and coatings have been used to help preserve frozen fish. The oils in oily fish such as herring and mackerel can become rancid through oxidation even when quick frozen and stored at low temperatures. If the fish is frozen in a calcium alginate jelly, the fish is protected from the air and rancidity from oxidation is very limited. The jelly thaws with the fish so they are easily separated. If beef cuts are coated with calcium alginate films before freezing, the meat juices released during thaw are re-absorbed into the meat and the coating also helps to protect the meat from bacterial contamination. If desired, the calcium alginate coating can be removed by re-dissolving it with sodium polyphosphate.

For further details

For more information about alginate gels, how they form, calcium salts to use, retardants, acid-release agents, and effect of alginates from different seaweeds, the most thorough discussion is to be found in King (1983: 141–154). While this may appear to be an old reference, these basics of gel formation are still the same. Other, briefer, treatments of gel formation are available in Clare (1993), Nussinovitch (1997) or Onsoyen (1997).

Re–structured foods are discussed in Chapter 20 in Nussinovitch (1997).

A brief tabular summary of alginate applications in food can be found in Onsoyen (1997).

5.3.3 Immobilized biocatalysts

Many commercial chemical syntheses and conversions are best carried out using biocatalysts such as enzymes or active whole cells. Examples include the use of enzymes for the conversion of glucose to fructose, the production of L-amino acids for use in foods, the synthesis of new penicillins after hydrolysis of penicillin G, the use of whole cells for the conversion of starch to ethanol (for beer brewing), and the continuous production of yoghurt. To carry out these processes on a moderate to large scale, the biocatalysts must be in a concentrated form and be recoverable from the process for re-use.

This can be achieved by "immobilizing" the enzymes or cells by entrapping them in a material that will still allow penetration by the substance to be converted or changed. Originally, single enzymes were isolated and used for a specific conversion, but now similar or better results can be obtained using whole cells, and this is more economical. An added advantage of immobilization is that the cells last longer. Ordinary suspended cells may have good activity for only 1–2 days, while immobilized cells can last for 30 days. Beads made with calcium alginate were one of the first materials to be used for immobilization. The whole cells are suspended in a solution of sodium alginate and this is added dropwise to a calcium chloride solution. The beads form in much the same way as described for artificial cherries. In use, they are packed into a column and a solution of the substance to be converted is fed into the top of the column and allowed to flow through the bed of beads containing the immobilized biocatalyst in the cells. The conversion takes place and the product comes out at the bottom. A simple example is to immobilize yeast cells, flow a solution of sugar through the beads, and the sugar is converted to alcohol.

For further details

Details of methods for making immobilized materials using alginates are available from alginate manufacturers (such as FMC Biopolymers, ISP Alginates, etc.). Today, many other materials besides alginate are used for immobilization. Nussinovitch (1997), in Chapter 15, discusses immobilization by a variety of polymers, including alginate, and gives many examples of its applications.

5.3.4 Pharmaceutical and medical uses

If a fine jet of sodium alginate solution is forced into a bath of a calcium chloride solution, calcium alginate is formed as fibres. If low viscosity alginates are used, a strong solution can be used without any viscosity problems and the calcium bath is not diluted as rapidly. The fibres have very good strength when both wet and dry. As with most polymer fibres formed by extrusion, stretching while forming increases the linearity of the polymer chains and the strength of the fibre. Good quality stable fibres have been produced from mixed salts of sodium and calcium alginate, and processed into non-woven fabric that is used in wound dressings. They have very good wound healing and haemostatic properties and can be absorbed by body fluids because the calcium in the fibre is exchanged for sodium from the body fluid to give a soluble sodium alginate. This also makes it easy to remove these dressings from large open wounds or burns since they do not adhere to the wound. Removal can be assisted by applying saline solutions to the dressing to ensure its conversion to soluble sodium alginate. Recently, the consumer division of a multinational pharmaceutical company launched a new line of adhesive bandages and gauze pads based on calcium alginate fibres. They are being promoted as helping blood to clot faster – twice as fast as their older, well established product.

Alginic acid powder swells when wetted with water. This has led to its use as a tablet disintegrant for some specialized applications. Alginic acid has also been used in some dietary foods, such as biscuits; it swells in the stomach and, if sufficient is taken, it gives a "full" feeling so the person is dissuaded from further eating. The same property of swelling has been used in products such as Gaviscon™ tablets, which are taken to relieve heartburn and acid indigestion. The swollen alginic acid helps to keep the gastric contents in place and reduce the likelihood of reflux irritating the lining of the oesophagus.

Alginate is used in the controlled release of medicinal drugs and other chemicals. In some applications, the active ingredient is placed in a calcium alginate bead and slowly released as the bead is exposed in the appropriate environment. More recently, oral controlled-release systems involving alginate microspheres, sometimes coated with chitosan to improve the mechanical strength, have been tested as a way of delivering various drugs. Pronova Biomedical AS, a leading supplier of ultra-pure alginates and chitosans for controlled release and other medical materials applications, was acquired by FMC Bioploymer in early 2002; FMC had previously acquired Pronova Biopolymer, producer of food and technical grade alginates.

5.3.5 Other applications

Paper

The main use for alginate in the paper industry is in surface sizing. Alginate added to the normal starch sizing gives a smooth continuous film and a surface with less fluffing. The oil resistance of alginate films give a size with better oil resistance and enhances greaseproof properties. An improved gloss is obtained with high gloss inks. If papers or boards are to be waxed, alginate in the size will keep the wax mainly at the surface. They give better coating runability than other thickeners, especially in hot, on-machine coating applications. Alginates are also excellent film formers and improve ink holdout and printability. The quantity of alginate used is usually 5–10 percent of the weight of starch in the size.

Alginate is also used in starch adhesives for making corrugated boards because it stabilizes the viscosity of the adhesive and allows control of its rate of penetration. One percent sodium alginate, based on the weight of starch used, is usually sufficient.

Paper coating methods and equipment have developed significantly since the late 1950s with the demand for a moderately priced coated paper for high quality printing. Trailing blade coating equipment runs at 1 000 m/minute or more, so the coating material, usually clay plus a synthetic latex binder, must have consistent rheological properties under the conditions of coating. Up to 1 percent alginate will prevent change in viscosity of the coating suspension under the high shear conditions where it contacts the roller. The alginate also helps to control water loss from the coating suspension into the paper, between the point where the coating is applied and the point where the excess is removed by the trailing blade. The viscosity of the coating suspension must not be allowed to increase by loss of water into the paper because this leads to uneven removal by the trailing blade and streaking of the coating. Medium to high viscosity alginates are used, at a rate of 0.4–0.8 percent of the clay solids. Because of the solvent resistance of alginate films, the print quality of the finished paper is improved.

Welding rods

Coatings are applied to welding rods or electrodes to act as a flux and to control the conditions in the immediate vicinity of the weld, such as temperature or oxygen and hydrogen availability. The dry ingredients of the coating are mixed with sodium silicate (water-glass) which gives some of the plasticity necessary for extrusion of the coating onto the rod; it also acts as the binder for the dried coating on the rod. However, the wet silicate has no binding action and does not provide sufficient lubrication to allow effective and smooth extrusion. An additional lubricant is needed, and a binder that will hold the damp mass together before extrusion and maintain the shape of the coating on the rod during drying and baking. Alginates are used to meet these requirements. The quantities of alginates used are very dependent on the type of welding rod being coated and the extrusion equipment being used. Alginate manufacturers are the best source of information for using alginates in welding rod applications.

Binders for fish feed

The worldwide growth in aquaculture has led to the use of crude alginate as a binder in salmon and other fish feeds, especially moist feed made from fresh waste fish mixed with various dry components. Alginate binding can lower consumption by up to 40 percent and pollution of culture ponds is sharply reduced.

Release agents

The poor adhesion of films of alginate to many surfaces, together with their insolubility in nonaqueous solvents, have led to their use as mould release agents, originally for plaster moulds and later in the forming of fibreglass plastics. Sodium alginate also makes a good coating for anti-tack paper, which is used as a release agent in the manufacture of synthetic resin decorative boards. Films of calcium alginate, formed *in situ* on a paper, have been used to separate decorative laminates after they have been formed in a hot-pressing system.

5.4 MARKETS AND MARKETING OF ALGINATES

A summary of alginate markets is shown in Table 6. The total market has a value of about US$ 195 million.

There are difficulties and costs in the marketing of seaweed hydrocolloids, such as alginate, agar and carrageenan, which are not always apparent to those outside the industry. In some markets, one may compete with another; in others, one might be the only real choice. They must all compete, in at least some of their uses, with plant gums (such as guar and locust bean) and cellulose derivatives (such as carboxy methyl cellulose (CMC) and methyl cellulose) that are often cheaper. It is important to realize that price may not be the determining factor in a buyer's choice of a seaweed hydrocolloid; quality and its reproducibility from one batch to another may be more important. Frequently a buyer uses less than 1 percent of the hydrocolloid in his product, so a 20 percent price difference may be inconsequential in the total cost of a product. Many a buyer of seaweed hydrocolloids, satisfied with one particular brand or grade, will, despite a higher price, stay with it because the risks of changing may not seem to be worth the saving. So, in seaweed hydrocolloids, those brands already established in the market often hold a very strong, entrenched position. To dislodge them, a marketing group should include a strong technical team that can run tests and trials to convince the buyer of the equivalence of the new product; sometimes this requires a detailed knowledge of the buyer's industry. In promoting new sales, the hydrocolloid producer may have to provide complete formulations and technical know-how to potential buyers. Therefore selling costs of the seaweed hydrocolloids can be high and account must be taken of this by the potential producer.

The buyers of alginates fall into two groups. The first is a number of large buyers who know exactly what they want and who require little servicing because they have their own resources. This group includes those speciality gum companies who service smaller users by preparing their own blends of seaweed hydrocolloids and other hydrocolloids, according to the requirements of a particular customer.

The second and larger group are the smaller users who need some technical service support. Frequently this group yields more profitable sales in the long term because they may be sold specifically formulated products at a premium price and they are generally more reluctant to change to a competitor's product. At the same time, it takes more time and expense to establish such sales. Many of the major producers have such speciality products, shown by the large range of products listed by them.

Alginate manufacturers usually sell direct to the major markets, but in minor markets it is more economical to sell through an agent, leaving the task of market penetration to them, but providing technical support where necessary. Agents need to have an appreciation of

TABLE 6

Alginate markets (2001)

Application	tonnes	%
Food and pharmaceutical	10 000	33
All technical grades	20 000	67
Total	30 000	

Source: H. Porse, CP Kelco ApS, 2002, *pers. comm.*

the application of hydrocolloids and a knowledge of the client's industry. This ideal might be achieved by an agent selling a variety of chemicals to just one industry, like the food industry, but an agent who deals principally in hydrocolloids over a range of industries, which is a not uncommon situation, usually needs more backup from the producer. Large wholesalers or agents may buy from the producer and re-sell; otherwise they operate on a commission of 5–15 percent, depending partly on the degree of assistance required from the producer.

The above paragraphs are based on McHugh (1987), but the statements made are just as valid at the time of writing.

5.5 FUTURE PROSPECTS

The overall annual growth rate for alginates is 2–3 percent, with textile printing applications accounting for about half of the global market. However, the textile industry is flat at present, as it rides a trough in the cycle of peaks and troughs, and it is 90 percent based in Asia and the Near East (Turkey). Pharmaceutical and medical uses are about 20 percent by value of the market and have stayed buoyant, with 2–4 percent annual growth rates, driven by ongoing developments in controlled release technologies and the use of alginates in wound care applications. Food applications are worth about 20 percent of the market. That sector has been growing only slowly, and recently has grown at only 1–2 percent annually. The paper industry takes about 5 percent and the sector is very competitive, not increasing but just holding its own. The alginate industry faces strong competition from Chinese producers, whose prices do not reflect the real expense of cultivating *Laminaria japonica*, even in China, yet they do not appear to import sufficient wild seaweeds to offset those costs. The result is low profitability for most of the industry, with the best opportunities lying in the high end of the market, such as pharmaceutical and medical applications.

6. Seaweeds used as a source of carrageenan

6.1 GENERA AND SPECIES USED

Most carrageenan is extracted from *Kappaphycus alvarezii* and *Eucheuma denticulatum*. The original source of carrageenan was *Chondrus crispus*, and this is still used to a limited extent. *Betaphycus gelatinum* is used for a particular type of carrageenan. Some South American species that have previously been used to a limited extent are now gaining favour with carrageenan producers as they look for more diversification in the species available to them and the types of carrageenan that can be extracted. *Gigartina skottsbergii*, *Sarcothalia crispata* and *Mazzaella laminaroides* are currently the most valuable species, all collected from natural resources in Chile. Small quantities of *Gigartina canaliculata* are harvested in Mexico. *Hypnea musciformis* has been used in Brazil.

Over the last few years most of these seaweeds have been reclassified by marine biologists as they gain more knowledge of their structure. If readers are to go beyond this publication for further information, they need to be familiar with the both the old and new names, as listed below.

- *Betaphycus gelatinum* was *Eucheuma gelatinae*.
- *Chondrus crispus* remains unchanged, and is commonly known as "Irish Moss."
- *Eucheuma cottonii* is now *Kappaphycus alvarezii*, and commercially was and is called "cottonii".
- *Eucheuma denticulatum* was *Eucheuma spinosum* and commercially was and is called "spinosum".
- *Eucheuma gelatinae* is now *Betaphycus gelatinum*.
- *Eucheuma spinosum* is now *Eucheuma denticulatum* and commercially was and is called "spinosum".
- *Gigartina canaliculata* remains unchanged.
- *Gigartina skottsbergii* remains unchanged.
- *Gigartina stellata*, mentioned in earlier articles but now not so important, is now *Mastocarpus stellatus*.
- *Hypnea musciformis* remains unchanged.
- *Iridaea ciliata* is now *Sarcothalia crispata*.
- *Iridaea laminaroides* is now *Mazzaella laminaroides.*
- *Kappaphycus alvarezii* was *Eucheuma cottonii* and commercially was and is called "cottonii".
- *Mazzaella laminaroides* was *Iridaea laminaroides*.
- *Mastocarpus stellatus* was *Gigartina stellata*, mentioned in earlier articles but now not so important.
- *Sarcothalia crispata* was *Iridaea ciliata*.

6.2 NATURAL HABITATS

The definitions of the vertical zones of the shore, littoral fringe, eulittoral and sublittoral were given in Section 2.2.

Kappaphycus alvarezii (Figures 33 and 34) is found in the upper part of the sublittoral zone, from just below the low tide line, of reef areas on sandy-corally to rocky substrates where water flow is slow to moderate.

FIGURE 33
Fresh *Kappaphycus alvarezii.*

FIGURE 34
Dried *Kappaphycus alvarezii.*

FIGURE 35
***Betaphycus gelatinum* drying (Hainan Island, China).**

Eucheuma denticulatum thrives on sandy-corally to rocky substrates in areas constantly exposed to moderate to strong water currents.

Betaphycus gelatinum (Figure 35) grows on rocky, coralline substrates, a few metres from the reef-edge, where it is exposed to strong wave action and turbulence.

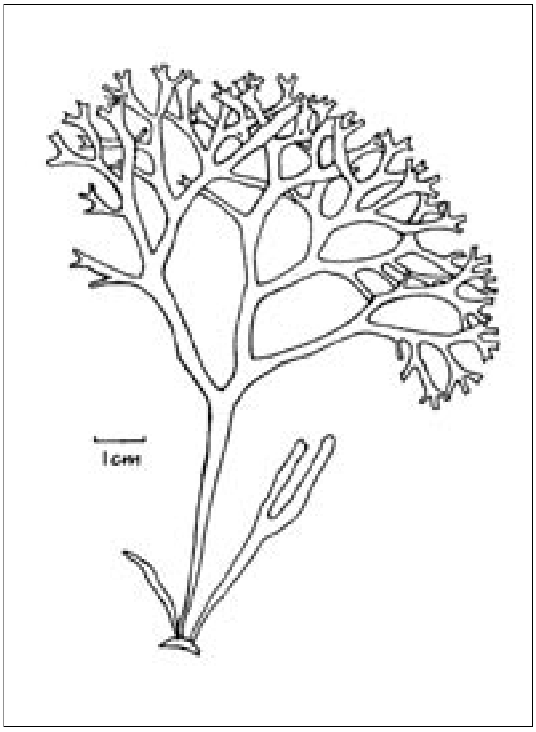
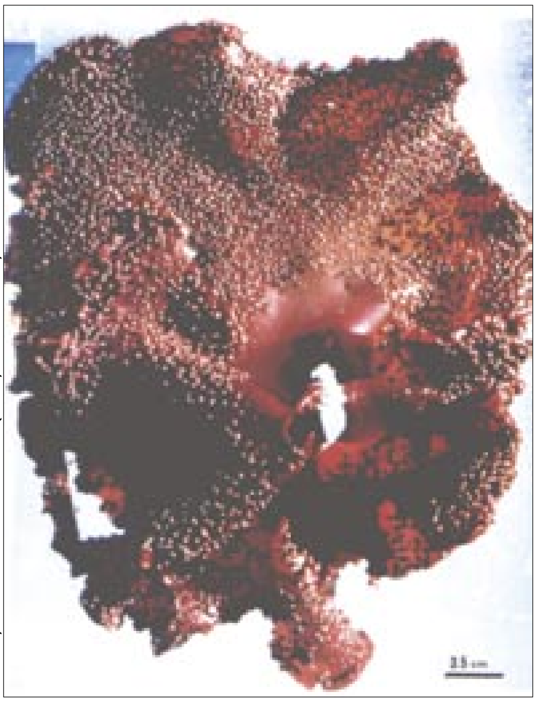


FIGURE 36
Chondrus crispus. **(after Hansen, Packard and Doyle, 1981).**



M. AVILA, INSTITUTO DE FOMENTO PESQUERO, PUERTO MONTT, CHILE

FIGURE 37
Gigartina skottsbergii

All three require water temperatures of 21°C or more and they thrive in bright light.

Chondrus crispus (Figure 36) grows from the littoral fringe to 20 m below mean low water, depending on the wave motion, transparency and rocky structures available. Usually it is most abundant from mean low water to the mid-sublittoral zone. It grows best on stable rock ledges and large boulders, preferring horizontal shelves, growing not so well on smaller rocks or sediment-covered rocks. Strongest growth is in late spring and summer; least growth is in winter.

Gigartina skottsbergii (Figure 37) grows in the sublittoral at depths of 9–15 m. It grows best in the summer.

Sarcothalia crispata is found from the eulittoral to the sublittoral, down to a depth of 10 m.

