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Seaweed Culture in Integrated
Multi-Trophic Aquaculture
—Nutritional Benefits and Systems for Australia—

RIRDC Publication No. 09/005



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**Rural Industries Research and
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Seaweed Culture in Integrated Multi-Trophic Aquaculture: Nutritional Benefits and Systems for Australia

by Pia Winberg, Dilip Ghosh and Linda Tapsell

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Researcher Contact Details

Dr. Pia Winberg
30 Victor Ave, Narrawallee
NSW, 2539, Australia
Phone: 61 2 4455 5518
Email: pia@sustainableseafood.com.au

In submitting this report, the researcher has agreed to RIRDC publishing this material in its edited form.

RIRDC Contact Details

Rural Industries Research and Development Corporation
Level 2, 15 National Circuit
BARTON ACT 2600
PO Box 4776
KINGSTON ACT 2604

Phone: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au
Web: <http://www.rirdc.gov.au>

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Foreword

The Rural Industries Research and Development Corporation invests in new and emerging industries on behalf of government and industry stakeholders

Taking advantage of the current investment and growth in aquaculture, seaweed culture can facilitate environmentally sustainable solutions for aquaculture systems, and address the need for new and functional foods that are well placed within the current interest in innovative cuisine. Seaweed markets already exist and are collectively a multibillion dollar industry internationally. Australia currently imports 5000 tons per annum primarily for food use, and the unique and untapped seaweed resources of Australia can open up new markets.

This review contains a summary of the nutritional analysis and potential health benefits of eight seaweed genera that have representative species in temperate Australia. In general, these seaweed genera have the potential to deliver proteins, carbohydrates, fibre, minerals, vitamins, and contain essential polyunsaturated fatty acid levels that are much higher than any traditional vegetables. In particular, seaweeds can address the serious deficiencies of iron and iodine in the western diets. Further, over 15,000 novel bioactives have been chemically isolated from seaweeds. The prospect of functional foods, biomedical and pharmacological applications is promising. Anti-tumor, antibacterial, anti-viral, gut health and anti-inflammatory properties are regularly reported.

Industries such as aquaculture and seaweed culture face a number of challenges – protocols for seaweed culture requires better knowledge of the growth conditions for seaweeds, and the development of product quality, quantity, markets and supply chains is essential. Many of these issues are underpinned by research and development, which is why RIRDC has invested in this report.

The importance of this report is that it identifies clear potential for seaweed to be cultured in Australia for domestic and export markets. To achieve an efficient return on industry investment, targeted markets should include the food and nutritional sectors as the health benefits of a variety of seaweeds are indicated in this report. The report also identifies enormous potential for growth and development of this sector as there are many unidentified nutritional and biologically active compounds in seaweeds, as well as emerging technology and markets in biofuels that address the issue of high yield of biomass.

This project was funded from RIRDC Core Funds which are provided by the Australian Government for New Plant Products. This report, an addition to RIRDC's diverse range of over 1800 research publications, forms part of our New Plant Products R&D program, which aims to facilitate the development of new industries based on plants or plant products that have commercial potential for Australia. Most of our publications are available for viewing, downloading or purchasing online through our website:

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Peter O'Brien

Managing Director

Rural Industries Research and Development Corporation

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Abbreviations

IMTA Integrated Multi-Trophic Aquaculture

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Executive Summary

What the report is about?

This review contains a summary of the nutritional analysis and potential health benefits of eight seaweed genera, to support decisions on genera/species that could be cultivated in South East Australia, and integrated into aquaculture production systems. The health benefits associated with seaweeds are critical in identifying marketable products for a future seaweed industry. By identifying the potential for seaweeds to be marketed as a healthy food, a strategy with which to progress the development of pilot commercial systems of seaweed culture of local species, and integrate these systems with the current developments in the aquaculture industry can be made. Australia may be just a few years away from becoming truly competitive in the seafood aquaculture industry, if it rises to the challenge of promoting itself as the healthy and environmentally friendly primary producer. Seaweed culture can be a key factor in this challenge.

Who is the report targeted at?

The report is targeted at government organisations and industry with the capacity and resources for research and development towards a seaweed industry in Australia; specifically linked to the quickly developing aquaculture industry where environmentally sustainable production methods are key to the success of the industry. Although recent technological developments in culture systems overseas are at a stage where a seaweed culture industry is being linked to the fast developing aquaculture industry, linking the technology to local species and conditions in Australia, requires further research and development. This includes identifying the seaweeds that have the potential for culture, developing technology and protocol for culture methods, developing seaweed products and getting them to a market; step that has been largely ignored. Therefore the marketability of seaweeds as a healthy and functional food ingredient needs further development.

Background

There are broad applications for seaweeds and seaweed-based products in Australia, including marine vegetables, functional foods/nutraceuticals and non-food products. The Australian seaweed industry is largely supported by imported seaweeds, with an annual import volume over 5,000 tonnes (2006-07) and had an approximate value of A\$15 million. Seaweed has been an important dietary component in some Asian countries such as Japan, China and Korea for thousand of years, and over 12,000 years in South America. During an era of industrialisation, seaweed lost favour in western countries as a recognisable whole food, although seaweed extracts remain a huge industry and are a key ingredient in a broad range of food products. In the current climate of innovative cuisines, and the strong influence of food from other cultures, particularly from Asia, there is renewed interest in seaweed as a whole food. For example, some other European and North American countries have significantly increased the consumption, production and marketing of seaweeds, and imports by Australia have increased five fold during the last five years. The total global production in the year 2004 was more than 15 million metric tonnes and it is becoming a multi-billion dollar industry. Most of this production is from various forms of culture rather than wild harvest, and more recently, fast developments are being made towards integrating seaweed culture with other species.

Aims/Objectives - who may benefit from the research

This report identifies genera of seaweeds local to NSW, that have the potential to be cultured and developed as a food industry, boosting sustainable primary production in Australia. The seaweeds identified in this report are reviewed for nutritional and health benefits with relevance to the Australian nutritional profile and needs.

Methods used

Seaweed genera were reviewed from the published literature and were selected based on three criteria:

- 1) Genera that have shown promise or have a history of being cultured
- 2) Representative species exist in temperate marine waters of Australia

- 3) Genera that have potential marketability as healthy and functional foods that address current gaps in the western nutritional profile

Results/Key findings

A range of seaweed genera that are cultured overseas have representative species in Australian coastal waters, indicating that there are untapped marine resources on our doorstep. In addition, many species are endemic to temperate Australia, and the diversity of species indicates a huge potential for novel and highly nutritional food products.