Mazzaella laminaroides grows in the eulittoral zone on wave-exposed sites, also in estuaries. Where people collect intertidal gastropods (potential algal grazers), the growth of *Mazzaella laminaroides* flourishes.

Gigartina canaliculata and *Hypnea musciformis* grow in the eulittoral zone.

6.3 SOURCES OF CARRAGEENOPHYTES

Kappaphycus alvarezii and *Eucheuma denticulatum* were originally harvested from natural stocks growing in Indonesia and the Philippines. In the 1970s, cultivation began in both countries and this now supplies most of these species, with only small quantities being collected from the wild. Cultivation has spread to other countries, most successfully in Tanzania (Zanzibar), Viet Nam and some of the Pacific Islands, such as those of Kiribati. Wild *Betaphycus gelatinum* is harvested mainly in Hainan Island, China, Taiwan Province of China and the Philippines, and it is cultivated on Hainan Island.

Chondrus crispus is harvested for carrageenan production in Canada (Nova Scotia and Prince Edward Island), United States of America (Maine and Massachusetts) and France.

Gigartina skottsbergii, *Sarcothalia crispata* and *Mazzaella laminaroides* are all harvested from natural resources in Chile, mainly central Chile from Valparaiso to Chiloe Island.

Some *Gigartina skottsbergii* is also harvested in Argentina.

Gigartina canaliculata is harvested in Mexico (Baja California), and is available from south of Ensenada to Punta San Antonio. *Hypnea musciformis* occurs along most of the coastline of Brazil, but production is erratic in both space and time, increasing the costs of harvesting.

The industry needs about 13 percent of the dry seaweed used annually for production of carrageenan as temperate-water *Gigartina*-like species. These contain lambda carrageenan and a "weak" kappa; the properties of the latter lie between those of a normal kappa (such as obtained from *Kappaphycus alvarezii*) and iota carrageenan. While 1 000–2 000 tonnes come from older sources, such as France and Canada, over 90 percent today comes from Chile. None of the carrageenophytes from Chile is currently cultivated, all come from natural regrowth. Nevertheless there seems to be no evidence of overharvesting and there are areas for expanding the harvest of the most important species, *Gigartina skottsbergii*. This seaweed grows from Puerto Montt to Puenta Avenas. While fishermen are not currently available to harvest along this coastline, an increase in demand would probably stimulate the population shift needed to meet the increase (H.R. "Pete" Bixler, 2002, *pers. comm.*).

6.4 HARVESTING METHODS FOR WILD CARRAGEENOPHYTES

Chondrus crispus has been harvested in Canada since the 1920s, but only came to prominence during the Second World War, when access to Japanese agar stopped and the Irish Moss beds in France also became inaccessible. Production on Prince Edward Island jumped from 5 dry tonnes in 1940 to 900 dry tonnes in 1942. The original collection was from storm tossed seaweed, driven onto the shore by strong winds. Local farmers picked it up from beaches and shores and sometimes waded into the surf with horse-drawn scoops to capture unattached moss. Fishermen took their boats offshore with hand rakes and scrapped the moss from the flat rock shelf where it grew. In the 1970s, large lobster boats equipped with drag rakes and winches were introduced; the steel rakes – about 1 m wide, 25 kg, with about 40 teeth – are dragged across the moss beds. The scale of operation of these boats had a rather severe effect on the regrowth of the beds and perhaps it was fortunate that demand for moss declined sharply as the cultivated *Kappaphycus* and *Eucheuma* became available from the Philippines in the 1980s. With a low demand from carrageenan processors, Irish Moss harvesting has returned to being a part-time fishery, where there is a place for operators equipped with small boats, outboard motors and hand rakes.

For further details of *Chondrus crispus* harvesting in Canada, with very good illustrations of equipment and operations, see Pringle and Mathieson (1986).

Chondrus crispus in France grows mainly around Brittany. However, there are no flat beds, as found in Canada, so the use of dredgers is not possible, only manual gathering. Harvesting is a part-time operation by about 3 000 people, although this number and the harvest are both falling as the living standards of the harvesters rise.

Betaphycus gelatinum on Hainan Island, China, is most abundant about 1 m below the low tide mark and was collected by hand, but cultivation has overtaken this practice.

Gigartina canaliculata grows in the eulittoral zone in Mexico and is harvested from May to September by fishermen, who pull it by hand during low tide.

Mazzaella laminaroides is harvested from the eulittoral zone by people walking around the rocks at low tide and pulling the seaweed from the rocks by hand.

Sarcothalia crispata is harvested from the sublittoral zone by fishermen who dive and use hooks to drag the seaweed off the rock and store it in bags called *chinguillos* while they work.

Gigartina skottsbergii is harvested from the lower sublittoral zone in the same way as *Sarcothalia crispata.* Depending on the area where they dive, each fisherman is able to harvest about 70 kg/hour from a natural bed.

6.5 CULTIVATION OF CARRAGEENOPHYTES

Kappaphycus and *Eucheuma* are both cultivated by the same methods, the two most popular being the fixed, off-bottom line method and the floating raft method.

The basics of the fixed, off-bottom line method are simple. First choose a suitable site, then drive two wooden stakes, about 5–10 m apart, into the bottom. Stretch either a monofilament nylon line or a polypropylene rope between the stakes; the line should be 20–30 cm above the sea bottom and the water must be deep enough to ensure that the seaweed is not exposed at low tide. Small pieces of seaweed (50–100 g) are tied to the line. Many of these lines are constructed, usually 1 m apart (Figure 38). If the site is suitable and farming maintenance is carried out regularly, the seaweed should reach 10 times its original size in 6–8 weeks, when it can be harvested. It is sun dried away from sand and dirt, then packed into bales ready for shipping.

The main factor determining success or failure is choosing a suitable site. If *Kappaphycus* or *Eucheuma* is growing naturally, the place is probably suitable. If not, the following criteria apply.

- Reefs, well away from any freshwater sources (small rivers, etc.), have proven to be good sites. If the seawater salinity (usually 35 parts of salt per 1 000 parts of water (parts per thousand = ppt)) falls below 30 ppt, the seaweed does not grow well.
- Water temperature should be 25–30°C; in shallow water near the beach, the water temperature may become too high during the day; a good site is between the low tide limit and the reef edge.
- The seaweed obtains its nutrients for growth from the water so water movement through the seaweed is important. Moderate water movement is preferable; this also helps to stabilize water temperature and salinity. If the current is too strong it can cause pieces of the growing plant to break off and be lost; wave action must be avoided for the same reason.
- The sea bottom type is important; a white, firm bottom with a limited amount of natural seaweed is good, too much seaweed or sea grass will compete for nutrients with the cultivated seaweed. Silt or mud on the bottom indicates possible poor water

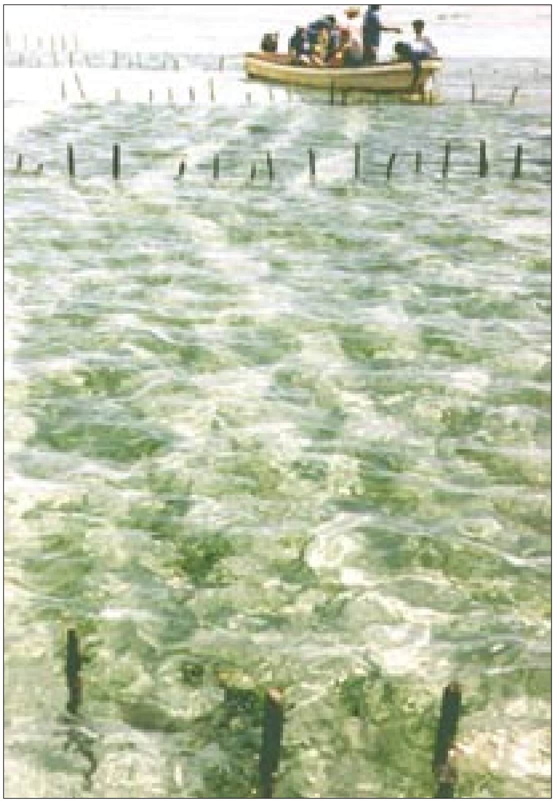


FIGURE 38
***Kappaphycus alvarezii* cultivation using fixed, off-bottom lines (Kiuva, Fiji).**

flow and if the silt is disturbed it may settle on the plants; muddy water will also reduce the light available to the seaweed.

- Plenty of sunlight is necessary for good growth; seaweed planted in shallow water (30–50 cm) grows well; in deeper water (more than 1 m) the light is reduced and growth is poor. Water depth is also important for farming: 0.5–1.0 m depth at low tide is good for the seaweed and allows the farmer to carry out maintenance more easily.
- Regular maintenance is essential. It consists of removing other seaweeds growing either on the lines or the crop itself, removing poorly growing plants, replacing lost plants, and making any necessary repairs to the stakes and lines.

Once a site has been chosen, a trial is made using the chosen species. A few lines are set out at each of several different parts of the site, small pieces of the seaweed are attached and their growth rate is monitored weekly. If after 2–3 months the daily growth rate is 3–5 percent, the site is probably suitable and a small farm can be established. Because of the larger capital outlay required for large installations, before venturing into large farms it is advisable to monitor conditions for a full year so that the effects of all weather and other ecological factors are known. Small family farms have been the most successful, partly because there is more incentive to provide the necessary care and maintenance to the farm they own rather than one owned by an employer.

Various problems can arise. Grazing fish can damage the crop. Siganids (rabbitfish) and puffers are common pests. Siganids are the most destructive, especially if the plants are all small: the entire crop can be devoured and even dense beds can be severely damaged. There is no simple solution except to move to another site where they are not prevalent. Turtles pose a special problem: they obviously take large bites but they also crawl through a farm, causing devastating physical damage. Long-spined sea urchins are also a pest, and can cause injury to the farmer as they try to remove them. The most common symptom of bad health is *ice-ice,* so named because of the white segments that appear on the plants, causing them to break at that point. There is some disagreement about its cause: some say it is a symptom of a bacterial or viral infection, others attribute it to physical stress caused by changes in the environment in which it is growing. Storms lead to strong water movement that can cause plants to break apart and even cause physical damage to the lines and stakes. So localities that are subject to seasonal cyclones, etc., should be avoided, or precautions taken during the periods – usually about 3 months of the year – when bad weather can be expected.

The materials required include the wooden stakes used to hold the lines, which can be made from mangrove timbers or any other timber that can withstand immersion in seawater for at least a year; they need to be 5–10 cm diameter, sharpened at one end (Figure 39) and driven into the bottom until held very firmly. Monofilament

FIGURE 39
Stakes from mangrove trees for use with fixed, off-bottom lines.

FIGURE 40
Fixing "tie-ties" to seedlings, using 20–25 cm pieces of blue plastic raffia.

nylon line with a breaking strain of 90 kg (200 lb) is used to support the seaweed, or 3 mm diameter polypropylene rope. The rope has an advantage in that the string used to tie the seaweed to the line can actually be inserted through the twist of the rope, ensuring it does not slide along the rope. The seaweed is tied to the line with a soft synthetic string, often called a "tie-tie", preferably using a slip knot so that the seaweed can be easily removed at harvest time. The seedlings, 50–150 g pieces obtained from the last harvest or the nearest farm, are prepared by fixing the tie-ties to them (Figure 40), ensuring that they are kept moist all the time that they are not in the water. Seedlings and tie-ties are then fixed to the ropes at 20–25 cm intervals (Figure 38), the ropes can already be in the water attached to the stakes or it can be done on the land and the ropes then stretched between the stakes. At harvest time, the whole plant is removed and new seedlings are cut from the tips.

To maintain the value of the crop, careful post-harvest treatment is necessary. It must be kept away from sand and dirt, so drying racks or mats are used (Figure 41). In some areas, the entire line is removed from the sea and hung over a tall "fence" to allow drying, the seaweed being untied after it has dried. In most areas, sun drying for about 2–3 days is sufficient to reduce the moisture content to the required 35 percent level. With practice, farmers can estimate the moisture level by feeling the seaweed, by its firmness and how it bends. If the moisture is above 40 percent the seaweed may rot during storage and transport; below 35 percent the seaweed becomes too firm and bouncy and it is difficult to compress it into bales. During drying, white salt-like crystals appear on the outside

FIGURE 41
Drying *Kappaphycus alvarezii.*

FIGURE 42
A raft for use in the floating-raft method of cultivation.

of the seaweed; any that are loose and can be shaken off are removed. Buyers do not like damp seaweed, nor foreign matter such as sand, dirt, stones, coral pieces or excessive salt. Some less scrupulous farmers have been known to add salt to the dried product since they are paid by weight and salt is cheaper than seaweed.

The second method of cultivation is the floating raft method. This is suitable in protected areas where water current is weak or where the water is too deep for fixed bottom lines. The selected areas must meet the criteria previously described, at least as they apply to this situation, and trials should be conducted in the same way. A white, silt-free bottom is not necessary. A floating construction is used to suspend the seaweed about 50 cm below the surface. Often a 3×3 m square timber frame, made from bamboo or mangrove timber, is used with 3 mm polypropylene ropes stretched parallel in one direction between the timbers, at 10–15 cm intervals (Figure 42). The seedlings are tied to the ropes and the raft is anchored to the bottom. The anchor ropes may need to hold the raft below the surface at the beginning, but as the plants grow and add weight to the raft, it may need extra support (such as polystyrene foam boxes tied to the corners of the raft) to prevent it sinking too low in the water. The seedlings can be tied to the raft on land and the raft towed into position. Regular maintenance during growth is still required. At harvest time the entire raft can be removed and used as a drying rack by suspending it between four corner supports, such as large drums.

The off-bottom line farming method allows easier access since the farmer can walk around the lines at low tide, but the floating rafts have the advantage that they can be easily moved to another position if necessary, and removed from the water altogether in bad weather, thus avoiding destruction by heavy seas and strong winds.

For further details

Methods and illustrations can be found in Trono (1993) and its associated CD-ROM, Critchley and Ohno (1997). For a thorough discussion of cultivation and some of its associated problems see Doty (1986), who also examines some of the costs and returns from farming.

Very practical guides to *Eucheuma* and *Kappaphycus* cultivation, with useful illustrations, can be found in Foscarini and Prakash (1990) or Ask (1999).

Foscarini and Prakash (1990) is written for the person actually setting up a farm, written simply but carefully, and answers questions such as:

- How much will it cost to start seaweed farming?
- How can I organize my work at the farm?
- What should I do to maintain my farm?
- What records do I need to keep?

- How much will I earn from my seaweed farm?

Copies are available upon request from the FAO David Lubin Library (see reference for details).

Ask (1999) is similar, and copies may be available from the author (see references).

Similar guides may be available from other carrageenan producers, listed in Section 7.2.

In Viet Nam, *Kappaphycus* is being cultivated in offshore areas using floating rafts, in lagoons and inlets using fixed off-bottom monolines, and it is the only country to date that has also used ponds for *Kappaphycus*. Fixed off-bottom monolines and fixed off-bottom nets have been used in ponds with muddy bottoms, while broadcasting seedlings directly onto the bottom is used where the bottom is sandy or coralline. Sometimes the ponds are used for seaweed for six months and then rotated with shrimp for six months.

Betaphycus gelatinum is cultivated on Hainan Island, China. Pieces of wild seaweed are fastened to coral branches with rubber rings and thrown onto sublittoral reefs, where divers rearrange them. Some long-line cultivation has also been used.

In France, one company cultivated *Chondrus crispus* in raceways and found it an economic proposition from 1978 to 1996. Its success was related to the selection of a fast-growing strain and an automated system that together produced a growth rate ten times faster than the natural rate. However, by 1996, the cost of wild *C. crispus* had fallen and the operation was no longer considered economic.

Methods for the cultivation and restocking of *Gigartina skottsbergii* have resulted from collaboration between the Division of Aquaculture, Instituto de Fomento Pesquero, and the Department of Oceanography, Universidad de Concepción, Chile, and have been published as Romo, Ávila and Candia (2001).

Cultivation methods for *Sarcothalia crispata* are being developed.

6.6 QUANTITIES HARVESTED

About 120 000 dry tonne/year is harvested of *Kappaphycus alvarezii*, mainly from the Philippines, Indonesia and Tanzania (Zanzibar). For *Eucheuma denticulatum,* the harvest is around 30 000 dry tonne/year, again mainly from the same countries. About 300 dry tonne/year of *Betaphycus gelatinum* is harvested yearly from Hainan Island, mainly from cultivation.

Until the early 1970s, *Chondrus crispus* was the main source of carrageenan and Canada provided about 70 percent of the world production. By 1992, with the success of cultivation of *K. alvarezii* and *E. denticulatum,* the demand for *C. crispus* had fallen to 3.8 percent of the total requirement for carrageenophytes, and of this, Canada supplied only 12 percent. In 1992, only about 7 000 wet tonnes was harvested, compared with the peak production of 50 000 wet tonnes in 1974. In France, there has also been a decline in harvesting, from about 6 000 wet tonnes in 1975 to about 3 000 wet tonnes in 1996.

The *Gigartina skottsbergii* harvest in Chile was 30 100 wet tonnes in 2000. The *Gigartina canaliculata* in Mexico has fallen from a maximum production of 1 100 dry tonnes in 1978 to 200 dry tonnes, and it is all exported. Small quantities of other species are collected from Mexico, Morocco and Peru.

Table 7 summarizes estimates of harvests of carrageenophytes, all in dry tonness.

TABLE 7
Carrageenophyte resources, tonnes dry weight (2001)

Chondrus		
Canada	2000	
France, Spain and Portugal	1 400	
Republic of Korea	500	
Subtotal	3 900	2.3%
Eucheuma and *Kappaphycus*		
Indonesia	25 000	
Philippines	115 000	
Tanzania (Zanzibar)	8 000	
Others	1 000	
Subtotal	149 000	88.5%
Gigartina		
Chile	14 000	
Morocco, Mexico and Peru	1 500	
Subtotal	15 500	9.2%
Total	168 400	100%

Source: H. Porse, CP Kelco ApS, 2002, *pers. comm.*

FIGURE 43
Marketing channel for seaweed – Indonesia (Burges Watson, 1999).

6.7 MARKETS

For *Kappaphycus* and *Eucheuma*, the farmers usually sell to middlemen; sometimes there may be two in the chain. They sort and clean up the seaweed before selling it on to the carrageenan processors. The middlemen frequently help to finance the farmers with loans for equipment and seedlings. As cultivation in the Philippines has developed, some of the major processors have set up extraction factories there, eliminating the former transport costs to Europe. Two distinct grades of carrageenan are produced: refined and semi-refined. Large quantities of seaweed produced in the Philippines are now processed there, producing all grades of carrageenan.

In Indonesia, again, there are active middlemen and a few local companies making semi-refined carrageenan (SRC). Figure 43 shows the marketing chain for *Kappaphycus* in Indonesia, and this is also typical of the situation in other countries, such as the Philippines. A large proportion of the seaweed is exported to Japan and the Republic of Korea. In Zanzibar (Tanzania) all the production is exported, mainly to the companies who helped to establish the industry. Pacific nations such as Kiribati have a transport cost problem but have entered into contracts with at least one major producer who is willing to pay a fixed price if the supply is assured. The farmgate price of these seaweeds has undergone severe fluctuations in the past, with boom and bust cycles that are harmful to both buyer and seller in the long term. Fixed price contracts assure the farmers of a steady income, otherwise when the farm gate price falls too low they simply abandon seaweed farming and return to fishing and other activities that sustain a subsistence living. This eventually leads to a shortage, a demand that cannot be met, giving rise to increased prices. In Chile there is large internal consumption by four processors; the remainder is exported through several intermediary companies. A useful review of trends of seaweed production in Chile includes a diagram showing the marketing channels within Chile (Norambuena, 1996). All the *Betaphycus gelatinum* produced in China is used there. In France, all *Chondrus* harvested is used locally. Canadians operate fishermens' cooperatives that sell *Chondrus* to FMC Biopolymer, based in nearby Maine, and also export to Europe.

6.8 FUTURE PROSPECTS

Demand for carrageenan has risen at a steady rate of about 5 percent annually, and this should continue for several years as a continuing increase in demand is forecast. Carrageenan extractors actively pursue a policy of assistance to those interested in establishing seaweed farms, so future prospects for the industry are very encouraging.

7. Carrageenan

There are several carrageenans, differing in their chemical structure and properties, and therefore in their uses. The carrageenans of commercial interest are called iota, kappa and lambda.

Their uses are related to their ability to form thick solution or gels, and they vary as follows.

Iota	Elastic gels formed with calcium salts. Clear gel with no bleeding of liquid (no synaeresis). Gel is freeze/thaw stable.
Kappa	Strong, rigid gel, formed with potassium salts. Brittle gel forms with calcium salts. Slightly opaque gel, becomes clear with sugar addition. Some synaeresis.
Lambda	No gel formation, forms high viscosity solutions.

The carrageenan composition in red seaweeds differs from one species to another.

Chondrus crispus	mixture of kappa and lambda.
Kappaphycus alvarezii	mainly kappa.
Eucheuma denticulatum	mainly iota.
Gigartina skottsbergii	mainly kappa, some lambda.
Sarcothalia crispata	mixture of kappa and lambda.

7.1 CARRAGEENAN PRODUCTION METHODS

There are two different methods of producing carrageenan, based on different principles.

In the original method – the only one used until the late 1970s–early 1980s – the carrageenan is extracted from the seaweed into an aqueous solution, the seaweed residue is removed by filtration and then the carrageenan is recovered from the solution, eventually as a dry solid containing little else than carrageenan. This recovery process is difficult and expensive relative to the costs of the second method.

In the second method, the carrageenan is never actually extracted from the seaweed. Rather the principle is to wash everything out of the seaweed that will dissolve in alkali and water, leaving the carrageenan and other insoluble matter behind. This insoluble residue, consisting largely of carrageenan and cellulose, is then dried and sold as semi-refined carrageean (SRC). Because the carrageenan does not need to be recovered from solution, the process is much shorter and cheaper.

7.1.1 Refined carrageenan and filtered carrageenan

Refined carrageenan is the original carrageenan and until the late 1970s–early 1980s was simply called carrageenan. It is now sometimes called filtered carrageenan. It was first made from *Chondrus crispus,* but now the process is applied to all of the above algae.

The seaweed is washed to remove sand, salts and other foreign matter. It is then heated with water containing an alkali, such as sodium hydroxide, for several hours, with the time depending on the seaweeds being extracted and determined by prior small-scale trials, or

FIGURE 44
Sun drying semi-refined carrageenan (alkali treated *K. alvarezii*).

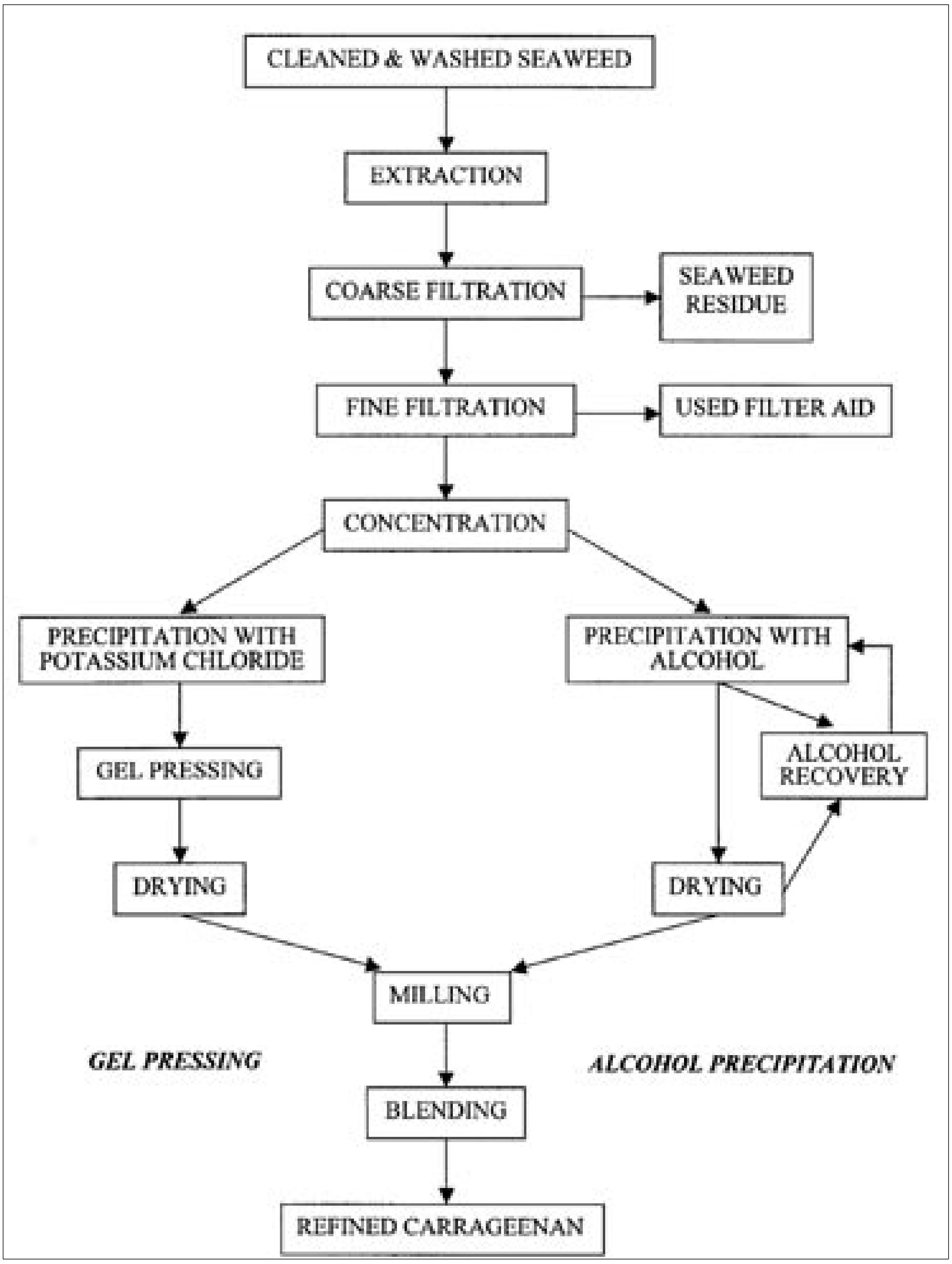


FIGURE 45
Flow chart for the production of refined carrageenan (after Porse, 1998).

experience. Alkali is used because it causes a chemical change that leads to increased gel strength in the final product. In chemical terms, it removes some of the sulphate groups from the molecules and increases the formation of 3,6-AG: the more of the latter, the better the gel strength. The seaweed that does not dissolve is removed by centrifugation or a coarse filtration, or a combination. The solution is then filtered again, in a pressure filter using a filter aid that helps to prevent the filter cloth becoming blocked by fine, gelatinous particles. At this stage, the solution contains 1–2 percent carrageenan and this is usually concentrated to 2–3 percent by vacuum distillation and ultrafiltration.

The processor now has a clear solution of carrageenan and there are two methods for recovering it as a solid, both rather similar to those described previously for agar production. An alcohol-precipitation method can be used for any of the carrageenans. A gel method can be used for kappa-carrageenan only, and the gel can be dehydrated either by squeezing or by subjecting it to a freeze-thaw process.

In the alcohol method, isopropanol is added until all the carrageenan is precipitated as a fibrous coagulum that is then separated using a centrifuge or screen (a fine sieve). The coagulum is pressed to remove solvent and washed with more alcohol to dehydrate it further. It is then dried and milled to an appropriate particle size, 80 mesh or finer. For the process to be economic the alcohol must be recovered, both from the liquids and the dryer, and recycled.

The gel method relies on the ability of kappa carrageenan to form a gel with potassium salts. The gel may be formed in various ways. For the freeze-thaw process it is convenient to form it as spaghetti-like pieces by forcing the carrageenan solution through fine holes into a potassium chloride solution. The fine "spaghetti" is collected and washed with more potassium chloride to remove more water, pressed to remove surplus liquid and then frozen. When allowed to thaw, separation of water occurs by synaeresis, the pieces are washed with more potassium chloride, chopped up and dried in a hot air dryer. Inevitably the product contains some potassium chloride. The alternative to freeze-thaw is to force water out of the gel by applying pressure to it, using similar equipment to that used for agar (Figure 10). After squeezing for several hours the sheets of gel are chopped, dried in a hot air dryer and milled to an appropriate particle size. Many agar processors are now using their equipment and similar techniques to produce kappa carrageenan as well.

Figure 45 summarizes the above processes.

7.1.2 Semi-refined carrageenan and seaweed flour

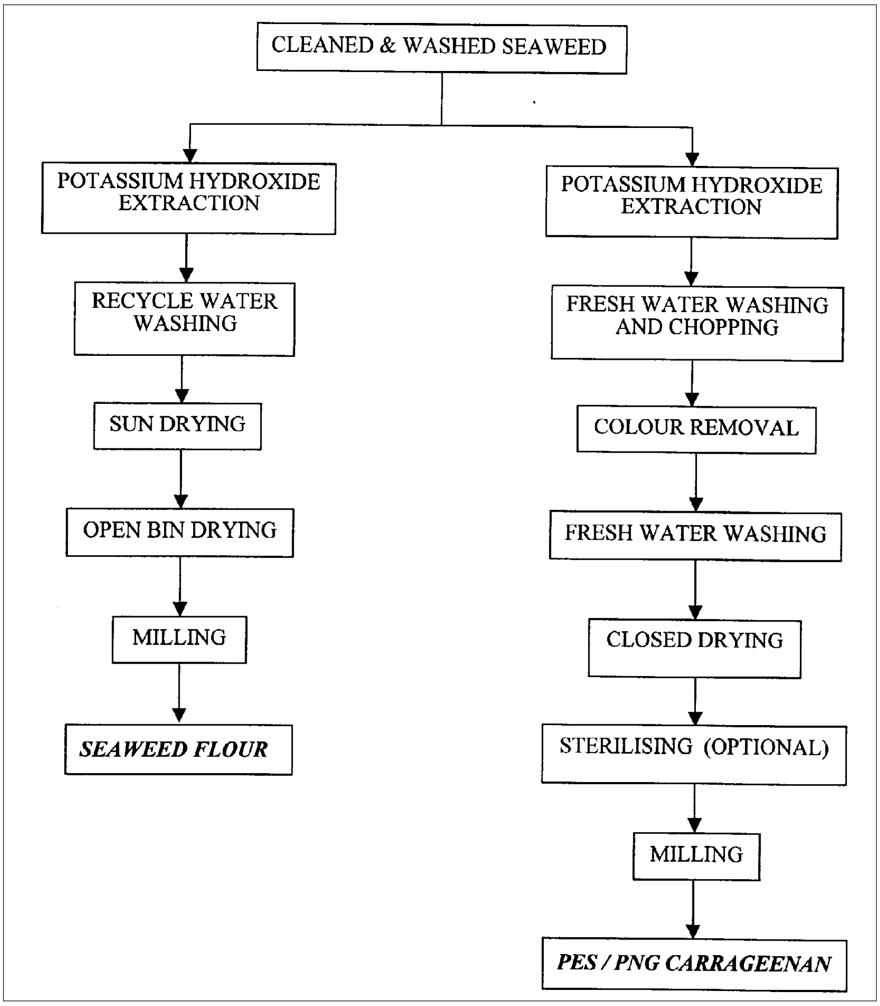
Semi-refined carrageenan (SRC) was the name given to the product first produced by the second method of processing noted in Section 7.1. This is the method in which the carrageenan is never actually extracted from the seaweed.

In the production of SRC, *Kappaphycus alvarezii*, contained in a metal basket, is heated in an alkaline solution of potassium hydroxide for about two hours. The hydroxide part of the reagent penetrates the seaweed and reduces the amount of sulphate in the carrageenan, increases the 3,6-AG so the gel strength of the carrageenan in the seaweed is improved. The potassium part of the reagent combines with the carrageenan in the seaweed to produce a gel and this prevents the carrageenan from dissolving in the hot solution. However, any soluble protein, carbohydrate and salts do dissolve and are removed when the solution is drained away from the seaweed. The residue, which still looks like seaweed, is washed several times to remove the alkali and anything else that will dissolve in the water. The alkali-treated seaweed is now laid out to dry; in hot climates, like the Philippines, usually on a large concrete slab (Figure 44). After about two days it is chopped and fed into a mill for grinding to the powder that is sold as SRC or seaweed flour.

The above process is summarized in Figure 46 (seaweed flour branch).

However, the seaweed flour is coloured, often has a high bacterial count and is not suitable for human consumption. Nevertheless it immediately found a large market in canned pet food because it is a good gelling agent and was so much cheaper than refined

FIGURE 46
Flow chart for the production of seaweed flour and PES/PNG carrageenans (after Bixler, 1996).



carrageenan. The temperatures used in the canning process destroy any bacteria so the high bacterial count in the SRC is not a problem. Sometimes the dried product is just chopped into pieces, not milled, and sold as a raw material to refined carrageenan processors. It is called alkali treated cottonii (ATC) or alkali treated cottonii chips (ATCC), or even simply cottonii chips. If this treatment is done in the country of origin of the seaweed, such as the Philippines or Indonesia, this means processors in Europe and United States of America have cheaper transport costs per tonne of carrageenan, compared with shipping dried seaweed. They have also left behind some waste products, which reduces their waste treatment costs.

Kappaphycus alvarezii is used in this process because it contains mainly kappa carrageenan and this is the carrageenan that forms a gel with potassium salts. Iota-containing seaweeds can also be processed by his method, although the markets for iota carrageenan are significantly less than those for kappa. Lambda carrageenans do not form gels with potassium and would therefore dissolve and be lost during the alkali treatment.

The simplicity of the process means the product is considerably cheaper than refined carrageenan.

There is no alcohol involved that must be recovered, no distillation equipment to purify alcohol, no equipment for making gels, no refrigeration to freeze the gels, nor any expensive devices to squeeze the water from the gel.

7.1.3 Philippine natural grade (PNG) and processed *Eucheuma* seaweed (PES)

Producers in the Philippines developed a higher quality product, suitable for human consumption, by modifying the process just described for SRC.

After the alkali treatment and water washing, the product is chopped and treated with bleach to remove the colour (chopping improves penetration by the bleach, and bleach also helps to reduce the bacterial count). After washing to remove any bleach, the product is dried in a closed dryer. In this type of dryer, indirectly heated hot air passes up through a bed of the unground pieces or chips that are being carried through the dryer on a chain-type belt. This closed system dryer is usually sufficient to keep the bacterial count low enough to make a human-food grade product. If bacteria reduction is required, the dried chips can be milled and then washed with alcohol (ethanol) followed by vacuum evaporation to recover the alcohol. A simpler process is to treat the milled powder with superheated steam.

The above process is summarized in Figure 46 (PES/PNG carrageenan branch).

The product was originally called Philippine natural grade carrageenan (PNG).

Attempts to market this product as food grade in the United States of America and Europe resulted in strong opposition from the producers of refined carrageenan who did not wish to lose market share to this cheaper product. Eventually in the United States of America, the Food and Drug Administration declared it suitable for use in human food and to be labelled as “carrageenan”, the same status as that of the refined product.

In Europe, both refined and PNG are permitted in human food, but carry different labels:

- refined carrageenan is labelled “carrageenan” and E-407; while
- Philippine natural grade is labelled “processed *Eucheuma* seaweed” or “PES”, and E-407a.

So PNG and PES are the same grade of carrageenan.

The main difference between refined carrageenan and PNG is that PNG contains the cellulose that was in the original seaweed while in refined carrageenan this has been removed by filtration during the processing. Refined carrageenan will therefore give a clear solution, while PNG gives a cloudy solution. Where clarity of a user’s product is of no consequence, PNG is suitable.

For further details

Detailed information on any methods of carrageenan extraction are not easy to find. As Stanley (1987) said, they are closely guarded as trade secrets by the several manufacturers. Some information can be found in Stanley (1987), Stanley (1990) and Therkelsen (1993).

7.2 CARRAGEENAN PRODUCERS AND DISTRIBUTORS

A summary of the capacity of carrageenan producers according to their broad geographical location is given in Table 8, and the principal producers and distributors are listed in the next section.

TABLE 8
Carrageenan processors. Capacity in tonnes (2001)

	Alcohol process	Gel process	PES	Total	%	ATC[1]
Europe	8 100	5 000	500	13 600	32	
Americas	4 700	3 350	1 100	9 150	21	
Asia-Pacific	2 000	8 280	9 900	20 180	47	16 000
Total	14 800	16 630	11 500	42 930		16 000

[1] ATC = Alkali treated cottonii or seaweed flour, used mainly for pet food.
Source: H. Porse, CP Kelco ApS, 2002, *pers. comm*.