The nutritional composition of the eight seaweeds varies widely, but, in general, all of them have potential to deliver proteins, carbohydrates, fibre, minerals, vitamins and essential fatty acids in diet depending on the amount required to achieve levels that are significant in terms of requirements. Although seaweeds have low lipid content, the percentage of essential polyunsaturated fatty acids is much higher than any traditional vegetables. Polyunsaturated fatty acids from seaweeds have attracted considerable interest among academics and industry groups in recent years. Over 15,000 novel bioactives have been chemically isolated from a diverse range of algae and the prospect of biomedical and pharmacological applications is promising. Sulphated polysaccharides, halogenated furanones and kahalalide have been considered top of the list for developing drugs. The toxicological aspects associated with some of these components must be taken into account when developing seaweed-based functional foods.

The co-production of fish culture with seaweed culture addresses the decline in production of Australia's seafood, as well as barriers to developing environmentally sustainable aquaculture in Australia. Overseas studies and current investment in research and development indicate that environmentally sustainable aquaculture can be achieved by replicating natural ecological processes. There are also financial benefits of value adding to an otherwise wasted resource, production diversification, and reduced energy costs.

Implications for relevant stakeholders

In summary and of relevance to policy makers, industry investors and regional and primary production communities facing a vacuum of new sustainable industries, the integration of aquaculture and seaweed culture addresses many of the current concerns in Australia regarding reduced productivity. The main points of interest are:

- The clean waters and natural resources in Australia are an opportunity for highly marketable products
- Production of NSW species of seaweed can provide novel, healthy food products with nutrients such as iron and iodine that are currently deficient in the western diet, and in addition have a range of health benefits including anti-cancer and anti-cholesterol properties.
- Co-production with fish, when compared to all of the terrestrial animal production systems, is extremely efficient at producing high quality, nutritious protein. Integrated systems are water efficient, and co-production of energy, heat, protein and plants reduced the environmental footprint of food production enormously
- Culture offsets the declining and unsustainable wild capture fisheries
- Local employment supporting regional sustainable communities.

Recommendations

This project demonstrates a significant opportunity to boost productivity in Australia and NSW with fully environmentally sustainable technologies. Therefore, strategic investment in research and development in this field, as well as capacity building for the necessary skills in this industry are recommended. Further opportunities exist for major expansion in this field, including other markets for seaweed and marine microalgae products, including biofuels for microalgae in particular which contain a high oil content.

1 Introduction

1.1 Background

Seaweed has a huge and fast growing global market with quantities of about 130 million tons and a market value of over US\$6 billion dollars (FIGIS 2004), most of which is for food (Ernst 2003, Lee 2007, Lee and Momdjian 1997). Seaweed and seaweed products were estimated to be imported into Australia to a net value of approximately AUD \$14M (Lee and Momdjian 1997), following a close to five fold increase in import tonnage during 2003-2007 (Fig. 1-1).

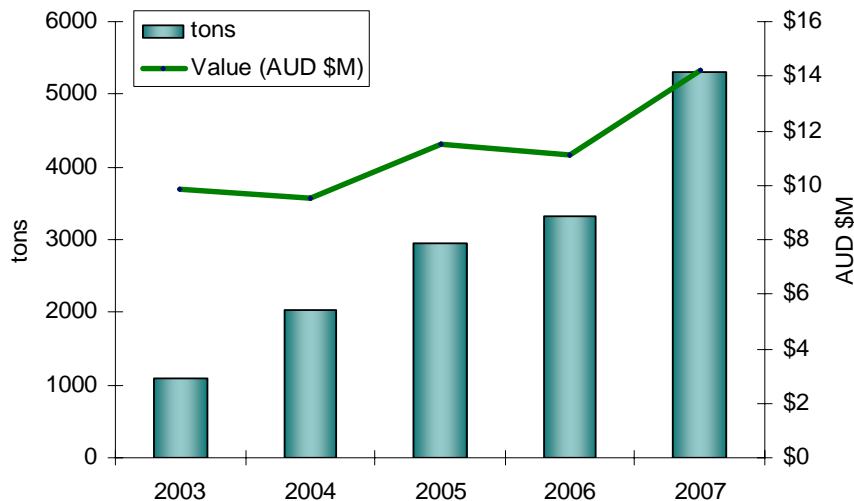


Figure 1-1 Australian import value and quantity of frozen and dried seaweed between 2003-2007. Data source Australian customs data from the Australian Bureau of Statistics (2007).

The global growth of this industry and its multiple markets, the potential health benefits associated with high dietary intake of seaweed, a shift in the Australian cuisine to be more experimental and health focused, and the potential for seaweed to be grown with other species in environmentally-sustainable, integrated aquaculture culture systems, provides an opportunity to investigate the potential for a seaweed industry in Australia.

Indeed, the viability of seaweed industries and the culture of seaweed has been demonstrated in many countries, and globally, seaweed is the largest marine aquaculture produce (by weight) at close to 14 million tons. Today cultured product makes up most of the US\$7 billion market (Fig. 1-2) (FIGIS 2004).

However industry and market conditions in Australia differ to where seaweed is currently cultured; mostly in developing countries with lower labour costs. In addition, limited coastal embayments or sheltered water, and Australian government and state environmental legislation, limit the potential for large, seabased culture close to the coast. Tourism, recreation and environmental concerns would outcompete the need for sea-based culture in most instances (McHugh and King 1998).

Therefore, competitiveness of an Australian seaweed industry requires that the choice of market is carefully assessed, and balanced against the production and processing technology costs to ensure that the financial viability and potential growth of the industry is realised. Of particular interest is culture technology that can be integrated with the co-production of fish and other marine species, thereby value-adding to the waste production of one industry by the second. This type of culture is termed integrated multi-trophic aquaculture (IMTA systems), as species from different feeding or trophic levels are integrated in one culture system to make efficient use of waste products and resources. Further efficiencies can be gained in such controlled systems by reducing the demand

on limited fresh water resources for primary production, co-production of energy and heat for efficient use of energy source, and the potential to integrate with CO₂ emission industries to offset the green house gas output for Australian industries.

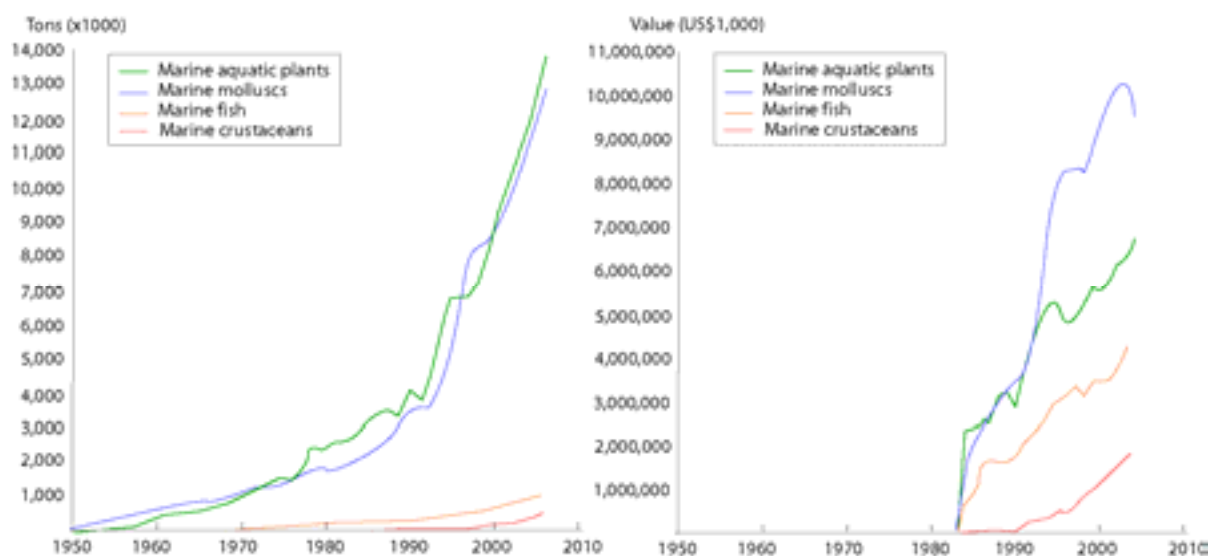


Figure 1-2 (a) Quantity and (b) value of marine aquaculture products globally. Seaweed and molluscs are the dominant products of marine aquaculture, followed by fish and crustaceans (FIGIS data 2004).

1.2 Potential Markets

High value products such as pharmaceuticals and nutraceuticals would be the most competitive seaweed market for an industrialised country such as Australia; especially as there now exist biotechnology and processing industries (eg. Marinova in Tasmania). However these markets require a medium to long term effort in high technological research and development before commercial profits can be realised (Smit 2004). At the other end of the scale, a significant industry targeting biofuels and fertilizers would require such large facilities for production to ensure profits from economies of scale, that investment at this stage is risky.

Table 1-1 Markets ranked by order of value according to authors own interpretation and knowledge of the seaweed industry (based on literature, products and discussions with industry experts). This ranking order needs to be investigated further.

Market	Value/weight seaweed	Commercial Production
1. Pharmaceuticals	Very high	Very long term (>10 years)
2. Nutraceuticals	High	Long term (5+ years)
3. Organic/sustainable food	Very good	Medium term (<5 years)
4. Health and beauty products	Good	Medium term (<5 years)
5. Food	Good	Medium term (<5 years)
6. Aquaculture/animal feed	Quite good	Medium term (<5 years)
7. Biofuels	Lower	Medium term (<5 years)
8. Organic fertilizers	Lower	Medium term (<5 years)
9. Fertilizers	Low	Medium term (<5 years)

Food products from seaweeds are probably a realistic market to target today in terms of time to commercial profit in the current market place, and a relatively good market value (Table 1); especially when grown to enhance the financial viability and environmental sustainability of fish aquaculture. Current import statistics of the 5000 tons of seaweed brought into Australia each year show that most seaweed is in a dried or frozen form and is used for food products (Fig. 1-3) (ABS 2007). The frozen product has a higher value that seems to be stabilizing at about AUD\$8.00/kg.

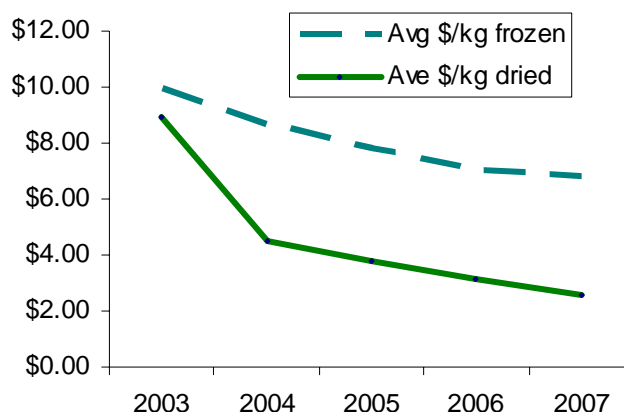


Figure 1-3 The average kilogram price (\$AUD) of dried and frozen seaweeds imported into Australia between 2003 – 2007. Data source (ABS 2007).

The current major supplier of seaweed to Australia is Ireland, which supplied 4000 tons of dried product in 2007. In contrast, the leading suppliers of seaweed from Asia provided mostly frozen product, of which Australia imported approximately 280 tons in 2007. Value added seaweed salad with dressing and spices is currently a popular product in seafood retail outlets in both cities and regional areas of Australia. The retail price of this frozen product imported from Japan is currently sold at approximately AUD\$18/kg, which is comparable to the lower end value of fish products from an aquaculture system.

The justification for an initial food market focus for an Australian seaweed industry for is as follows:

- 1) Current demand for healthier foods, especially foods that address nutritional deficiencies (eg. iron and iodine) (AAS 2007)
- 2) Current demand for socially responsible/organic/environmentally sustainable production methods (SCA 2007, SCA 2008)
 - a. In this regard, there is potential to market Australian seaweed as distinct from imports because of the demand for
 - i. quality control and food safety regulations in culture and processing
 - ii. environmental sustainability by harvesting cultured rather than wild stocks
 - iii. environmental sustainability by integration with saline fish culture highlighting the smart use of limited resources such as fish feed
- 3) Opportunity for integration of industry with development of environmentally sustainable aquaculture at a scale that can supply food markets
- 4) Current acceptance by Australians to experience new and innovative cuisine
- 5) Competitiveness
 - a. Organic/Sustainable production profile for niche market
 - b. Carbon credits
 - i. From reduced import transport costs
 - ii. From carbon uptake into plants
 - c. Diversification of fish culture and therefore production risks associated with market and production fluctuations.
 - d. Potential for higher end markets such as pharmaceuticals after research and development into untapped chemical properties of local species