7.2.1 Refined carrageenan producers and distributors

CP Kelco ApS
Ved Banen 16
4623 Lille Skensved
Denmark
Tel: [INT+45] + 5616 5616
Fax: INT+45] + 5616 9446
Website: www.cpkelco.com

Shemberg Marketing Corporation
corner Lapu-lapu and Osmena Boulevard
Cebu City
The Philippines
Tel: [INT+63] + (32) 346 0866
Fax: [INT+63] +(32) 346 1892; 346 0863

Shemberg Biotech Corporation
Carmen, Cebu City
The Philippines
Tel: [INT+63] + (32) 254 9380
Fax: [INT+63] + (32) 254 9388

Ingredients Solutions Inc.
PO Box 407
Searsport, ME 04974-0407
United States of America
Tel: [INT+1] + (207) 548 0074
Fax: [INT+1] + (207) 548 2921

Marcel Carrageenan Corporation
926 Araneta Avenue
Quezon City 1104
Philippines
Tel: [INT+63] + (2) 712 2631/2640/2841
Fax: [INT+63] + (2) 712 1989/5879

FMC Biopolymer
1735 Market Street
Philadelphia PA 19103
United States of America
Tel: [INT+1] + (215) 299 6000
Fax: [INT+1] + (215) 299 5809
Websites: www.fmc.com;
www.fmcbiopolymer.com

Degussa Texturant Systems
Lise-Meitner-St.34
85354 Freising
Germany
Tel: [INT+49] + (8161) 548 266
Fax: [INT+49] + (8161) 548 582
Website: www.texturantsystems.com

Danisco Cultor
Edwin Rahrs Vej 38
8220 Brabrand
Denmark
Tel: [INT+45] 89 43 50 00
Fax: [INT+45] 86 25 06 81
Website: www.daniscocultor.com

Rhodia Food
40, rue de la Haie-Coq
93306 Aubervilliers Cedex
France
Tel: [INT+33] 1 53 56 50 00
Fax: [INT+33] 1 53 56 55 55
Website: www.rhodiafood.com

Gelymar S.A.
Av. Pedro de Valdivia Norte 061
Providencia, Santiago
Chile
Tel: [INT+56] + 2 230 9400
Fax: [INT+56] + 2 232 1544

CEAMSA
"Les Gandaras", PO Box 161
36400 Porrino (Pontevedra)
Spain
Tel: [INT+34] + (986) 344 089
Fax: [INT+34] + (986) 336 621
Website: www.ceamsa.com

Hispanagar, S.A.
Avenida López Bravo, 98
Polígono de Villalonquejar
Apartado Postal 392
08080 Burgos
Spain
Tel: [INT+34] + (947) 298519
Fax: [INT+34] + (947)298518
Website: www.hispanagar.net

Ina Food Industry Co., Ltd.
574 Tsurumakicho, Waseda
Shijuku
Tokyo 162
Japan
Tel: [INT+81] + (3) 3235 8861
Fax: [INT+81] + (3) 3235 8863

Myeong Shin Chemical Ind. Co., Ltd.
439-13, Soju-Ri, Ungsang-Up,
Yangsan-gun, Kyeong-Nam,
The Republic of Korea
Tel: [INT+82] + (55) 389 1001
Fax: [INT+82] + (55) 389 0478
(Head Office and carrageenan factory)

Soriano S.A.
9 de Julio 745
9100 Trelew
PCIA Chubut
Argentina

Chuo Food Materials Co.Ltd
Osaka
Japan

Marine Science Co Ltd
Higashi-kanda Towa-building 6F , 2-3-3,
Higashi-kanda
Chiyoda-ku
Tokyo 101-0031 Japan
Tel: [INT+81] + (3) 3865 3485
Fax [INT+81] + (3) 3865 3450

7.2.2 PNG and PES and seaweed flour producers and distributors

Ingredients Solutions Inc.
PO Box 407
Searsport ME 04974-0407
United States of America
Tel: [INT+1] + (207) 548 0074
Fax: [INT+1] + (207) 548 2921

Marcel Carrageenan Corporation
926 Araneta Avenue
Quezon City 1104
The Philippines
Tel: [INT+63] + (2) 712 2631/2640/2841
Fax: [INT+63] + (2) 712 1989/5879

Shemberg Marketing Corporation
corner Lapu-lapu and Osmena Boulevard
Cebu City
The Philippines
Tel: [INT+63] + (32) 346 0866
Fax: [INT+63] + (32) 346 1892/0863

Quest International Philippines Corp.
Mactan Export Processing Zone,
G/F SFB Pt. 1,
Lapu-Lapu City
Cebu
The Philippines.
Tel: [INT+63] + (32) 340 0322/0319/0764
Fax: [INT+63] + (32) 340 0328/0324

FMC Corporation
Ouano Compound
Looc, Mandaue City
6014 Cebu
The Philippines.
Tel: [INT+63] + (32) 85097, 346 0882
Fax: [INT+63] + (32) 54098, 3461182/1187

Geltech Hayco, Inc.
2211 Taft Avenue
Metro Manila
The Philippines.
Tel: [INT+63] + (2) 521 3094, 571 306
Fax: [INT+63] + (2) 526 0591

TBK Manufacturing Corp.
Brgy 76, Hollywood, Nula-tula
Tacloban city
6500 Leyte
The Philippines
Tel: [INT+63] + (2) 727 6891
Fax: [INT+63] + (2) 725 5163

Iberagar S.A.
Estrada Nacional 10, km. 18
Coina
Portugal
Tel: [INT+35] + (121) 210 9252
Fax: [INT+35] + (121) 2109255
Website: www.iberagar.com

P.T. Surya Indoalgas Jln Kedungdoro – 60
Surabaya 60251
Indonesia
Tel: [INT+62] + (31) 548 2003
Jakarta office:
Tel: [INT+62] + (21) 564 7270
Fax: [INT+62] + (21) 564 9285

C.V. Cahaya Cemerlang
Jln S. Cerekang – 16(34)
Ujung Pandang
Indonesia
Tel: [INT+62] + (411) 31 53 58
Fax: [INT+62] + (411) 31 82 27

P.T. Gumindo Perkasa Industri
Wisma UIC, 2nd Floor
Jln Jend Gatal Kav 6-7
Jakarta 12930
Indonesia
Tel [INT+62] + (21) 520 0832
Fax: [INT+62] + (21) 529 60004

P.T. Asia Sumber Laut Indonesia
Jln Rajawali 64 K
Surabaya 60176
Indonesia
Tel: [INT+62] + (31) 357 7892
Fax: [INT+62] + (31) 357 7901

For further information about the Philippines contact:
Secretary General
Seaweed Industry of the Philippines
T.R. Martinez Bldg, 2nd Floor
Osmena Blvd
Cebu City,
The Philippines
Tel: [INT+63] + (32) 253 7433
Fax: [INT+63] + (32) 254 8780

For further details about Indonesia and other Indonesian companies contact:
Indonesian Seaweed Industry Association (APBIRI) at:
Asosiasi Pengusaha Budidaya dan Industri Rumput Laut Indonesia (APBIRI)
BPPT Lt. 13
Jl. MH Thamrin No. 8
Jakarta Pusat 10340
Indonesia
Tel: (62) 21 322430

7.3 CARRAGEENAN USES

Before discussing uses, some explanations of the properties of carrageenans are necessary.

Both kappa and iota carrageenan form gels with potassium and calcium salts. Aqueous solutions of both carrageenans must be heated above 60°C for the carrageenan to dissolve, and after addition of the salt, the gel forms as the solution cools. For kappa, as little as 0.5 percent in water and 0.2 percent in milk is sufficient to form gels.

Kappa forms gels most strongly with potassium salts, followed by calcium salts. Potassium gives a rigid, elastic gel while calcium produces a stiff, brittle gel. Kappa gives the strongest gels of all carrageenans, but they are also the ones most likely to bleed (most subject to synaeresis). This liability can lessened in a couple of ways. If iota and lambda carrageenans are blended in with the kappa, bleeding can be reduced, so will also the rigidity and brittleness of the gel; however, the gel strength may also be lowered. Synaeresis can also be reduced by adding locust bean gum (obtained from the seeds of the carob tree (*Ceratonia siliqua*), growing in Spain, Italy, Cyprus, etc.). This gum also allows the amount of kappa to be reduced while still maintaining the same gel strength. The kappa can be reduced to one-third of the concentration that would be needed if no locust bean gum were used. The resulting gels are more resilient than those with kappa alone. As long as locust bean gum is cheaper than kappa there is also an economic advantage. However, the cost of locust bean gum can fluctuate depending on the harvest and demand.

Iota forms gels most strongly with calcium salts, followed by potassium salts – the reverse of kappa reactivities. Calcium gels are soft and resilient and are virtually free of bleeding. They can be frozen and thawed without destroying the gel. They show an unusual property for a gel: thixotropic flow; this means the gel can be stirred and it will flow like a thick liquid, but if left to stand it will gradually reform a gel.

A similar thixotropic behaviour is found with very low concentrations of kappa carrageenan in milk; a weak gel forms that is easily made to flow by shaking. The weak gel is strong enough to suspend fine particles in the milk, such as cocoa in chocolate milk.

Protein reactivity of carrageenans is an important property that is utilized in several applications. Carrageenan molecules carry negative charges; this is what enables them to combine with positively charged particles like the potassium found in potassium salts. They can also combine with positively charged proteins. Carrageenan will combine with the protein in milk (casein) to form a three-dimensional gel network. The exact nature of the interaction of proteins with carrageenans appears to be more complex than this simple explanation, and the interested reader can find more detail in the references suggested in Section 7.3.8.

7.3.1 Dairy products

The main applications for carrageenan are in the food industry, especially in dairy products.

Frequently, only very small additions are necessary, 0.01–0.05 percent. For example, kappa carrageenan (at 0.01–0.04 percent) added to cottage cheese will prevent separation of whey, and a similar amount added to ice cream also prevents whey separation that may be caused by other gums that were added to the ice cream to control texture and ice crystal growth. The cocoa in chocolate milk can be kept in suspension by addition of similar amounts of kappa; it builds a weak thixotropic gel that is stable as long as it is not shaken strongly. Dry instant chocolate mixes, to be mixed with water or milk, can have improved stability and mouth feel using lambda or a mixture of carrageenans.

Lambda or a mixture can also improve liquid coffee whiteners by preventing the separation of fat; these applications require 0.2–0.3 percent additions, but much smaller quantities will prevent fat separation in evaporated milks. Those small containers of UHT sterilized milk found in the refrigerators of some hotels may have kappa added to prevent fat and protein separation. Lambda or kappa may be added to natural cream to help maintain the lightness (incorporated air) if it is whipped. Many more uses in milk and dairy products can be found in the references below.

7.3.2 Water-based foods

With the appearance of bovine spongiform encephalopathy (BSE, or mad cow disease) and foot-and-mouth disease, efforts have been made to find suitable substitutes for gelatin. Gelatin jellies have long been favoured because they melt at body temperature, giving a smooth mouth feel and easy release of flavours. However, if they are stored for a day or two, they toughen and are less pleasant to eat. Gels made from iota carrageenan have the disadvantage of a high melting temperature, so they are not as smooth to eat as gelatin gels. They do not melt on hot days and do not require refrigeration to make them set, so these are advantages in hot or tropical climates, and a further advantage is that they do not toughen on storage. In the last two years there have been several claims by food ingredients companies for products, made from a mixture of hydrocolloids, that imitate the properties of gelatin. Carrageenan producers find that by combining various carrageenans with locust bean gum, konjac flour and starch, they can provide a variety of melting and non-melting gels and gel textures to meet the requirements of most of their clients. Long-life refrigerated mousse desserts, based on carrageenan and pectin rather than gelatin, are suitable for vegetarians and some ethnic groups.

Conventional fruit jellies are based on pectin and a high sugar content to help set the jelly. In a low- or non-calorie jelly the pectin must be replaced, and mixtures of kappa and iota have proved to be suitable. Fruit drink mixes to be reconstituted in cold water contain sugar (or aspartame), acid and flavour. Addition of lambda carrageenan gives body and a pleasant mouth feel. Sorbet is a creamy alternative to ice cream with no fat; use of a mixed kappa and iota together with locust bean gum or pectin provides a smooth texture to the sorbet.

Low-oil or no-oil salad dressings use iota or kappa to help suspend herbs, etc., and to provide the mouth feel that is expected from a normal salad dressing. The low oil content of reduced-oil mayonnaise normally gives a thin product, rather like a hand lotion; additives are needed to thicken it and to stabilize the oil-in-water emulsion. A combination of carrageenan and xanthan gum is effective. Xanthan gum is made by a bacterial fermentation process; its development was pioneered in the early 1960s by the Kelco Company, then the largest producer of alginate; it is now an accepted and widely used food additive. The interaction of carrageenan and protein can be used in the clarification of beer, with the complex formed precipitating from the wort. More water-based applications of carrageenan are given in the references below.

7.3.3 Meat products

In preparing hams, addition of carrageenan to the brine solution used in pumping improves the product because the carrageenan binds free water and interacts with the protein so that the soluble protein is retained. For successful penetration, the brine solution must have a low viscosity, but dissolved carrageenan would increase the viscosity. The carrageenan is therefore dispersed in the water after the brine salts are added; the carrageenan does not dissolve because of the high salt concentration, but as the ham cooks it does dissolve and is then effective.

There is a growing consumer demand for pre-cooked poultry products such as chicken and turkey pieces. Poultry processors were concerned about the loss of water during cooking (this lowered their yield per unit weight of product) and the loss in texture and eating quality that resulted. By injecting a brine containing salt, phosphate and carrageenan into the muscle of the meat, these problems are overcome. As the meat cooks, the carrageenan binds water within the poultry muscle and improves texture and tenderness. The processors are pleased because they now have a higher yield; in fact they find that he can even add some extra water to the poultry and it will be retained. The consumer receives a better product. The carrageenan producer is pleased because about 0.5 percent carrageenan is added, much more than the 0.05–0.1 percent used in dairy products. The future looks bright for this kind of application in meat products.

Hydrocolloids are being tried as fat replacements in low-fat products, with varying degrees of success. When fat or salt are reduced, meat and poultry can suffer loss of tenderness, juiciness and flavour. Low-fat products formulated with phosphates and carrageenan can have the juiciness and tenderness restored. Kappa carrageenan has been used with some success in replacing half the normal fat in frankfurters. Reduction of fat in ground meat products like hamburgers results in a different mouth feel and dry taste, which consumers do not always accept. Iota can be mixed with fresh ground beef and when cooked it provides fat-like characteristics and moisture retention that make the product more acceptable. This was the basis for McDonald's "MacLean" hamburger.

7.3.4 Pet food

This is the largest application for SRC, known as seaweed flour (see Section 7.1.2), using about 5 500 tonnes annually. Refined carrageenan could also be used, but its cost is too high and seaweed flour is about one-quarter of its price. Seaweed flour becomes an even better proposition because when combined with locust bean gum, less carrageenan is required, but this combination still gives an excellent product and it is very affordable. The meat used in canned pet foods is usually waste cuts from the abattoir. It is chopped into chunks or smaller pieces, mixed with water, flavours, seaweed flour (kappa carrageenan) and locust bean gum, canned and cooked. The two hydrocolloids help to bind the meat together and, depending on the concentrations used, either provide a thickened gravy around the meat pieces or a flavoured jelly, either of which enhances the appearance of the product as it is removed from the can. Konjac (or konjaku) gum, made from the konjac tuber or elephant yam (*Amorphophallus konjac*), can be used in place of locust bean gum. Konjac gels are clearer than locust bean gels and can help with costs when the price of locust bean gum rises, as it does occasionally.

7.3.5 Air freshener gels

When you need to improve the odours in your room, air freshener gels are one of the products available at supermarkets. They are made from kappa carrageenan, a potassium salt, water and perfume. When mixed, the perfumed gel forms and it is moulded to a shape to fit the holder. When purchased, the holder is sealed; to use, the holder is opened slightly and the moisture plus perfume are gradually released from the gel. Eventually the gel dries out leaving a small residue in the holder, which is then discarded. About 200 tonne/year of seaweed flour grade of carrageenan is the estimated consumption for this application.

7.3.6 Toothpaste

The essential ingredients in toothpaste are chalk or a similar mild abrasive, detergent, flavour, water and a thickening agent that will provide enough body to the paste to ensure that the abrasive is kept in suspension and that there is no separation of water. A thixotropic thickener is preferable, i.e. that has gel-like properties when allowed to stand but that will flow when pressure is applied to it. Iota carrageenan, at about 1 percent, is one of the most useful thickening agents, it meets the above criteria and gives a paste that is easily rinsed from the toothbrush. When the size of the toothpaste market is considered, even at 1 percent concentration this represents a large market for iota.

7.3.7 Immobilized biocatalysts

This application was discussed for alginates in Section 5.3.3. Carrageenan gels are another medium for immobilizing enzymes or whole cells. Kappa carrageenan gives the strongest gels and beads made from this show sufficient mechanical strength for packing in columns, and yet they are permeable to most substances.

7.3.8 For further details

More information about the properties and applications of carrageenans can be found in the following references, the first two of which are probably the most useful: Stanley (1990), Therkelsen (1993), Nussinovitch (1997), Stanley (1987).

For quick reference to a list of uses and the concentrations of carrageenan required, see Tables 3.4 and 3.5 in Thomas (1997).

7.3.9 Refined grade vs natural grade

Natural grade carrageenan is cheaper to make and requires a smaller capital outlay, therefore its price is lower than the refined or filtered grade. Natural grade is now approved for human use in most applications and jurisdictions. For a very useful and interesting discussion of the pros and cons of refined versus natural grades in regard to their purity, composition, and comparative performance in various applications, see Bixler (1996).

7.4 MARKETS AND MARKETING OF CARRAGEENAN

A summary of carrageenan markets is shown in Table 9. The total market has a value of about US$ 300 million. The marketing of carrageenan poses similar problems to those previously described in Section 5.4 for alginate. The original companies invested heavily in processing equipment and provided strong research and development facilities to assist customers and promote sales. These companies are now part of large multinationals and have a strong commitment to selling the refined carrageenan that they have always produced, and they operate at about 80–85 percent capacity. With the introduction of the simpler processing required for seaweed flour, many small companies entered that market, which required very little R&D because sales were mainly to pet food producers who knew exactly what they wanted and how to use it. Some of these companies then expanded their operations to produce the PES/PNG grade for human consumption. They make a few basic kappa and iota carrageenans for use in meat products, and to a lesser degree in dairy products. However, they lack the technical marketing skills to sell their products against the larger multinationals. These smaller companies are mainly in the Philippines and Indonesia, and operate at probably about 50 percent capacity and some are possibly struggling to survive. Despite this, new production facilities continue to be built in China and eastern Africa.