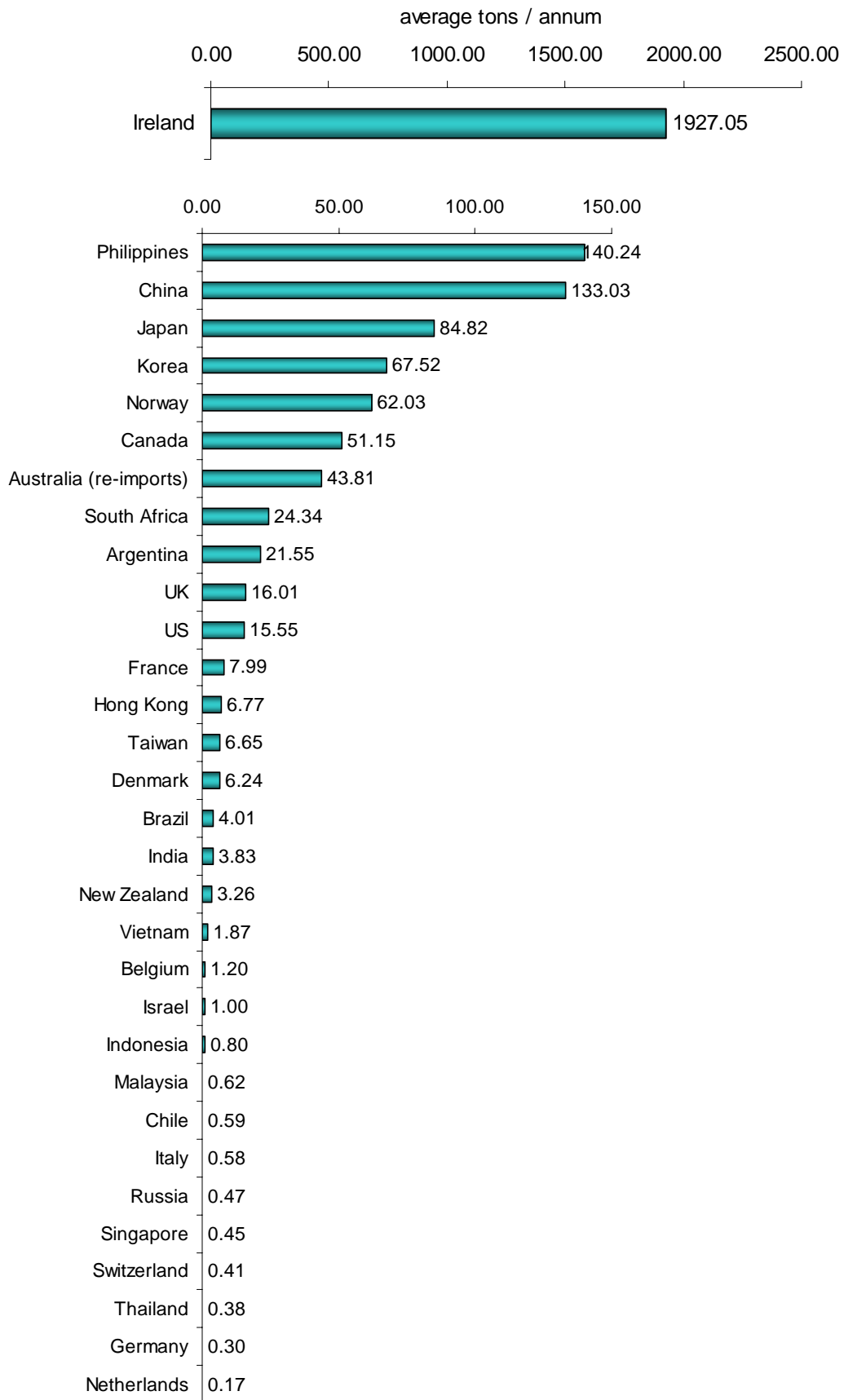


Figure 1-4 The average tonnage of seaweed imports during 2003-2007, separated into the country of origin.

1.3 Production methods

Wild harvesting of considerable quantities of seaweed have been regarded as sustainable practices in certain parts of the world, specifically when natural biomass is considered to have increased due to nutrient pollution of natural marine systems, if it is harvested manually at a small scale (eg. Acadian seaplants), or if the harvested species is a pest (eg. *Undaria* sp. in Tasmania). However beach harvesting and *in situ* harvesting in large quantities are generally regarded as undesirable alternatives to seaweed culture, and at a large scale would cause significant environmental impacts (Troell et al. 2006).

The culture of seaweeds has existed at an extensive scale and has been used in traditional foods for thousands of years (Critchley 2004). Only recently, it was discovered that the first human inhabitants of South America used seaweeds from distant beaches as important food and medicine over 12,000 years ago (Dillehay et al. 2008).

Land based culture of seaweeds in pond or tank systems are one promising method for the development of a seaweed industry in Australia, considering the undesirability of wild harvesting in large quantities as well as anticipated environmental impacts of *in situ* culture techniques. Such large scale production systems in industrialised countries have already been proven, most notably in the commercial operations of the Canadian company Acadian Seaplants (<http://www.acadianseaplants.com>).

Such land based culture techniques ensure quality and safety control for food production, ease of harvest, and boost production rates, environmental sustainability and value adding to the production of fed seafood such as fish or abalone. By compartmentalisation of the culture of multiple species (Fig. 1-5), integrated multi-species systems have demonstrated high production rates from semi-intensive culture systems that are competitive with modern monoculture systems (Mata et al. 2007, Neori et al. 2004). Additional benefits are anticipated for recirculation of seaweed culture water into fish tanks as oxygenation and removal of pathogens from water have been broadly documented (Neori et al. 1996, Pang et al. 2006).

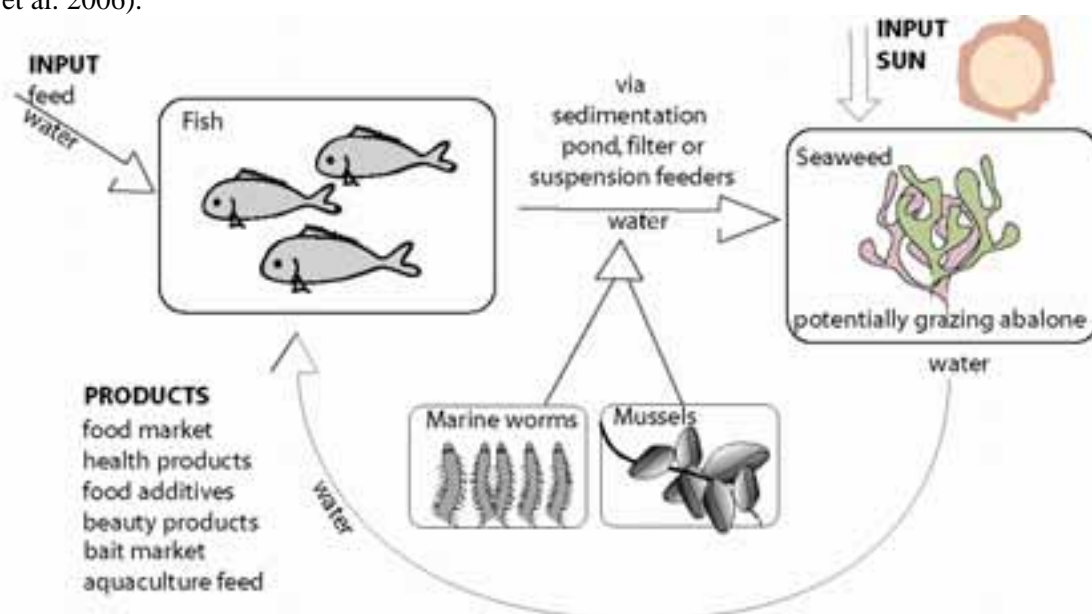


Figure 1-5 Integrated aquaculture system which can use a variety of species balanced in a mini-ecosystem. Here marine worms and mussels are used, but other species can also be used in place of these according to market demands and the system design.

2 Potential seaweed for Integrated Multi-Trophic Aquaculture systems in Australia

In this Chapter we consider a range of seaweed genera that occur in temperate Australian waters, and that might be suitable as the initial candidates for a seaweed culture industry in Australia. The fact that temperate Australia also boasts a large degree of endemism of seaweed species suggests that there is a real opportunity for discovery of untapped resources; particularly in terms of biologically active compounds.

The production methods and the market value of seaweed products discussed in Chapter 1, are also the key limitations in developing a successful seaweed industry in Australia. Although we have a rich flora of seaweed genera that are commercially cultivated overseas, especially temperate Australian species, variations in reproductive cycles, optimum culture conditions, and the nutritional profiles of seaweeds can vary considerably between species. Therefore the culture method protocols and nutritional marketability require further research and development, and the choice of seaweed needs first to consider a range of potential seaweed genera and species.

“The great successes in seaweed culture achieved in such countries as Japan and China are generally attributed to achievements in controlling the biological cycle and satisfying the physiological requirements of the species both in the laboratory and in the field. Thus, in countries where culture systems or technologies are highly sophisticated, production itself becomes much less of a problem than the monitoring and the control of the culture in order to produce high quality crops to make the industry cost effective. On the other hand, in the countries where these basic informations are not yet available, the development of culture techniques in order to enhance production is the major concern.” (Trono 1989)

There are numerous potential species for high intensity integrated aquaculture and many of these have been reviewed elsewhere (Critchley 2004, McHugh 2003). For this report, genera that are known to be successfully cultivated abroad, undergoing trials in integrated multi-trophic systems or used in Australian laboratories for experiments, and that have representative species in NSW temperate waters, were considered and prioritised for a nutritional review in the peer-reviewed scientific literature (Chapter 3). Listed below are some of the genera of primary interest as identified to date, and which served as the basis for a first nutritional review. However, this does not exclude the potential for many other genera of seaweed that may have unknown and nutritionally unique properties, and may also be well suited to culture.

2.1 *Ulva* species (Green alga) (Family Ulvaceae)

The primary species of interest would be for the local species of *Ulva* or *Enteromorpha* (Sanderson 1997) which have been demonstrated to work effectively in integrated systems with fed species (Neori et al. 2004, Neori et al. 2000). *Ulva* sp. are efficient removers of ammonium (NH_4^+) (Bracken and Stachowicz 2006) and have a morphology well suited to tumble culture. Fast growth rate of the species might be of importance for ease of culture and to out compete potential epiphytes or other species. As *Ulva* species are often intertidal, they have a high temperature and irradiance tolerance range.

Ulva is cultured for the global food market, but is generally of a lower value than other red or brown seaweeds. However as it is attractive and is purported to have good nutritional value, appropriate marketing may increase the value as appears to be the case of late as demand seems to have increased (Critchley 2004). Current claims in the food market and elsewhere (Kirby 2001) state that *Ulva* sp.

contain 15% protein, 50% sugar and starch, less than 1% fat, high in iron, iodine, aluminum, manganese and nickel, it contains vitamins A, B1 and C, sodium, potassium, magnesium, calcium, soluble nitrogen, phosphorous, chloride, silicon, rubidium, strontium, barium, radium, cobalt, boron and trace elements. It is also supposed to be good roughage for the digestive system.

In addition, *Ulva* sp. are suitable as feed for abalone or sea urchins (Neori et al. 2004, Neori et al. 2000); especially as abalone grow out has been demonstrated to produce faster growth rates when fresh rather than dry or pelleted feed is used (Troell et al. 2006).

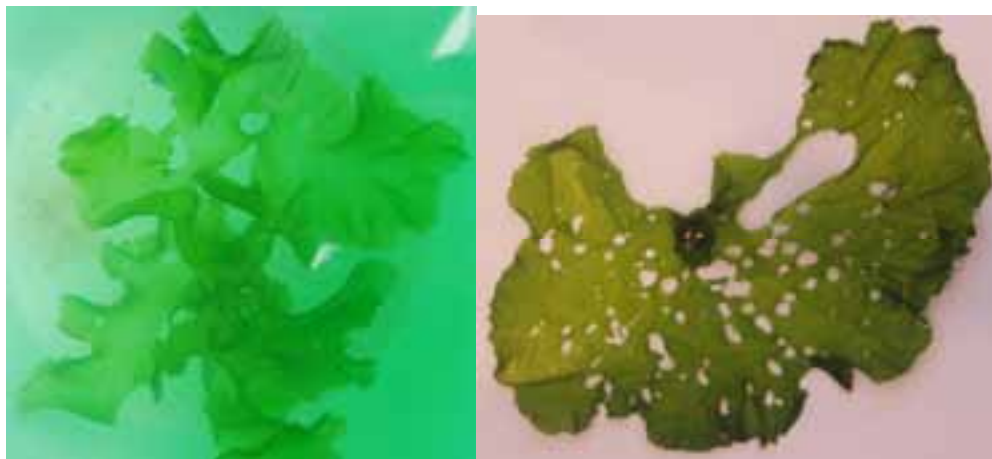


Figure 2-1 NSW species of *Ulva*, fresh *U. lactuca*, and dried *U. australis* (P. Winberg).

2.2 *Gracilaria* sp. (Red alga) (Family Gracilariaceae)

This genus is one of the most widely cultivated genera, and is widely cultured extensively for subsistence farming and agar extraction, and is an important component of many traditional foods. *Gracilaria* species contribute to 70% of the world's agar. It is already cultured in integrated systems as an efficient remover of phosphates (Salazar 1996) and is used in genetic engineering trials to take up nutritional properties of other seaweeds (Phang et al. 2007).

2.3 *Porphyra* sp. (Red alga) (Family Bangiaceae)

This is the biggest commercially produced seaweed for human consumption as a whole food and is reviewed extensively elsewhere (FAO 1987, McHugh 2003, Trono 1989). There may be room in the industry to develop a local grown Australian *Porphyra* sp. product that targets the environmentally and health conscious consumer using clean Australian waters.