TABLE 9

Carrageenan markets (2001)

Application	tonnes	%
Dairy	11 000	33
Meat and poultry	5 000	15
Water gels	5000	15
PES food grade	8 000	25
Toothpaste	2 000	6
Other	2 000	6
Total	33 000	100

Source: H. Porse, CP Kelco ApS, 2002, *pers. comm.*

While there are difficulties in production of carrageenan, marketing can be even more difficult without adequate technical expertise to assist customers in the use of the product. Producers of refined carrageenan are not especially interested in selling the less expensive PES grade if such sales are going to replace sales of their refined grade. So there are opportunities for PES producers to penetrate the human food market with their less expensive product, if they are willing to invest in the technical expertise needed to service those sales. This has already occurred in the United States of America, where about 20 percent of the market is now PES grade. There appear to be similar opportunities awaiting PES producers in European markets that are still predominantly users of the refined grade (H.R. "Pete" Bixler, 2002, *pers. comm.*).

7.5 FUTURE PROSPECTS

In developed markets, such as the United States of America, Europe and Japan, all known applications are almost fully exploited. There could be some expansion by replacement of some of the gelatin market because of health concerns about bovine spongiform encephalopathy, but also due to a growing vegetarian population. Elderly people tend to use more processed foods in their diets and as this population increases so too will carrageenan consumption. Taking these factors into account, a 2–4 percent growth per annum can be expected in developed countries, and there the market splits about 50:50 between dairy and meat applications.

In areas such as Central and South America, Eastern Europe and Southeast Asia, growth will be stronger. Here the per capita consumption of carrageenan should increase by 50 percent over the next five years, due to market penetration alone. Allowing for population growth and assuming a moderate economic growth, an expansion of carrageenan consumption by 5–7 percent per annum is likely. At present the market is split into approximately 20 percent dairy and 80 percent meat applications, but this is likely to change with a gradual increase in the dairy foods market (H.R. "Pete" Bixler, 2002, *pers. comm.*).

For further details, see Bixler (1996), who discusses recent developments in the manufacturing and marketing of carrageenan and is excellent reading for anyone interested in obtaining an overall view of the carrageenan industry.

8. Seaweeds used as human food

8.1 INTRODUCTION

For several centuries there has been a traditional use of seaweeds as food in China, Japan and the Republic of Korea. As people from these countries have migrated around the world, this custom has moved with them, so that today there are many more countries where the consumption of seaweed is not unusual. Coastal dwellers in tropical climates such as Indonesia and Malaysia have also eaten fresh seaweeds, especially as salad components.

In recent years there has been a strong movement in France to introduce seaweed into the European cuisine, with some success, although it is still regarded as an exotic component of the menu. It has gained more acceptance in regions like California and Hawaii, where communities of Japanese are larger and the taste for seaweeds spreads out into the surrounding population through finding them on restaurant menus and supermarket shelves.

On the east coast of United States of America and Canada, around Maine, New Brunswick and Nova Scotia, some companies have begun cultivating seaweeds onshore, in tanks, specifically for human consumption, and their markets are growing, both in those two countries and with exports to Japan. Ireland and Northern Ireland are showing a renewed interest in seaweeds that were once a traditional part of the diet. Already on the market in many countries around the world are cooking books incorporating recipes using "sea vegetables". With the current trend for consumers to embrace organically grown foods and "natural" foods from clean environments, seaweeds should receive an increasing acceptance.

8.2 NORI OR PURPLE LAVER (*Porphyra* spp.)

This is the purplish-black seaweed often seen wrapped around a small handful of rice in sushi. It comes largely from cultivation in Japan, the Republic of Korea and China. In Japan's list of products from marine culture, nori has the highest production, followed by oysters, yellowtails and wakame, the last being another seaweed used as food.

Nori grows as a very thin, flat, reddish blade (Figure 47), and is found in most temperate intertidal zones around the world, illustrated by its history of being eaten by the indigenous peoples of northwest America and Canada, Hawaii, New Zealand and parts of the British Isles.

J.M. JONES

FIGURE 47
***Porphyra umbilicalis.* Scale: width of specimen is about 20 cm.**

FIGURE 48
Net cultivation of *Porphyra*

It is among the most nutritious seaweeds, with a protein content of 30–50 percent, and about 75 percent of that is digestible. Sugars are low (0.1 percent), and the vitamin content very high, with significant amounts of Vitamins A, B_1, B_2, B_6, B_{12}, C, niacin and folic acid, but the shelf life of vitamin C can be short in the dried product. During processing to produce the familiar sheets of nori, most salt is washed away, so the sodium content is low. The characteristic taste of nori is caused by the large amounts of three amino acids: alanine, glutamic acid and glycine.

While *Porphyra* can be collected by hand from natural sources, most is now derived from cultivation. *Porphyra* has an unusual life cycle that was not understood until the early 1950s. Until then it had been cultivated but nobody knew where the spores came from, so there was little control over the whole cultivation process.

The seaweed, as we know it, sheds spores and these settle on mollusc shells: in nature it is any nearby; in cultivation they are deliberately placed beneath the blades of the seaweed. An alternate generation of filamentous algae develops from these spores and burrow into the surface of the shell; this is called the conchocelis stage. With lowered light (shorter days) and lower temperatures, more, but different, spores form from the filaments and these are allowed to settle onto nets. It is these spores that develop into the blades of *Porphyra*. The nets are placed in the ocean in such a way that they are exposed to air for a few hours a day (Figure 48). The *Porphyra* is reasonably resistant to some drying out, but the pest seaweeds that try also to grow on the nets do not survive. The nets were originally set up in intertidal flat areas, but as space became short, a new system of floating nets in deeper water was devised. The spores germinate on the nets and grow into new blades of *Porphyra*.

For more information about the life cycle of *Porphyra* and the methods used to seed nets and manipulate them in the sea, descriptions with useful illustrations can be found in Oohusa (1993), Kain (1991) or Mumford and Muira (1988). For information on its nutritive value, see Nisizawa (1987) or Chapman and Chapman (1980: 108–109). For a review of the nutritional value of proteins in nori and other edible seaweeds, see Fleurence (1999).

Good quality nori is in demand in the Republic of Korea, where production methods differ between the northern and southern areas. The floating system is used in the south and production costs are cheaper than in the north, where the original shallow-water pole system is used. However, the northern quality is better and it commands a higher price.

Attempts have been made to cultivate *Porphyra* in non-Asian countries, notably the west and east coasts of United States of America. Cultivation on the west coast – Puget Sound in Washington State – was successful but became unviable commercially when residents of the shore areas objected to the presence of seaweed farms and access to sufficient space to expand the pilot farm was refused. In Maine, on the east coast, cultivation

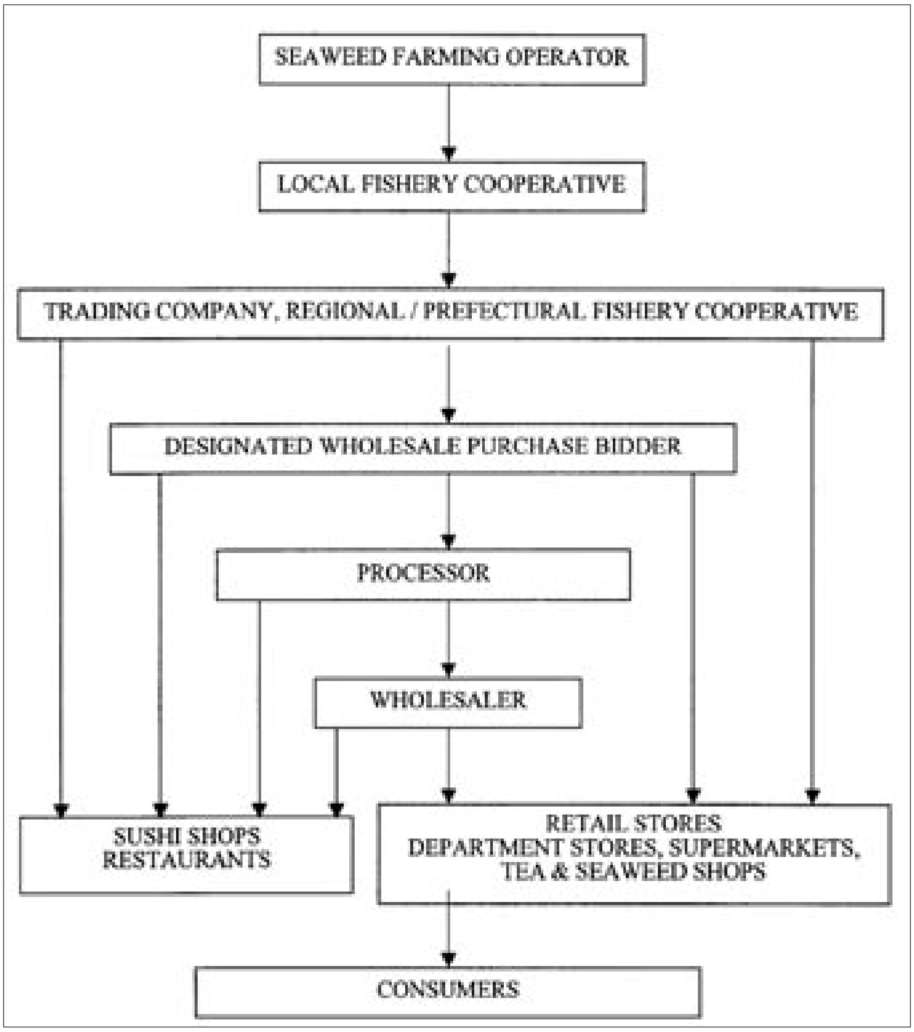


FIGURE 49
Distribution and marketing chain for seaweeds in Japan (after Pacific Islands Centre, Tokyo).

problems with indigenous species of *Porphyra* slowed progress, but as these were being overcome, regulatory issues between landholders and commercial fishermen again delayed progress. In the meantime, the company was reorganized, decided to develop other marine biotechnology interests and to discontinue the nori project.

Japanese cultivation of *Porphyra* yields about 400 000 wet tonne/year and this is processed into ca 10 billion nori sheets (each 20×20 cm, 3.5–4.0 g), representing an annual income of US$ 1 500 million. In the Republic of Korea, cultivation produces 270 000 wet tonnes, while China produces 210 000 wet tonnes.

Processing of wet *Porphyra* into dried sheets of nori has become highly mechanized, rather like an adaptation of the paper-making process. The wet *Porphyra* is rinsed, chopped into small pieces and stirred in a slurry. It is then poured onto mats or frames, most of the water drains away, and the mats run through a dryer. Rate of drying is carefully controlled by adjusting conveyer speed and temperature. The sheets are peeled from the mats and packed in bundles of ten for sale. This product is called *hoshi-nori,* which distinguishes it from *yaki-nori*, which is toasted. Toasted nori is nori pre-toasted and sold in sealed packages; in use it may be brushed with a mixture of soy sauce, sugar, sake and seasonings.

Nori is used mainly as a luxury food. It is often wrapped around the rice ball of sushi, a typical Japanese food consisting of a small handful of boiled rice with a slice of raw fish on the top. After a short baking (slight toasting or baking brings out the flavour), nori can be cut into small pieces and sprinkled over boiled rice or noodles. It can be incorporated into soy sauce and boiled down to give an appetising luxury sauce. It is also used as a raw material for jam and wine. In China it is mostly used in soups and for seasoning fried foods. In the Republic of Korea it has similar uses to Japan, except that a popular snack with beer is hoshi-nori that has been quickly fried in a pan with a little oil.

The distribution and marketing chain for nori and other Japanese seaweeds is illustrated in Figure 49. Dried nori is in constant oversupply in Japan and producers and dealers are trying to encourage its use in United States of America and other countries. Production and markets in China are expanding, although the quality of the product is not always as good as that from the Republic of Korea and Japan. Good quality nori is in demand in the Republic of Korea.

8.3 AONORI OR GREEN LAVER (*Monostroma* spp. and *Enteromorpha* spp.)

These two green seaweed genera are now cultivated in Japan. *Enteromorpha* cultivation has also been attempted in the Republic of Korea but with limited success.

Monostroma latissimum occurs naturally in the bays and gulfs of southern areas of Japan, usually in the upper eulittoral zone. It is cultivated in shallow, calm waters, such as are found in bays and estuaries, but, like *Porphyra*, it can also be grown in deeper waters using floating rafts. It is a flat, leafy plant and only one cell thick. It averages 20 percent protein and has a useful vitamin and mineral content. It has a life cycle involving an alternation of generations (see Section 1.5), one generation being the familiar leafy plant, the other microscopic and approximately spherical. It is this latter generation that releases spores that germinate into the leafy plant.

For cultivation, these spores are collected on rope nets by submerging the nets in areas where natural *Monostroma* populations grow; the spores settle on the nets as they are released by the microscopic spheres. There are other artificial ways of seeding the nets that are used if the waters around the natural populations are too muddy. The seeded nets are then placed in the bay or estuary using either of the two methods previously described for *Porphyra*, fixed to poles so that they are under water at high tide and exposed for about four hours at low tide, or using floating rafts in deeper water. The nets are harvested every 3–4 weeks (for the method, see below for *Enteromorpha*) and the growing season allows about three to four harvests. The harvested seaweed is washed well in seawater and freshwater. It can then either be processed into sheets and dried, as described for *Porphyra*, for sale in shops, or dried, either outside or in dryers, and then boiled with sugar, soy sauce and other ingredients to make “nori-jam”.

Enteromorpha prolifera and *Enteromorpha intestinalis* (Figure 50) are both cultivated, although the production of *Monostroma* is much greater. Both species are found in bays and river mouths around Japan, and are also found in many other parts of the world, including Europe and North America. It can thrive in both salt and brackish waters and is usually found at the top of the sublittoral zone. It contains about 20 percent protein,

FIGURE 50
Enteromorpha intestinalis
(Specimen from National Herbarium, Royal Botanic Gardens, Sydney. Collector: S. Skinner).

little fat, low sodium and high iron and calcium. Its vitamin B-group content is generally higher than most vegetables, and while its vitamin A is high, it is only half of that found in spinach. It was and is collected from natural sources, but careful cultivation can ensure greater uniformity and better colour (green is good, greener is better). Again the life history involves an alternation of generations, but this time both generations have the same appearance of long, tubular filaments.

For cultivation, rope nets are seeded with spores by submerging them in areas where *Enteromorpha* is growing naturally, usually attached to rocks; the better areas have calm waters and sandy bottoms. In the Republic of Korea, seed collection is from June to August and the strings or ropes are taken to culture sites in September; in Japan, seeding is done in September, and by early November young plants are visible. The nets are placed in calm bays or estuaries using either fixed poles in shallow waters or floating rafts in deeper waters.

Harvesting can be done 2–3 times during the growing period, either by hand picking from the nets or by machine. As with *Porphyra* and *Monostroma*, the nets are dragged out of the water and over a cylinder equipped with cutters, mounted in a boat, and then fed back into the water. This is well illustrated in Figure 17A in Ohno and Largo (1998). Hand picking yields the best product, but is slow in comparison with machine harvesting. The harvested seaweed is washed in freshwater and dried in large trays. It can be lightly toasted to improve the flavour, and powdered for use as a condiment on soups and foods, or it can be crushed into small pieces and used as a garnish.

"Sea lettuce" adequately describes a thin green seaweed, a species of *Ulva*, that appears in the mid to lower eulittoral zone. It is collected from the wild and sometimes added to the above two seaweeds as part of aonori. It has a higher protein content than the other two, but much lower vitamin content, except for niacin, which is double that of *Enteromorpha.*

For further details

For the life cycles of *Monostroma* and *Enteromorpha*, and the methods used to seed nets and manipulate them in the sea, descriptions with useful illustrations can be found in Ohno (1993) and there is also some information in Kain (1991).

For data on their nutritive values and those of *Ulva*, see Nisizawa (1987).

8.4 KOMBU OR HAIDAI (*Laminaria japonica*)

Kombu is the Japanese name for the dried seaweed that is derived from a mixture of *Laminaria* species. These include *L. longissima, L. japonica, L. angustata, L. coriacea* and *L. ochotensis.* These are all harvested from natural sources, mainly on the northern island of Hokkaido, with about 10 percent coming from the northern shores of Honshu. The first three of the above are the main components of the harvest. The plants grow on rocks and reefs in the sublittoral zone, from 2–15 m deep. They prefer calm water at temperatures between 3° and 20°C.

Haidai is the Chinese name for *Laminaria japonica*, a seaweed that was introduced to China accidentally from Japan in the late 1920s. Previously, China had imported all requirements from Japan and the Republic of Korea. It is now cultivated on a large scale in China. It is a large seaweed, usually 2–5 m long, but it can grow up to 10 m in favourable conditions (Figure 51). It requires water temperatures below 20°C. *Laminaria japonica* grows naturally in the Republic of Korea and is also cultivated, but on a much smaller scale; the demand is lower because Koreans prefer *wakame* (*Undaria pinnatifida*).

Laminaria species contain about 10 percent protein, 2 percent fat and useful amounts of minerals and vitamins, though generally lower than those found in nori. For example, it has one-tenth the amounts of vitamins B_2, B_{12} and niacin, half the amount of B_1 but three times the amount of iron compared with nori. Brown seaweeds also contain iodine, which is lacking in nori and other red seaweeds.

FIGURE 51
Fresh *Laminaria japonica* (longer piece on right) and *Undaria pinnatifida*.

Japan has a tradition of eating kombu, going back for several centuries, and had a plentiful supply of *Laminaria* by harvesting from its natural beds on Hokkaido. The naturally growing plants are biennial and are ready for harvesting after 20 months. Harvesting is from June to October, from boats. Hooks of various types are attached to long poles and used to twist and break the seaweed from the rocky bottom. As demand grew in the 1960s, attempts were made to develop artificial cultivation methods, but the two-year cycle meant the costs were too high. In the 1970s, forced cultivation was introduced, reducing the cultivation period to one year, similar to the system developed in China in the early 1950s. Today, about one-third of Japan's requirements come from cultivation, with the remaining two-thirds still coming from natural resources.

China had no natural sources of *Laminaria* but it appeared in the northern city of Dalian in 1927 with the importation of logs from Hokkaido in Japan. The Japanese, who then occupied that part of China, tried to increase the growth by their traditional method of throwing rocks into the sea. As it spread, it was harvested from these sublittoral rocks, but there had always been a strong demand for haidai in China, so importation was still necessary. In the 1950s, China developed revolutionary techniques for its cultivation and today about 4 million tonnes of wet seaweed are harvested annually.