Other potential species include but are not limited to *Martensia* sp., Calosiphonaceae (*Schmitzia japonica*), *Caulerpa filiformis* (potential for sediment remediation), *Rhodoglossum* (Red tongue), *Placomium*, *Branchioglossum* (red weed on NSW beaches), *Kallymenia rosea* (similar morphology to *Ulva* sp.). Sanderson (1997) provides a thorough review of the distribution of seaweed species that might be of interest.



Figure 2-2 *Porphyra* species growing on the south coast of NSW (P. Winberg)

2.4 *Asparogopsis armata* (Red alga) (Family Bonnemaisoniaceae)

Also known as *Falkenbergia rufolanosa* as the unattached life phase was considered a separate species until recently. It is a shallow water local seaweed that has already been cultured in the lab in Australia for research on evolution of chemical defences (Paul 2006). *Asparogopsis armata* has a high level of iodine and bromine and is an important food source for blacklip abalone (Edgar 1997).

A patent has been applied for by the SeaPura group for the technology to propagate, cultivate, harvest as well as extract and characterize antimicrobial agents from *Falkenbergia*, and their application in finished products such as cosmetics or paints (SEAPURA 2004). A bioactive polysaccharide compound in this species is a key product in commercial anti-aging creams such as Athanor and Aldavine as it inhibits the cytokine VEGF pathway in the skin from environmental stressors such as UV radiation.



Figure 2-3 *Asparogopsis armata* from southern NSW (P. Winberg).

2.5 *Grateloupia* sp. (Red alga) (Family Halymeniaceae)

Has suggested strong anti-viral properties (against *Vibrio* in seawater (Pang et al. 2006)). Common NSW species in rockpools is *G. luxurians* (Cronulla).

2.6 *Gelidiacea* (Red alga family)

There are common local species in NSW, one of which is *Pterocladium* sp. found prolifically in NSW along coastal walls just below the surf zone (personal comment A. Millar). *Gelidium* sp. researched elsewhere (Chubchikova et al. 2007, FAO 1987). This species has a high quality agar with a high gel strength that is sought after. It can be propagated vegetatively and trials in Chile indicate the some species might be good candidates for culture (Rodriguez 1996, Rojas et al. 1996).



Figure 2-4 Co-culture of gelidiacea species with *Ulva* sp. in lab.

2.7 *Ecklonia radiata* (Brown kelp) (Family Alariaceae)

This is an abundant local species with the potential for integration with abalone culture as a feed source (Troell et al. 2006). However it is potentially hard to culture in tanks due to large morphology.



Figure 2-5 *Ecklonia* species collected on NSW south coast (P. Winberg)

2.8 *Sargassum* sp. (Brown alga) (Family Sargassaceae)

Sargassum species grows prolifically in NSW estuaries and along the coast and was observed growing on subsediment cockle shells in estuaries. It is good sea urchin food



Figure 2-6 *Sargassum* species collected on NSW south coast (P. Winberg)

3 Nutritional review of seaweed species

Seaweeds or macroalgae are a very interesting natural source of new compounds with biological activity that could be used as functional ingredients. One of the reasons for this is that macroalgae live in complex extreme habitats (for example, changes of salinity, temperature, nutrients, UV-vis irradiation) and interacts constantly with hostile micro-organisms. They therefore adapt rapidly to new environmental conditions to survive, producing a great variety of secondary (biologically active) metabolites, which cannot be found in other organisms (Carlucci, et al. 1999).

The marine-based food industry has shown interest in seaweeds due to ease of cultivation, rapid growth (for many of the species) and the possibility of controlling the production of some bioactive compounds by manipulating the cultivation conditions. Microalgae may be considered as genuine natural reactors being, in some cases, a good alternative to chemical synthesis for certain bioactive compounds.

Seaweeds are extensively used as food, food ingredients, as ingredients in cosmetics and fertilizers, and in the production of hydrocolloids (e.g. agar and alginate). The total global seaweed production in the year 2004 was more than 15 million metric tones (FAO, 2006). Global utilisation of macroalgae is a multi-billion dollar industry. Most of the commercial exploitation is based on farming of edible species or on the production of agar, carrageenan and alginate. Of all seaweed products, hydrocolloids have had the biggest influence on modern western societies, through their use in various industries which exploit their physical properties such as gelling, water-retention and their ability to emulsify (Renn, 1997). So far in terms of dollar value, little commercial exploitation of products extracted from seaweeds occurs outside the hydrocolloid industry. However, in recent years pharmaceutical firms have started looking towards marine organisms, including seaweeds, in their search for new drugs from natural products. Prior to the 1950s, the medicinal properties of seaweeds were restricted to traditional and folk medicines (Smit, 2004). During the 1980s and 90s, compounds with biological activities or pharmacological properties were discovered in marine bacteria, invertebrates and algae (Smit, 2004). According to Ireland et al. (1993), algae are the source of about 35% of the newly discovered chemicals between 1977–1987, followed by sponges (29%) and cnidarians (22%). However, the discovery of new products from seaweeds has decreased since 1995 and attention has now shifted to marine micro-organisms (Smit, 2004).

3.1 Nutritional Review Objectives

- To produce evidence from the scientific literature on the nutritional properties and health benefits of the following genera of seaweeds:
 - Ulva*
 - Gracilaria*
 - Porphyra*
 - Asparagopsis*
 - Grateloupia*
 - Gelidium*
 - Ecklonia*
 - Sargassum*
- To summarise potential risks from seaweed consumption
- To report on the relative nutritional value of different species of seaweed, the use of seaweed in cuisine patterns, and areas of product development occurring in the Australian and overseas markets.

3.2 Methods

A defined search strategy in Scopus (1990-2008), Medline (1990-2008) and Science Direct (1990-2008) was used to obtain publications relating to the identified seaweed genera (Table 1). The search was limited to articles written in English. The review categorised the type of research undertaken, including mechanistic studies, population based surveys and clinical trials. A brief description of the extent to which the literature indicated benefits from seaweed consumption was also provided.

Studies identified in (3.1) which also reported risks associated with seaweed consumption were summarised. A brief comment on any regulatory positions regarding food safety and seaweed consumption was also included.

The literature obtained in (3.1) and nutrient databases were searched for information on the nutritional properties of seaweed. Popular cookbooks, cooking databases and market newsletters were searched for seaweed recipes and seaweed-based products emerging on the market.