For cultivation, *Laminaria* must go through its life cycle, and this involves an alternation of generations. The seaweed itself is the so-called sporophyte stage of the cycle. The spores that it sheds cannot survive above 20°C and the system developed in China overcame this problem by ensuring the spores are shed in seawater that has been cooled below 20°C. In early summer, mature seaweed is dried out slightly and plunged into cooled seawater in tanks. The drying out helps to induce the liberation of the spores. Prior to this, string is wound around frames and placed in the tank of cooled seawater so that when the spores are released, they settle on the string. The frames are then moved into shallow (20–30 cm deep) tanks in a glasshouse and kept in water at 8–10°C that is enriched with nitrogen and phosphate fertilizers. The spores on the string then develop into microscopic gametophytes, which is the alternate generation. The gametophytes mature on the string and after a few weeks they release eggs and spermatozoids that fuse together, and from this a new sporophyte grows. In one to two months, the string becomes crowded with young sporophytes (sporelings) 1–2 mm high. When the sea temperature has fallen below 20°C, the sporelings on the strings are placed in the sea for 1–2 months, until they grow to 10–15 cm.

By now it is November, and the young sporelings are removed from the string and placed individually in the lay of a rope; the rope is untwisted a little, the sporeling placed between the cords and then the rope is allowed to resume its normal twist. The ropes with the young sporophytes are attached to floating rafts. There are two basic types of these rafts.

The first type is the single-rope or hanging-kelp rope raft, which uses a large diameter rope about 60 m long that is kept floating using glass or plastic buoys fixed every 2–3 m. Each end of the rope is anchored to a wooden peg driven into the sea bottom. Hanging down from this rope at 50 cm intervals are the ropes with the young sporophytes attached. Each rope is from 1 to 2 m long and with a bag of stones on the end to weigh it down (Figure 52a). The floating ropes are laid out in the sea about 10 m apart, to allow the passage of a small boat between the ropes.

The second type of raft is the double-raft or horizontal-line raft (Figure 52b). Here three long ropes with floats attached are laid out parallel, about 5 m apart. The short ropes holding the young sporophytes are tied across two ropes so that the sporophyte ropes are more or less horizontal (Figure 53). This arrangement means each sporophyte has about equal access to light, whereas with the vertical lines, the plants on the deeper end get less light and do not grow as well as those at the top end, a problem that can be overcome by reversing the rope halfway through the growing season.

The horizontal-line raft is more resistant to water movement and therefore has less access to nutrients. Generally, the single-rope raft method is better, especially in clear water, and it has the advantage that the depth at which the plant is growing can be easily adjusted. If the water is turbid, the double raft method is used.

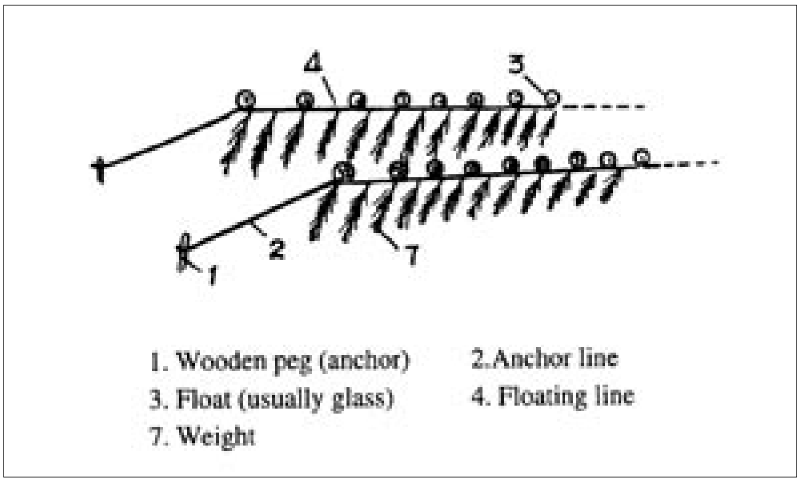


FIGURE 52A
Hanging-kelp raft (after Tseng 1987).

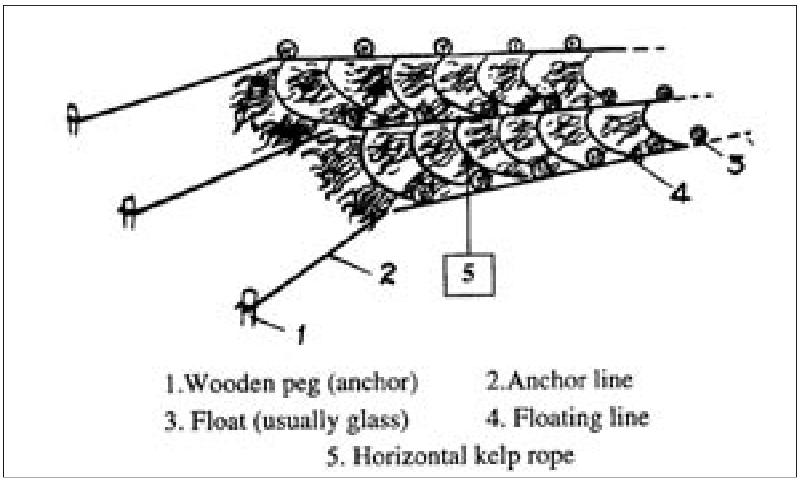


FIGURE 52B
Horizontal-line raft (after Tseng 1987).

FIGURE 53
Horizontal-line raft with Laminaria japonica (Yanti, China).

FIGURE 54
Harvested *Laminaria japonica.* The rope (on left-hand edge of the seaweed) holding the seaweed was removed from between the two floating ropes in Figure 53.

In China, the largest region for *Laminaria* cultivation is in the Yellow Sea, which has been found to be low in nitrogen fertilizer. Yields are increased when the floating raft areas, which are usually set out in rectangles, are sprayed with a nitrate solution using a powerful pump mounted in a boat. The plants take up the nitrate quickly and very little is lost in the sea. In Japan, the cultivation is mainly in the waters between Honshu and Hokkaido islands and fertilizing is not necessary. Harvesting is done from mid-June to early July. The kelp ropes are detached from the floating ropes and collected in small boats (Figure 54), many of which are towed in line by a motor boat. The kelp is usually laid out in the sun to dry (Figure 55), and then packed into bales.

In Japan, the whole seaweed is washed thoroughly with seawater, cut into 1 m lengths, folded and dried; the product is *suboshi kombu* and is delivered to the local fisheries cooperative. From there it follows the type of marketing chain previously shown in Figure 49.

In China, haidai is regarded as a health vegetable because of its mineral and vitamin content, especially in the north, where green vegetables are scare in winter. It is usually cooked in soups with other ingredients. In Japan, it is used in everyday food, such as a seasoned and cooked kombu that is served with herring or sliced salmon. Suboshi kombu can be treated by placing it in a boiling solution of a dye, malachite green, to give it a dark green colour, after which it is partly dried and then shredded with a plane; this is *aokombu* or green kombu. Kombu tea is like green kombu but shaved a second time so the shavings are like tea leaves. Other variations are used to produce different kombu types. In cooking, green kombu is boiled with meat, fish and soups. Powdered kombu is

FIGURE 55
Drying *Laminaria japonica* (Yanti, China).

added to sauces and soups, and to rice. Green kombu and tea kombu are used to make a tea-like beverage.

For further details

- For more information on the nutrients in *Laminaria,* see Nisizawa (1987) and Nisizawa *et al.* (1987).
- For more details of *Laminaria* cultivation, see Tseng (1987), Kain (1991), and Kawashima (1993).
- For more about different types of kombu and ways of cooking them, see Chapman and Chapman (1980: 76–78) and Nisizawa (1987).

8.5 WAKAME, QUANDAI-CAI (*Undaria pinnatifida*)

Undaria pinnatifida, a brown seaweed (Figures 51 and 56), occurs on rocky shores and bays in the temperate zones of Japan, the Republic of Korea and China. It grows on rocks and reefs in the sublittoral zone, down to about 7 m. It grows best between 5° and 15°C, and stops growing if the water temperature rises above 25°C. It has been spread, probably via ship ballast water, to France, New Zealand and Australia.

Wakame has a high total dietary fibre content, higher than nori or kombu. Like the other brown seaweeds, the fat content is quite low. Air-dried wakame has a similar vitamin content to the wet seaweed and is relatively rich in the vitamin B group, especially niacin; however, processed wakame products lose most of their vitamins. Raw wakame contains appreciable amounts of essential trace elements such as manganese, copper, cobalt, iron, nickel and zinc, similar to kombu and hiziki.

Undaria is an annual plant with a life cycle similar to *Laminaria*. It has an alternation of generations with the large seaweed as the sporophyte and a microscopic gametophyte as the alternate generation. Some wild material is collected and used locally, but all the commercial products are from cultivated plants. Cultivation methods are very similar to those used for *Laminaria*, although some of the temperature tolerances are different. The Republic of Korea is the largest producer of wakame. There, seeding starts in April; string is wound around frames and these are immersed in tanks. Fresh, mature plants

FIGURE 56
***Undaria pinnatifida,* dried specimen (China).**

(sporophytes) are air-dried in the shade for about an hour and then immersed in the tanks so spores are released and settle on the strings. The tanks are exposed to natural light and the seawater in the tanks is changed monthly; the water temperature must be kept below 25°C or the gametophytes may die. The gametophytes mature, fertilized eggs form on the strings and develop into young sporophytes. During September–October the sea water drops below 23°C and the frames or strings are moved to protected intermediate culture areas so that the young plants can adapt to open seawater conditions.

Once the young plants are 1–2 cm long, the strings are removed from the frames and wound around a rope that is suspended by floats and anchored to the bottom at each end. However, a variation from the *Laminaria* cultivation is that the rope long-lines are suspended 2–3 m below the surface. In sheltered bays, the ropes are placed 10 m apart; in open waters, where there is more movement, the single ropes are assembled into a grid pattern using connecting ropes to hold the long-lines about 2 m apart. Harvesting is in two stages. First the plants are thinned out by cutting them off at a point close to the rope. This is done by pulling the rope over the edge of a boat, cutting and dragging the plant into the boat. The remaining plants on the rope have plenty of space and continue to grow. Harvesting finishes in April. In Japan, the seeded strings are often cut into small lengths and inserted in the twist of a rope that is then hung vertically from a floating rope, much the same as is done with *Laminaria.* Harvesting in southern Japan is from March to May, but around Hokkaido it is from May to July.

Cultivation has also been undertaken in France. Here the above methods were found to be inappropriate because the high nutrient concentrations in the water allowed a large variety of other plant and animal life (epiphytes) to grow on the frames holding the strings. The constant cleaning of the frames proved to be too expensive. Instead, the alternate generation, the gametophytes, are formed and maintained in a sterile laboratory medium. One month before out-planting the gametophytes are brought to maturation. After fertilized eggs (zygotes) are formed, the solution with the suspended zygotes is sprayed onto a nylon line that is wound around a frame. The zygotes germinate and young sporophytes begin to grow on the frames, which are free of epiphytes. The sporophytes are out-planted on floating ropes in the usual way.

After harvesting, the plants are washed with seawater, then freshwater, the central midrib is removed and the pieces are dried in the sun or a hot air dryer; this is *suboshi wakame*. However, this product often fades during storage because various enzymes are still active. To overcome this, another process can be used in which the fresh seaweed is mixed with ash from wood or straw, spread on the ground for 2–3 days, then placed in a plastic bag in the dark. The alkalinity of the ash inactivates the enzymes. The plants are washed with seawater, then freshwater to remove the salt and ash, the midrib is removed and the pieces are dried. This is *haiboshi wakame* and it keeps its deep green colour for a long time.

Blanched and salted wakame is the major wakame product. Fresh wakame is plunged into water at 80°C for 1 minute and cooled quickly in cold water. About 30 kg of salt per 100 kg of seaweed are mixed and stored for 24 hours. This dehydrates the wakame; excess water is removed and the seaweed stored at -10°C. When ready for packaging, it is taken from storage, the midribs are removed and the pieces placed in plastic bags for sale. It is a fresh green colour and can be preserved for long periods when stored at low temperatures.

Cut wakame is a very convenient form, used for various instant foods such as noodles and soups. It is one of the most popular dried wakame products. It is made from blanched and salted wakame which is washed with freshwater to remove salt, cut into small pieces, dried in a flow-through dryer and passed through sieves to sort the different sized pieces. It has a long storage life and is a fresh green colour when rehydrated.

In the Republic of Korea, wakame is enjoyed as an ingredient in soybean and other soups, as well as vinegared seaweed salads. In recent times there has been an overproduction of wakame and this has led to increased marketing efforts through the introduction of new products, such as seaweed salad, pre-cooked wakame, powdered wakame for use as a condiment and further expansion of the uses of cut, dried wakame.

Wakame is more popular in the Republic of Korea than in Japan, although the market in Japan has expanded. Wakame is traditionally regarded as a luxury food in both countries, although overproduction has led to reduced prices in recent times. The Republic of Korea produces ten times more *Undaria* than *Laminaria* ; it produces four times more *Undaria* than Japan. Production in China has apparently increased, as has its exports to Japan. In 2001, the Chinese seaweed industry agreed to reduce exports of wakame to Japan, beginning in April 2002. Japanese wakame producers agreed to support Chinese seaweed growers in finding other overseas markets and expanding demand in China. Japan imported 180 000 tonnes of wakame from China from mid-1999 to mid-2000, a 2.4-fold increase from four years earlier. Production in Japan halved during that one year period.

For further details

For further detail on the nutrients in *Undaria*, see Nisizawa (1987) and Nisizawa *et al.* (1987).

For more information about the cultivation of *Undaria* in the Republic of Korea, see Sohn and Kain (1989), Kain (1991) and Sohn (1998). For cultivation in Japan, see Ohno and Matsuoka (1993).

For details of the cultivation method used in France see Kaas (1998).

Methods of processing raw *Undaria* into marketable products are discussed in Nisizawa *et al.* (1987) and Yamanaka and Akiyama (1993).

8.6 HIZIKI (*Hizikia fusiforme*)

Hizikia fusiforme is a brown seaweed with a finer frond (leaf) structure (Figure 57) than wakame and kombu. It is collected from the wild in Japan and cultivated in the Republic of Korea, grows at the bottom of the eulittoral and top of the sublittoral zones, and is on the southern shore of Hokkaido, all around Honshu, on the Korean peninsula and most coasts of the China Sea. About 90 percent of the Republic of Korea production is processed and exported to Japan.

The protein, fat, carbohydrate and vitamin contents are similar to those found in kombu, although most of the vitamins are destroyed in the processing of the raw seaweed. The iron, copper and manganese contents are relatively high, certainly higher than in kombu. Like most brown seaweeds, its fat content is low (1.5 percent) but 20-25 percent of the fatty acid is eicosapentaenoic acid (EPA).

Some is collected from the wild, but this has decreased as cultivation has grown. For example, in 1990 in the Republic of Korea, 10 000 wet tonnes was collected from the wild and 20 000 wet tonnes was cultivated, but by 1995 these amounts had changed to 6 000 and 37 000 wet tonnes, respectively. However, for cultivation there are still problems in artificial seed production, so instead, young fronds are collected from the natural beds and 3–4 are inserted in a rope at 10 cm intervals. Seeding ropes are attached to the main cultivation rope (Figure 58), which is kept at a depth of 2–3 m using flotation buoys along the rope and anchoring it to the seabed at each end – as described previously for *Undaria.* Cultivation is from November to May, mainly to avoid a clash with activities connected with wakame cultivation. Harvesting is in May–June. More convenient methods of farming are being tried, including vegetative reproduction.

After harvesting, it is washed with seawater (Figure 59) and dried in the sun (Figure 60). However, *Hizikia* is a very dark colour and contains higher than usual amounts of a pigment, phlorotannin, that gives it an astringent, bitter taste. Further processing involves boiling in water for 4–5 hours with another brown seaweed added, *Eisenia bicyclis* or *Ecklonia cava.* Boiling removes some of the pigment from *Hizikia* and it has been found that the addition of *Eisenia* or *Ecklonia* provides it with replacement colour. After boiling,

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FIGURE 57
***Hizikia fusiformis,* mature plants from cultivation.**

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FIGURE 58
***Hizikia fusiformis.* The seeding rope (white) was attached to the main rope when the seedlings were small.**

the seaweed is steamed for 4–5 hours to remove the phlorotannins. Then it is cut into short pieces and sun-dried. The product is called *hoshi hiziki.* It is sold packaged in dried, black, brittle pieces that are soaked for 10–15 minutes before use. Typically it is cooked in stir fries, with fried bean curd and vegetables such as carrot, or it may be simmered with other vegetables.

Sun-dried hiziki is collected at local cooperatives and sold by auction to wholesalers, who later sell to processors. They prepare the hoshi hiziki by the boiling and steaming process and package it for retail sale.

For further details

More detailed information about the nutritive value of *Hizikia* is available in Nisizawa (1987) and Nisizawa *et al*. (1987).

Cultivation is described in Sohn (1998), with useful illustrations, and in Sohn (1999).

Limited processing information is found in Nisizawa (1987), Nisizawa *et al*. (1987) and Sohn (1998).

8.7 MOZUKU (*Cladosiphon okamuranus*)

Mozuku (*Cladosiphon okamuranus*) is a brown seaweed that is harvested from natural populations in the more tropical climate of the southern islands of Japan (Kagoshima and Okinawa Prefectures). *Cladosiphon* grows in the sublittoral, mainly at depths of 1–3 m. In the 5–6 months from late October to April it grows from 1–2 cm to its full size of

FIGURE 59
Washing *Hizikia fusiformis* (Cheju Island, the Republic of Korea).

FIGURE 60
Sun drying *Hizikia fusiformis* (Cheju Island, the Republic of Korea).

20–30 cm. It prefers reef flats in calm water, although a moderate water current is needed to supply sufficient nutrients.

Its life history involves an alternation of generations, with the seaweed being the sporophyte, while the alternate generation, the gametophyte, are microscopic plants. Cultivation involves collecting spores from the sporophytes and storing them in transparent polycarbonate tanks during summer. In autumn, seed nets are prepared and transferred to a nursery ground, preferably seagrass beds or similar sea beds with moderate currents. When young sporophytes have grown to 2–5 cm, the nets are moved to the main cultivation sites. These have a water depth of up to 3 m at low tide and the nets are placed 30–40 cm above the bottom. The plants are harvested after about 90 days, when they have grown to 30 cm. Harvesting is done by divers using a suction pump that draws the seaweed up and into a floating basket beside the attending boat. The harvested seaweed must be protected from sunlight. Processing for market involves cleaning and salting with 20–25 percent salt. It is stored to dehydrate for about 15 days, drained and sold in wet, salted form in packages ranging from 250 g to 18 kg.