Table 3-1 Search strategy and outcome

Database ¹	Search term:(1) seaweeds OR Ulva OR Gracilaria OR Porphyra OR Asparagopsis OR Grateloupia OR Gelidium OR Ecklonia OR Sargassum	Search term:(2) macroalgae OR Ulva OR Gracilaria OR Porphyra OR Asparagopsis OR Grateloupia OR Gelidium OR Ecklonia OR Sargassum	Search term: combined (1) with nutrition OR nutritional	Search term: combined (2) with nutrition OR nutritional	Search term: combined (1) with health OR medical*	Search term: combined (2) with health OR medical*	Search term: combined (1) with risk OR safety OR toxicity	Search term: combined (2) with risk OR safety OR toxicity	Final papers considered
Scopus	21,059	17,210	3,206	2,482	3,324	2,280	3,372	2,781	75
Medline	692	735	14	15	19	21	36	47	30
Science Direct	9,635	7,279	2,046	1,544	3,422	2,191	3,609	2,617	82
Total	31,386	25,224	5,266	4041	6765	4492	7017	5445	187

¹1990 to 2008

3.3 Chemical and nutritional composition

Seaweed has been an important dietary component since at least the fourth century in Japan and the sixth century in China (McHugh, 2003). Recently, other countries, such as the Republic of Korea, the United States of America, South America, Ireland, Iceland, Canada and France have significantly increased the consumption, production and marketing of seaweeds, along with above two countries (McHugh, 2003). From a nutritional point of view, seaweeds are low-calorie foods, with a high concentration of minerals (Mg, Ca, P, K and Na), vitamins, proteins and indigestible carbohydrates and a low lipid content (Norziah and Ching, 2000., Sánchez-Machado et al. 2004a and b., Wong and Cheung, 2000). Seaweeds also contain more vitamin A, B-12, and C, β -carotene, pantothenate, folate, riboflavin, and niacin than fruits and vegetables (Kanazawa, 1963, Ruperez, 2002). Dietary fibre content ranges from 33% to 75% of dry weight, and mainly consists of soluble polysaccharides. One very important nutrient, iodine is generally found in all seaweeds at high levels. The iodine content in brown algae ranges from 500 to 8000ppm (parts per million). Red and green algae have relatively lower content of these nutrients, but remain high in comparison to other standard foods (Table 2, 3, 4). A recent study on 59 marine algae showed iron concentrations ranging from 52 to 3410mg/kg (Garcia-Casal et al. 2007). Gracilaria sp and Sargassum sp had the highest iron content, followed by Ulva sp and Porphyra sp. Based on the actual iron absorption value calculated, it was demonstrated that Sargassum sp is the best source of iron (15g dose meeting >100% of the daily iron requirement of 1-2mg), followed by Ulva sp (~0.7mg) and Porphyra sp (~0.3mg). Considering high concentration of vitamin C, it may be possible to supply 100% of the daily dietary recommendation with 43g of Ulva sp, 7g of Porphyra sp or only 3g of Sargassum sp (Garcia-Casal et al. 2007).

Seaweeds generally show great variation in nutrient contents and this is related to various environmental factors such as water temperature, salinity, light and nutrients (Marinho-Soriano et al. 2006). This review refers to eight above mentioned algal genera based on available information (Fleurence, 1999., Norziah and Ching, 2000., McDermid and Stuercke, 2003., de Padua et al. 2004., De Quiros et al. 2004., Sanchez-Machado et al. 2004a., Martinelango et al. 2006., Marinho-Soriano et al. 2006., Ortiz et al. 2006., Dawczynski et al. 2007., Garcia-Casal et al. 2007., MacArtain et al. 2007., Marsham et al. 2007., Perez et al. 2007., Plaza et al. 2008). Macroalgae can be used as a bio-indicator of nutrients in the water column because of their ability to assimilate rapidly surrounding nutrients and their tissue nutrient content can reflect the local nutrient regime within relatively a short time period (Ryther et al. 1981., Horrocks et al. 1995., Jones et al. 1996).

Table 3-2 Nutritional composition of eight selected macroalgae^a

Genera	Protein (% dry weight)	Lipid (% dry weight)	Carbohydrate (% dry weight)	Dietary fibre (% dry weight)	Folic acid ¹	Vitamins [§]	LC-PUFA Ω 3 ²	Iron ^{3§§}
<i>Ulva</i>	27.2 [#]	0.3 [#]	61.5 [#]	60.5 [#]		1071.4 ^{b#} 125 ^e	Low-moderate	57.47
<i>Gracilaria</i>	14.21 [*]	3.3 ⁺	49.70 [*]	24.7 ⁺		28.5 ^{c+} 5.2 ^d 37.5 ^e 0.70 ^f 0.006 ^h	High	195.89
<i>Porphyra</i>	33-47 [±]	2.1 [‡]	40.70 [#]	48.6 [‡]	36.25 ^{**}	430 ^e	High	17.72
<i>Asparagopsis</i>	N/A	N/A	N/A	N/A	N/A	N/A	High	N/A
<i>Grateloupia</i>	N/A	N/A	N/A	N/A	N/A	N/A	High	N/A
<i>Gelidium</i>	11.80	0.90	43.10				High	
<i>Ecklonia</i>	N/A	N/A	N/A	N/A	N/A	N/A	Low-moderate	N/A
<i>Sargassum</i>	12.24 [*]	0.45 [*]	35.76 [*]	6.57	N/A	78.5 ^e 0.70 ^f 0.06 ^g	Low-moderate	156.90

^a Compiled data from different sources (see references below)

^b Total 'tocols' (mg/kg)

^c Vitamin C (mg/100g)

^d β -carotene (mg/100 g)

^e β -carotene (IU/ g)

^f Niacin (mg/g)

^g Thiamine (mg/g)

^h Riboflavin (mg/g)

¹ μ g/100 g dry weight

² Compare (%) to FAME (fatty acid methyl esters)

³ mg/ 100g dry weight

[§]McDermid and Stuercke, 2003

^{§§}Perez et al. 2007, Garcia-Casal et al. 2007

[#]Ortiz et al. 2006

^{*}Marinho-Soriano et al. 2006

⁺Norziah and Ching, 2000

[±]Fleurence, 1999

[‡]Dawczynski et al. 2007

^{**}de Quiros et al. 2004

^{N/A} Not available

From the limited information available, seaweeds can be seen as providing mainly carbohydrate and fibre with potential in providing some minerals and omega (ω) 3 fatty acids, depending on the amount required to achieve levels that are significant in terms of requirements (Table 3-2). Although seaweeds have low lipid content, the percentage of essential polyunsaturated fatty acids (PUFA) is much higher than any traditional vegetables (Darcy-Vrillon, 1993). The amount of this PUFA class varied between 34% of total fatty acid methyl esters (FAME) in *Porphyra* sp to 74% in *Undaria* sp. Linolenic acid, alpha linolenic acid, stearidonic acids, arachidonic acid, and eicosanoid acids are the predominant PUFAs found in seaweeds (Dawczynski et al. 2007). The average ω 6/ ω 3 ratio in seaweeds is 4.1 and less, which is much below the recommended level of 10 (Ortiz et al. 2006). Depending on species, they may provide significant amounts of Calcium, and Iron but the levels of Potassium and Iodine can be relatively low and of sodium may be too high compared with other micronutrients (high sodium intakes are a recognised problem in Australia) (Table 3-3).