After washing to remove the salt, it is used as a fresh vegetable, eaten with soy sauce and in seaweed salads. Due to increasing demand, cultivation was started around Okinawa Island in the 1980s. By 1995, production was 10 000 wet tonne/year and there was an oversupply. It has also been cultivated on the islands of Tonga in the Pacific, looking to an export market in Japan, but the oversupply there has stifled progress.

For further details

A full explanation of the life cycle and cultivation method is available in Toma (1993).

8.8 SEA GRAPES OR GREEN CAVIAR (*Caulerpa lentillifera*)

There are many species of the genus *Caulerpa,* but *Caulerpa lentillifera* and *C. racemosa* are the two most popular edible ones. Both have a grape-like appearance and are used in fresh salads. They are commonly found on sandy or muddy sea bottoms in shallow protected areas. The pond cultivation of *C. lentillifera* has been very successful on Mactan Island, Cebu, in the central Philippines, with markets in Cebu and Manila and some exports to Japan. About 400 ha of ponds are under cultivation, producing 12–15 tonnes of fresh seaweed per hectare per year.

C. lentillifera (Figure 61) is the species best adapted to pond culture, although some strains of *C. racemosa* also give good yields. *C. lentillifera* is sensitive to changes of salinity, so pond areas must be placed away from any freshwater sources, and in the wet season in the Philippines surface drains are placed around the ponds to remove freshwater. The seaweed can tolerate a salinity range of 30–35 parts per thousand. Successful cultivation depends on good water management and the ponds must be designed so that tidal flows can be used to change the water in the ponds every second day. Water temperature can range between 25° and 30°C. Pond depth should be about 0.5 m and areas of about 0.5 ha are usual.

Planting is done by hand; about 100 g lots are pushed into the soft bottom at 0.5–1 m intervals. Sometimes broadcasting is used but this is not as efficient, the plants are loose on the bottom and can be moved by water motion induced by wind action on the surface. Key factors to control during growth are water exchange, weeding of other species of seaweed that would otherwise compete with the *Caulerpa*, and fertilization if the plants appear unhealthy or pale green to yellow in colour. Harvesting can commence about two months after the first planting; the seaweed is pulled out of the muddy bottom, but about 25 percent of the plants are left as seed for the next harvest. Depending on growth rates, harvesting can then be done every two weeks. The harvested plants are washed thoroughly in seawater to remove all sand and mud, then inspected, sorted and placed in 100–200 g packages; these will stay fresh for 7 days if chilled and kept moist. For local consumption, or air freight to Metro Manila, the seaweed may be packed in baskets lined with banana

FIGURE 61
***Caulerpa lentillifera* (the Philippines).**

leaves; 20–30 kg of seaweed is placed on the leaves, the basket is topped with more banana leaves and covered with a plastic sack that is then fixed to the basket.

For further details
A full description of pond culture of *Caulerpa lentillifera* and an analysis of the economics of a one-hectare farm can be found in Trono and Ganzon-Fortes (1988). However, that reference is out of print and may be difficult to locate. Other useful descriptions of the details of pond culture are in Trono and Toma (1993) and Trono (1998).

8.9 DULSE (*Palmaria palmata*)
Dulse, a red algae with leathery fronds (leaves) (Figure 62), is found in the eulittoral zone and sometimes the upper sublittoral. It is collected by hand by harvesters plucking it from the rocks at low tide. It is perennial and when either plucked or cut, new growth appears from the edge of the previous season's leaf. It is harvested mainly in Ireland and the shores of the Bay of Fundy in eastern Canada, and is especially abundant around Grand Manan Island, situated in the Bay of Fundy, in a line with the Canadian-United States of America border between New Brunswick and Maine. The harvest season here is from mid-May to mid-October. After picking, the seaweed is laid out to sun dry for 6–8 hours; if the weather is not suitable, it can be stored in seawater for a few days, but it soon deteriorates. Whole dulse is packed for sale in plastic bags, 50 g per bag. Inferior dulse, usually because of poor drying, is broken into flakes or ground into powder for use as a seasoning; sometimes it

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FIGURE 62
Dulse, *Palmaria palmata.* The smallest division on the scale is 1 mm, the large divisions are 1 cm.

is added to corn chips. In Nova Scotia and Maine, dried dulse is often served as a salty cocktail snack and bar owners often offer it free – it induces thirst.

In Ireland, it is sold in packages and looks like dark-red bundles of flat leaves. It is eaten raw in Ireland, like chewing tobacco, or is cooked with potatoes, in soups and fish dishes. One company in Northern Ireland is promoting its sale through pubs as a chewy, salty snack food, and through fruit and vegetable markets.

Dulse is a good source of minerals, being very high in iron and containing all the trace elements needed in human nutrition. Its vitamin content is also much higher than a vegetable such as spinach. In Canada, one company has cultivated it in land-based systems (tanks) and promotes it as a sea vegetable with the trade name "Sea Parsley". It is a variant of normal dulse plants, but with small frilly outgrowths from the normally flat plant. It was found by staff at the National Research Council of Canada's laboratories in Halifax, Nova Scotia, among samples from a commercial dulse harvester. For more information, go to www.oceanproduce.com. For those interested in some background information and opinions on why the North American dulse industry has not prospered, see Chopin (1998).

8.10 IRISH MOSS OR CARRAGEENAN MOSS (*Chondrus crispus*)

Chondrus crispus has already been discussed as a source of carrageenan, in Sections 6.2 to 6.4. Irish Moss has a long history of use in foods in Ireland and some parts of Europe. It is not eaten as such, but used for its thickening powers when boiled in water, a result of its carrageenan content. One example is its use in making blancmange, a traditional vanilla-flavoured pudding. In eastern Canada, a company is cultivating a strain of *Chondrus crispus* and marketing it in Japan as *hana nori*, a yellow seaweed that resembles another traditional Japanese seaweed that is in limited supply from natural resources because of overharvesting and pollution. First introduced to the Japanese market in 1996, the dried product, to be reconstituted by the user, was reported to be selling well at the end of 1999, with forecasts of a market valued at tens of millions of US dollars. It is used in seaweed salads, sashimi garnishes and as a soup ingredient.

8.11 WINGED KELP (*Alaria esculenta*)

This large brown kelp grows in the upper limit of the sublittoral zone. It has a wide distribution in cold waters and does not survive above 16°C. It is found in areas such as Ireland, Scotland (United Kingdom), Iceland, Brittany (France), Norway, Nova Scotia (Canada), Sakhalin (Russia) and northern Hokkaido (Japan). In Ireland it grows up to 4 m in length and favours wave-exposed rocky reefs all around the Irish coast. Eaten in Ireland, Scotland (United Kingdom) and Iceland either fresh or cooked, it is said to have the best protein among the kelps and is also rich in trace metals and vitamins, especially niacin. It is usually collected from the wild and eaten by local people, and while it has been successfully cultivated, this has not been extended to a commercial scale.

8.12 OGO, OGONORI OR SEA MOSS (*Gracilaria* spp.)

Gracilaria species have already been discussed as sources of agar, in Sections 2.2 and 2.3.

Fresh *Gracilaria* has been collected and sold as a salad vegetable in Hawaii (United States of America) for several decades. The mixture of ethnic groups in Hawaii (Hawaiians, Filipinos, Koreans, Japanese, Chinese) creates an unusual demand and supply has at times been limited by the stocks available from natural sources. Now it is being successfully cultivated in Hawaii using an aerated tank system, producing up to 6 tonnes fresh weight per week. *Limu manauea* and *limu ogo* are both sold as fresh vegetables, the latter usually mixed with raw fish. In Indonesia, Malaysia, the Philippines and Viet Nam, species of *Gracilaria* are collected by coastal people for food. In southern Thailand, an education programme was undertaken to show people how it could be used to make jellies by boiling and making use of the extracted agar. In the West Indies, *Gracilaria* is sold in markets as "sea moss"; it is reputed to have aphrodisiac properties and is also used as a base for a non-alcoholic drink. It has been successfully cultivated for this purpose in St Lucia and adjacent islands.

8.13 *Callophyllis variegata*

In Chile, the demand for edible seaweeds has increased and *Callophyllis variegata* ("carola") is one of the most popular. Its consumption has risen from zero in 1995 to 84 wet tonnes in 1999. This red seaweed has a high commercial value but knowledge of its biology is restricted. In 1997, a new research project was funded, which should result in recommendations for the management of the natural resources and opportunities for cultivation.

8.14 FUTURE PROSPECTS

The seaweeds eaten in large quantities in China, the Republic of Korea and Japan (nori, kombu nad wakame) are all in a state of full supply, if not oversupply, in those countries. Nori producers in Japan are looking for exports to United States of America and other countries to absorb their surplus production. This, taken with the experiences of the two companies that attempted nori production in United States of America, means it would not be advisable to invest in new production facilities for nori in the near future. Certainly any prospective investors in developed countries would first need to secure rights to all the cultivation areas they propose to use.

Those marketing wakame and other edible seaweeds in Europe, and France in particular, have shown that patience is needed to gain acceptance. However, the oversupply of wakame in the Republic of Korea has shown how new innovative products can expand a market. Similarly, there is something to be learned from the success of the two Canadian ventures, Sea Parsley and hana nori. Both are new products from seaweeds that have been accepted as human food for many decades. The success of their investors reflects both their ability to identify and exploit niche markets and the expertise to cultivate a consistent product.

The venture in Hawaii illustrates another approach that can be taken. Here there was an established market for fresh seaweeds but an unreliable supply from natural resources. By investing in the equipment and expertise for cultivation, a successful operation producing fresh edible seaweeds has been established. The Philippines experience with *Caulerpa* cultivation as a fresh vegetable is another illustration of using cultivation to widen a market first established from wild seaweed; it is surprising that this kind of enterprise has not been copied in other tropical countries.

Innovation, cultivation and niche markets: the combination of these three may lead to greater success for future investors, rather than attempts to break into the large markets for nori, kombu and wakame.

Finally, some useful ideas from D. Myslabodski (Great Sea Vegetables, United States of America. *pers. comm.*). Not everyone will jump at the opportunity of having a plate of *Caulerpa* with their salad or having dulse as a snack. He suggests a different approach to the use of seaweeds in human food: "sea farina". This is a food grade seaweed meal (ground dried seaweed) with a particle or mesh size dependent on the final application: fine for baking, coarser for use as salt substitute or condiment. This could be made on a small or large scale. There is a long list of sea plants that have been traditional sources of human food around the world and this information could be used as a reference for collection and cultivation. What would be the health benefits to people in developing countries if just 3 percent sea farina were added to the tortillas, pitas and breads of the world? Is there a market in developed countries for such a "natural" and "organically grown" additive to the normal diet? Properly dried sea vegetables and sea farina are stable for months, perhaps longer. They do not need to be frozen or refrigerated, and sea farina is very compact and so easy to transport.

A last word from Myslabodski and others in the food business. In the English language we have done ourselves a disservice calling it "seaweed": weeds are something we do not want, seaweed implies something negative about the product. When trying to convince others to eat it, "sea plants" or "sea vegetables" may be more appropriate words to describe it.

9. Other uses of seaweeds

9.1 FERTILIZERS AND SOIL CONDITIONERS

There is a long history of coastal people using seaweeds, especially the large brown seaweeds, to fertilize nearby land. Wet seaweed is heavy so it was not usually carried very far inland, although on the west coast of Ireland enthusiasm was such that it was transported several kilometres from the shore. Generally drift seaweed or beach-washed seaweed is collected, although in Scotland farmers sometimes cut *Ascophyllum* exposed at low tide. In Cornwall (United Kingdom), the practice was to mix the seaweed with sand, let it rot and then dig it in. For over a few hundred kilometres of the coast line around Brittany (France), the beach-cast, brown seaweed is regularly collected by farmers and used on fields up to a kilometre inland. Similar practices can be reported for many countries around the world. For example in a more tropical climate like the Philippines, large quantities of *Sargassum* have been collected, used wet locally, but also sun dried and transported to other areas. In Puerto Madryn (Argentina), large quantities of green seaweeds are cast ashore every summer and interfere with recreational uses of beaches. Part of this algal mass has been composted and then used in trials for growing tomato plants in various types of soil. In all cases, the addition of the compost increased water holding capacity and plant growth, so composting simultaneously solved environmental pollution problems and produced a useful organic fertilizer.

Seaweed meal is dried, milled seaweed, and again it is usually based on the brown seaweeds because they are the most readily available in large quantities. Species of *Ascophyllum*, *Ecklonia* and *Fucus* are the common ones. They are sold as soil additives and function as both fertilizer and soil conditioner. They have a suitable content of nitrogen and potassium, but are much lower in phosphorus than traditional animal manures and the typical N:P:K ratios in chemical fertilizers. The large amounts of insoluble carbohydrates in brown seaweeds act as soil conditioners (improve aeration and soil structure, especially in clay soils) and have good moisture retention properties. Their effectiveness as fertilizers is also sometimes attributed to the trace elements they contain, but the actual contribution they make is very small compared to normal plant requirements. One company in Ireland that produces milled seaweed for the alginate industry is developing applications for seaweed meal in Mediterranean fruit and vegetable cultivation. "Afrikelp" is another example of a commercially available dried seaweed, sold as a fertilizer and soil conditioner; it is based on the brown seaweed *Ecklonia maxima* that is washed up on the beaches of the west coast of Africa and Namibia. Weiersbye *et al.* (no date), in a paper on the Website of the University of Namibia, describe how *Ecklonia maxima* was tested for potential application as a fertilizer and soil conditioner. For the reader who is interested in more information, this paper illustrates the requirements for a seaweed in these applications

In a chapter about the agricultural uses of seaweeds, Blunden (1991) describes an interesting application of *Ascophyllum* as a soil conditioner in controlling losses of top soil. Like all brown seaweeds, *Ascophyllum* contains alginate, a carbohydrate composed of long chains. When calcium is added to alginate, it forms strong gels. By composting the dried, powdered *Ascophyllum* under controlled conditions for 11–12 days , the alginate chains are broken into smaller chains and these chains still form gels with calcium but they are weaker. The composted product is a dark brown, granular material containing 20–25 percent water and it can be easily stored and used in this form. Steep slopes are difficult to cultivate with conventional equipment and are likely to suffer soil loss by runoff. Spraying such slopes with composted *Ascophyllum*, clay, fertilizer, seed, mulch and water has given good results, even on bare rock. Plants quickly grow and topsoil forms after a few years. The spray is thixotropic, i.e. it is fluid when a force is applied to spread it but it sets to a weak gel when standing for a time and sticks to the sloping surface. It holds any soil in place and retains enough moisture to allow the seeds to germinate. Composted *Ascophyllum* has been used after the construction of roads in a number of countries, and has found other uses as well. For more detail see Blunden (1991: 66–68).

Maerl is a fertilizer derived from red seaweeds that grow with a crust of calcium carbonate on the outside, the calcareous red algae, *Phymatolithon calcareum* and *Lithothamnion corallioides*. They grow at depths of 1–7 m and are found mainly on the coast of France near the mouths of rivers and calm bays, where the water temperature must be 13°C or higher. They are harvested by dredging or digging and are used to neutralize acid soils, as a substitute for agricultural lime. Maerl is more expensive than lime but is alleged to be better because of the trace elements it contains; however, there may be cheaper ways of adding trace elements.

Seaweed extracts and suspensions have achieved a broader use and market than seaweed and seaweed meal. They are sold in concentrated form, are easy to transport, dilute and apply and act more rapidly. One of the earliest patents was applied for by Plant Productivity Ltd., a British company, in 1949. Today there are several products and brands available, such as Maxicrop (United Kingdom), Goëmill (France), Algifert (Norway), Kelpak 66 (South Africa) and Seasol (Australia).

They are all made from brown seaweeds, although the species varies between countries. Some are made by alkaline extraction of the seaweed and anything that does not dissolve is removed by filtration (e.g. Maxicrop and Seasol). Others are suspensions of very fine particles of seaweed (Goëmill and Kelpak 66).

For Goëmill, the seaweed (*Ascophyllum*) is rinsed, frozen at -25°C, crushed into very fine particles and homogenized; the result is a creamy product with particles of 6–10 micrometres; everything from the seaweed is in the product. Other chemicals may be added to improve the product for particular applications. Kelpak first appeared in 1983 and the originators say it is made from *Ecklonia maxima* by a cell-burst procedure that does not involve the use of heat, chemicals or dehydration. Fresh plants are harvested by cutting from the rocks at the stipe (stalk) and then they are progressively reduced in particle size using wet milling equipment. These small particles are finally passed under extremely high pressure into a low-pressure chamber so that they shear and disintegrate, giving a liquid concentrate.

Seaweed extracts have given positive results in many applications. There are probably other applications where they have not made significant improvements, but these receive less, if any, publicity. However, there is no doubt that seaweed extracts are now widely accepted in the horticultural industry. When applied to fruit, vegetable and flower crops, some improvements have included higher yields, increased uptake of soil nutrients, increased resistance to some pests such as red spider mite and aphids, improved seed germination, and more resistance to frost. There have been many, many controlled studies to show the value of using seaweed extracts, with mixed results. For example, they may improve the yield of one cultivar of potato but not another grown under the same conditions. No one is really sure about why they are effective, despite many studies having being made. The trace element content is insufficient to account for the improved yields, etc. It has been shown that most of the extracts contain several types of plant growth regulators such as cytokinins, auxins and betaines, but even here there is no clear evidence that these alone are responsible for the improvements. Blunden (1991) summarizes the situation when he says “there is a sufficient body of information available to show that the use of seaweed extracts is beneficial in certain cases, even though the reasons for the benefits are not fully understood”.

Finally there is the question, are seaweed extracts an economically attractive alternative to NPK fertilizers? Perhaps not when used on their own, but when used with NPK fertilizers they improve the effectiveness of the fertilizers, so less can be used, with a lowering of costs. Then there are always those who prefer an "organic" or "natural" fertilizer, especially in horticulture, so seaweed extracts probably have a bright future.

For further details

For useful discussions of most aspects of seaweeds as fertilizers, see Blunden (1991) and Chapman and Chapman (1980). The chapter by Metting *et al*. (1990) includes van Staden among the authors; he has made many studies on seaweed extracts so the chapter has a stronger emphasis on seaweed extracts, including a useful table summarizing studies that have been made on the effectiveness of seaweed extracts. For a review of the evidence for plant growth regulators in seaweed extracts, and their effectiveness, see Crouch and van Staden (1993).

9.2 ANIMAL FEED

For a long time, animals such as sheep, cattle and horses that lived in coastal areas have eaten seaweed, especially in those European countries where large brown seaweeds were washed ashore. Today the availability of seaweed for animals has been increased with the production of seaweed meal: dried seaweed that has been milled to a fine powder. Norway was among the early producers of seaweed meal, using *Ascophyllum nodosum*, a seaweed that grows in the eulittoral zone so that it can be cut and collected when exposed at low tide. France has used *Laminaria digitata*, Iceland both *Ascophyllum* and *Laminaria* species, and the United Kingdom, *Ascophyllum*.

Because *Ascophyllum* is so accessible, it is the main raw material for seaweed meal and most experimental work to measure the effectiveness of seaweed meal has been done on this seaweed. The seaweed used for meal must be freshly cut, as drift seaweed is low in minerals and usually becomes infected with mould. The wet seaweed is passed through hammer mills with progressively smaller screens to reduce it to fine particles. These are passed through a drum dryer starting at 700–800°C and exiting at no more than 70°C. It should have a moisture level of about 15 percent. It is milled and stored in sealed bags because it picks up moisture if exposed to air. It can be stored for about a year.

Analysis shows that it contains useful amounts of minerals (potassium, phosphorus, magnesium, calcium, sodium, chlorine and sulphur), trace elements and vitamins. Trace elements are essential elements needed by humans and other mammals in smaller quantities than iron (approximately 50 mg/kg body weight), and include zinc, cobalt, chromium, molybdenum, nickel, tin, vanadium, fluorine and iodine. Because most of the carbohydrates and proteins are not digestible, the nutritional value of seaweed has traditionally been assumed to be in its contribution of minerals, trace elements and vitamins to the diet of animals. In Norway, it has been assessed as having only 30 percent of the feeding value of grains.

Ascophyllum is a very dark seaweed due to a high content of phenolic compounds. It is likely that the protein is bound to the phenols, giving insoluble compounds that are not attacked by bacteria in the stomach or enzymes in the intestine. *Alaria esculenta* is another large brown seaweed, but much lighter in colour and in some experimental trials it has been found to be more effective than *Ascophyllum* meal. It is this lack of protein digestibility that is a distinct drawback to *Ascophyllum* meal providing a useful energy content. In preparing compound feedstuffs, farmers may be less concerned about the price per kilogram of an additive; the decisive factor is more likely to be the digestibility and nutritive value of the additive.

In feeding trials with poultry, adding *Ascophyllum* meal had no benefit except to increase the iodine content of the eggs. With pigs, addition of 3 percent *Ascophyllum* meal had no effect on the meat yield. However, there have been some positive results reported with cattle and sheep. An experiment for 7 years with dairy cows (seven pairs of identical twins) showed an average increase in milk production of 6.8 percent that lead to 13 percent more income. A trial involving two groups each of 900 ewes showed that those fed seaweed meal over a two-year period maintained their weight much better during winter feeding and also gave greater wool production.

The results of trials reported above and in the suggested reading below leave the impression that seaweed meal is probably only really beneficial to sheep and cattle. Certainly the size of the industry has diminished since the late 1960s and early 1970s, when Norway alone was producing about 15 000 tonnes of seaweed meal annually. Nevertheless, a Web search for "seaweed meal" shows that there are companies in at least Australia, Canada, Ireland, Norway, United Kingdom and United States of America advocating the use of seaweed meal as a feed additive for sheep, cattle, horses, poultry, goats, dogs, cats, emus and alpacas. The horse racing industry seems to be especially targeted. One interesting report from a United States of America university states that the immune system of some animals is boosted by feeding a particular Canadian seaweed meal. Obviously the industry is still active, pursuing niche markets and fostering research that might lead back to further expansion.

For further details

Chapman and Chapman (1980) discuss several feeding trials and has tables showing the protein, fat, ash and fibre of some fresh seaweeds and seaweed meal, as well as the vitamin and mineral content of seaweed meal. Indergaard and Minsaas (1991), also have some composition tables, a more detailed description of feeding trials, a discussion on the place of iodine in animal nutrition and the importance of seaweed meal as a source of iodine.

9.3 FISH FEED

In fish farming, wet feed usually consists of meat waste and fish waste mixed with dry additives containing extra nutrients, all formed together in a doughy mass. When thrown into the fish ponds or cages it must hold together and not disintegrate or dissolve in the water. A binder is needed, sometimes a technical grade of alginate is used. It has also been used to bind formulated feeds for shrimp and abalone. However, cheaper still is the use of finely ground seaweed meal made from brown seaweeds; the alginate in the seaweed acts as the binder. The binder may be a significant proportion of the price of the feed so seaweed meal is a much better choice. However, since the trend is to move to dry feed rather than wet, this market is not expected to expand.

There is also a market for fresh seaweed as a feed for abalone. In Australia, the brown seaweed *Macrocystis pyrifera* and the red seaweed *Gracilaria edulis* have been used. In South Africa, *Porphyra* is in demand for abalone feed and recommendations have been made for the management of the wild population of the seaweed. Pacific dulse (*Palmaria mollis*) has been found to be a valuable food for the red abalone, *Haliotis rufescens*, and development of land-based cultivation has been undertaken with a view to producing commercial quantities of the seaweed. The green seaweed, *Ulva lactuca*, has been fed to *Haliotis tuberculata* and *H. discus*. Feeding trials showed that abalone growth is greatly improved by a high protein content, and this is attained by culturing the seaweed with high levels of ammonia present. Much of the work on seaweeds and abalone has been published in the journals *Aquaculture* and *Journal of Shellfish Research*.

9.4 BIOMASS FOR FUEL

In 1974, the American Gas Association decided to look for a renewable source of methane (natural gas) and sponsored a project to produce seaweed on farms in the ocean, harvest it and convert it to methane by a process of anaerobic fermentation. The project was divided into two parts: one the production and harvesting of the seaweed (biomass), the other the conversion of the biomass to energy (methane, that could be burned to produce energy). The seaweed chosen was the "giant kelp" that grows off the coast of California, *Macrocystis pyrifera*, because of its high growth rate and ease of harvesting by mechanical means. A test farm was built in the ocean, 8 km off the coast of southern California, and 100 kelp plants, 12–22 m long and taken from natural beds were placed on the farm test structure.

Several storms and the resulting waves and currents caused abrasion of the kelp plants and many were lost. Further studies were made to find better ways of attaching the kelp and to make engineering improvements to the farm structure. However, it was eventually decided to move to smaller-scale, near-shore trials, but the offshore experiments did show that kelp would grow offshore and could utilize the nutrients in deep water upwelling by either natural or artificial means.

The near-shore work concentrated on kelp yield and agronomic practices to improve growth rate and yield and avoided involvement in the engineering of offshore structures. Useful information was gathered in this work, and other types of seaweed were also investigated, such as species of *Laminaria*, *Gracilaria* and *Sargassum.* However, those conducting the other half of the project – biomass conversion to methane by anaerobic fermentation – found that *Sargassum* gave a poor gas yield. For *Macrocystis*, the gas yield was good and dependent on the mannitol and alginate content of the seaweed; more gas was produced if the mannitol concentration was high. For *Gracilaria*, the methane yield related closely to the carbohydrate content, and sometimes the protein content as well.

More work is necessary to find better methods for the conversion step, biomass to methane, on a large scale, although the bench-scale work already done indicates that net energy can result from bioconversion, with good yields of methane. More engineering research is needed for the design of suitable open-ocean structures that will allow the kelp to survive storms and excessive wave movements and currents. Methane from marine biomass is a long-term project and research and development have been scaled down, probably to be revived when a crisis threatens in natural gas supplies.

For further details

A useful summary of the work done from 1974 to about 1990 is given by Flowers and Bird (1990). A much more detailed report of the project is in Bird and Benson (1987). Some parts of a chapter by Morand *et al.* (1991) that has a particular emphasis on work in Europe, may also be of interest.

9.5 COSMETICS

"Extract of seaweed" is often found on the list of ingredients on cosmetic packages, particularly in face, hand and body creams or lotions. This usually refers to the use of alginate or carrageenan in the product, and their uses in cosmetics have already been discussed in earlier sections. More information on the use of these two hydrocolloids, as well as agar, can be found in the reference suggested below for further reading.

The use of seaweeds themselves in cosmetics, rather than extracts of them, is rather limited.

Milled seaweed, packed in sachets, is sold as an additive to bath water, sometimes with essential oils added. Bath salts with seaweed meal are also sold. Thalassotherapy has come into fashion in recent years, especially in France. Mineral-rich seawater is used in a range of therapies, including hydrotherapy, massage and a variety of marine mud and algae treatments. One of the treatments is to cover a person's body with a paste of fine particles of seaweed, sometimes wrap them in cling wrap, and warm the body with infrared lamps. It is said to be useful in various ways, including relief of rheumatic pain or the removal of cellulite. Paste mixtures are also used in massage creams, with promises to rapidly restore elasticity and suppleness to the skin. The seaweed pastes are made by freeze grinding or crushing. The seaweed is washed, cleaned and then frozen in slabs. The slabs are either pressed against a grinding wheel or crushed, sometimes with additional freezing with liquid nitrogen that makes the frozen material more brittle and easier to grind or crush. The result is a fine green paste of seaweed.

There appears to be no shortage of products with ingredients and claims linked to seaweeds: creams, face masks, shampoos, body gels, bath salts, and even a do-it-yourself body wrap kit. The efficacy of these products must be judged by the user. One company recently pointed out that the lifetime of cosmetic products has reduced over the years and now rarely exceeds three or four years. Perhaps the seaweed products that are really effective will live longer than this.

For further details

An interesting chapter on the uses of seaweeds in cosmetics, especially in Europe, has been written by De Roeck-Holtzhauer (1991). Other information, including some of that in De Roeck-Holtzhauer, can be found on a website constructed by the Department of Botany, University of Cape Town, but more easily accessed via: www.unam.na/henties/research.html (look for "seaweeds and cosmetics"). For those who have access to a database such as the Dow Jones Interactive Publications Library, a search for articles containing "seaweed" with "cosmetics", "harvest", or similar combinations, should reveal the types of products currently available and their claimed benefits.

9.6 INTEGRATED AQUACULTURE

Cultivation of *Gracilaria* started in Taiwan Province of China in the 1960s as a source of raw material for its agar industry. At first cultivation was on ropes in ditches containing fish pond effluents, but by 1967 it was moved into the fish ponds themselves. This had the twofold benefit of the seaweed using the fish waste material as fertilizer and the fish eating the epiphytes, such as *Enteromorpha* species, that would otherwise become serious pests for the seaweeds. Control with tilapia (*Oreochromis mossambicus*) and milkfish (*Chanos chanos*) was satisfactory as long as the fish were removed before they started to eat the *Gracilaria*; larger fish were periodically removed and replaced by small fish.

This concept of polyculture, or integrated aquaculture to use the more recent terminology, has since been utilized in many situations where the effluent from the aquaculture of one species, potentially threatening environmental damage, can be utilized by another species to its advantage, with a reduction in pollution.

Various strategies have been tried. Seaweed cultivation around the outside of fish cages has led to significantly better growth of seaweed but was only partly successful in removing the large amount of nutrients coming from the fish cages (Figure 63). Unattached *Gracilaria* has been grown in the effluent from shrimp ponds (Figure 64).

Semi-enclosed or land-based systems have been suggested, but the higher capital investment has been a deterrent. In Israel, an integrated system has been tried. Here the effluent from Japanese abalone culture tanks drained into a fish tank that used pellet feeding. The fish effluent in turn drained into a seaweed cultivation tank (species of *Ulva*); the seaweed produced was used to feed the abalone. The abalone and fish grew well, a surplus of seaweed was produced and the ammonia nitrogen in the seaweed effluent was reduced to 10 percent of the total amount fed to the system.

In Hawaii, where *Gracilaria* species are eaten as fresh salad vegetables, shrimp farm effluent has been used to fertilize *Gracilaria* in floating cage culture. In Brazil, cage aquaculture of shrimp in the open sea has been studied in an attempt to reduce the environmental impact of the shrimp industry. It was found that culturing seaweed inside the shrimp cages can improve the economic result for both shrimp and seaweed. In Chile, when *Gracilaria* seaweed cultivation was integrated with salmon farms the seaweed grew well and removed a large amount of the ammonium excreted by the fish. In France, trials were run with *Gracilaria* growing in closed and semi-enclosed systems, in the effluents from oyster farms; 90 percent efficiency was recorded in removal of ammonia coupled with useful growth of the seaweed. *Porphyra* species are the source of the human food, nori, and so their use in integrated aquaculture is an attractive economic alternative, particularly because they are very efficient in taking up nutrients. Trials are being run on the east coast of Canada and United States of America to combine *Porphyra* with salmon farming.

These are just a few examples of the small- and large-scale uses that are evolving in the integrated aquaculture of seaweeds with other species. Integrated aquaculture is developing as

FIGURE 63
Gracilaria growing in fish cages (Songkhla Lagoon, Thailand).

FIGURE 64
Unattached *Gracilaria* growing in effluent drains from shrimp ponds (southern Thailand).

solutions are sought to problems of environmental sustainability, including the management of coastal areas and the disposal of effluents from large-scale aquaculture activities.

For further details
Troell *et al.* (1999) is especially recommended for an introduction to the topic. The references that follow elaborate on some of the examples given above, and in their introductions may provide the reader with other general background information and further references: Troell *et al.* (1999), Neori, Shpigel and Ben-Ezra (2000), Nelson *et al.* (2001), Lombardi, Marques and Barreto (2001), Buschmann, Troell and Kautsky (2001) and Chopin *et al.* (1999)

9.7 WASTEWATER TREATMENT

There are two main areas where seaweeds have the potential for use in wastewater treatment. The first is the treatment of sewage and some agricultural wastes to reduce the total nitrogen- and phosphorus-containing compounds before release of these treated waters into rivers or oceans. The second is for the removal of toxic metals from industrial wastewater.

9.7.1 Treatment of wastewater to reduce nitrogen- and phosphorus-containing compounds

Eutrophication is the enrichment of waters with nutrients such as minerals and nitrogen- and phosphorus-containing materials. This frequently leads to unwanted and excessive growth of aquatic or marine plants; blooms of blue-green algae are an example, unfortunately becoming more common. Eutrophication can occur naturally, but it can be accelerated by allowing water, rich in dissolved fertilizers, to seep into nearby lakes and streams, or by the introduction of sewage effluent into rivers and coastal waters.

Seaweeds can be used to reduce the nitrogen and phosphorus content of effluents from sewage treatments. Many seaweeds have a preference to take up ammonium as the form of nitrogen for their growth and ammonium is the prevalent form of nitrogen in most domestic and agricultural wastewater. Another important feature of many seaweeds is their ability to take up more phosphorus than they require for maximum growth. It would be preferable to use seaweeds that have some commercial value, but these do not necessarily have the ability to withstand the conditions encountered in the processing of the wastewater. There is a need for the seaweed to be able to tolerate a wide variation in salinity because of the dilution of salinity by the sewage or wastewater. Intertidal and estuarine species are the most tolerant, especially green seaweeds such as species of *Enteromorpha* and *Monostroma*. Of the red and brown seaweeds that are of interest because of their commercial value, tropical or subtropical forms have been successfully used, while cold-temperate species are usually too sensitive to changing seasons and may fail to grow (and remove nutrients) in the winter months. While many investigations have demonstrated the suitability of seaweeds for wastewater treatments, their use on a large scale is yet to be implemented, although this may change with the increasing realization of the need to protect marine environments.

For further details

A good discussion of this topic can be found in Schramm (1991b), which includes a table showing the seaweeds that have been tested or used for wastewater treatment, together with references to the original publications.

9.7.2 Removal of toxic metals from industrial wastewater

The accumulation of heavy metals (such as copper, nickel, lead, zinc and cadmium) by seaweeds became apparent when those seaweeds used as human foods were first analysed. The heavy metal content, especially of the large brown seaweeds, varied according to their geographic source and sometimes to their proximity to industrial waste outlets. From these studies came the idea of using seaweeds as biological indicators of heavy metal pollution, either from natural sources or from activities such as mining or disposal of industrial wastes. This has been successfully implemented using brown seaweeds such as *Sargassum*, *Laminaria* and *Ecklonia*, and the green seaweeds *Ulva* and *Enteromorpha*.

A further extension of this ability of some seaweeds to take up heavy metals is to use them to remove heavy metals in cleaning up wastewater. While there have been many small-scale trials, it is difficult to find reports of actual implementation on a large scale. Milled, dried species of the brown seaweeds *Ecklonia*, *Macrocystis* and *Laminaria* were able to adsorb copper, zinc and cadmium ions from solution. In another laboratory-scale trial, *Ecklonia maxima*, *Lessonia flavicans* and *Durvillaea potatorum* adsorbed copper, nickel, lead, zinc and cadmium ions, though to varying extents depending on the seaweed type and metal ion concentration. After the extraction of alginate from brown seaweeds there is an insoluble waste product, mostly cellulose, and the adsorbing properties of this have been tested and found to equal some of the brown seaweeds. Using such a waste material is obviously more attractive than use of the dried seaweed itself. Another waste product, from the production of Kelpak, the liquid fertilizer previously mentioned, has also been tested and found to adsorb copper, cadmium and zinc just as effectively as the seaweed from which it is derived. So there is the potential to use either seaweed or residues remaining from seaweed extraction. It is a matter of whether this is the most economical way to do so, depending on their availability and cost at the source of the wastewater.

For further details

A recent review by Pan, Lin and Ma (2000) is a useful starting point. For some examples of trials using seaweeds and seaweed residues, see Valdam and Leite (2000), Stirk and van Staden (2000), Aderhold, Williams and Edyvean (1996) and Figueira *et al*. (2000). In this last reference, look in the Introduction for earlier papers published by B. Volesky as these illustrate the type of investigations that have been made in this topic over the past decade.

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At present, the total output of the world's seaweed industry amounts to around US$6 billion, with more than 8 million tonnes of wet seaweed used annually. Seaweeds are widely used as food but are also an important ingredient for the cosmetics industry. They also serve to produce hydrocolloids (alginate, agar and carrageenan), which are used as thickening and gelling agents. This document highlights the rising importance of seaweed farming and shows how an essential Asian food has become popular in North and South America as well as in Europe. The report will be useful to those who wish to know more about the seaweed industry, about the markets for commercial seaweeds and about the various sources and methods of production. It is written with a minimum of technical language and is designed to assist in making decisions concerning seaweeds and the seaweed industry.

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