Most of the published nutritional reviews on seaweeds have mainly focused on nutritional profiles of seaweeds, rather than the levels of nutrients compared to dietary intake and per-portion amounts. Table 3 demonstrates some comparison of seaweeds nutritional value with Recommended Dietary Intakes (RDI) and Adequate Intake (AI) (MacArtain et al. 2007, NHMRC, 2005). Assuming culinary exchange (with 100g serves), this comparison and previous nutritional data confirms the potential nutritional value for seaweed lies in fibre, calcium (for *Ulva*), potassium, iron, few vitamins and protein (for *Porphyra*) but the high levels of sodium may be a problem.

Table 3-3 Mineral content¹ as compared with Recommended Dietary Intake (RDI) values^{2, 3, and 4}

Seaweed ³	Calcium	Potassium ⁴	Sodium ⁵	Iron	Iodine ⁵
<i>Porphyra</i>	24 (1000)	212 (3800)	84 (460-920)	3.7 (8)	0.94 (150)
<i>Ulva</i>	260 (1000)	196 (3800)	272 (460-920)	12.2 (8)	1.3 (150)

¹ mg/8 g (8 g of seaweed is a typical daily portion size in Asian cuisine)
² Adapted and modified from MacArtain et al. 2007
³ NHMRC, 2005
⁴ RDI value in bracket (mg/day)
⁵ Adequate Intake (AI)

Table 3-4 Fibre and mineral composition of two major seaweeds compared to whole foods¹

Food type	Total fibre	Carbohydrates ³	Calcium ³	Potassium ³	Sodium ³	Iron ³	Iodine ³	Zinc ³	Vitamin C ³
Seaweed									
<i>Porphyra</i>	3.8	5.4	34.2	302.2	119.7	5.2	1.3	0.7	12.885
<i>Ulva</i>	5.4	4.1	325.0	245.0	340.0	15.3	1.6	0.9	10.000
<i>Sargassum</i>	0.52	2.86	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Whole food									
Brown rice	3.8	81.3	110.0	1160.0	28.0	12.9	Tr	16.2	N/S
Lentils	8.9	48.8	71.0	940.0	12.0	11.1	Tr	3.9	2.44
Bananas	3.1	23.2	6.0	400.0	1.0	0.3	8.0	0.2	11.00
Whole milk	Tr	11.3 ⁴	115.0	140.0	55.0	0.1	15.0	0.4	0.17
Tomatoes	0.19	0.54	Tr	17.73	Tr	0.04	Tr	Tr	1.52

¹ MacArtain et al. 2007
² g/8g wet weight (portion size) (MacArtain et al. 2007)
³ mg/8 g weight (portion size) (MacArtain et al. 2007)
⁴ g/ounces of milk
N/A. Data not available in literature
Tr Traces

Following is a brief overview of nutritional composition of eight seaweed genera exist globally and are represented by species native to Australia. Whether the nutrients referred to have any nutritional meaning will depend on how much a person has to consume in the diet to achieve levels that are significant in terms of requirements- and that these levels make culinary sense. The overview provides some direction for further investigation as well as indications for culinary opportunities.

3.3.1 *Ulva* sp.

Ulva spp. belongs to the group of green algae and is considered as a natural source of algal protein, carbohydrate, minerals and vitamins, while maintaining a low level of lipids. The main sterols in this group are cholesterol and isofucosterol (Kapetanovic et al. 2005). *U. oxysperma* and other *Ulva* spp. have high levels of minerals for a relatively low energy value, but variable levels of protein content, most likely due to the nutrient environment in which it is grown as well as the different species composition. Some species of *Ulva*, such as *U. lactuca* and *U. fasciata* have a higher content of protein (De Padua et al. 2004). *Ulva lactuca* was found to have higher vitamin C and iron contents.

3.3.2 *Gracilaria* sp.

Gracilaria, red drift algae that resembles matted hair, are “crunchy like celery, with a slightly salty, piquant taste” and are considered good natural sources of carbohydrates and fibre. They have moderate levels of proteins, minerals and vitamins when compared to other varieties. This suggests some opportunities for inclusion in recipes. In one recent Brazilian study (Marinho-Soriano et al. 2006), several species of *Gracilaria* were shown to have a high carbohydrate content (631.34 g kg⁻¹) and moderate levels of protein (197.04 g kg⁻¹). *Gracilaria tikvahiae* can assimilate and store enough nitrogen (N) in 6 h to allow it to grow for two weeks at non-N-limited levels (Ryther et al. 1981), but does not have implications in integrated production systems, which are loaded with nitrogen. Jones et al. (1996) have shown that the amino acid composition appeared to be a sensitive parameter for detection of bioavailable N concentration in *G. edulis*. One particular species of *Gracilaria*, i.e.,

G.changgi showed vitamin A activity of 865 µg retinol eq/100 g sample (Norziah and Ching, 2000). It also contained a high composition of unsaturated fatty acids (74%), mainly ω3, and 26% of saturated fatty acids and also relatively high level of calcium and iron. The current interest in omega 3s as nutritionally valuable in our diet suggests this genera, should be investigated further.

3.3.3 *Porphyra* sp.

Porphyra sp. belongs to the group of red algae and represents opportunity for the food industry due to their low caloric content and high content in vitamins, minerals and fibre (Plaza et al. 2008). Sanchez-Machado et al. (2004a) have shown that these group of algae possessed a high proportion of protein (as high as 24%) and a low percentage of lipids (approx. 1%). The relative percentage of these nutrients is variable from species to species. In one study, Robollosa-Fuentes et al. (2000) estimated the relative nutritional composition of *P. cruentum* as carbohydrates 32.1% (w/w), crude proteins 34.1%, ash 20% and lipids 7%. Interestingly, they also showed a low lipid content, but with a high proportion of healthy polyunsaturated omega 3 fatty acids. The predominant sterols (sterols are a subgroup of [steroids](#) with a [hydroxyl group](#)) found in *Porphyra* sp. are demosterol (337 µg/g of dry weight) and cholesterol (8.6%) (Sánchez-Machado et al. 2004b). *Porphyra* is also a good source of folic acid, an essential nutrient to prevent neural tube defects. In most red algae, the soluble fibre was composed of sulphated galactans and insoluble fibre was formed of cellulose (Goni et al. 2000., Sánchez-Machado et al. 2004b). The reported mineral composition (Fe+Zn+Mn+Cu) of *P. vietnamensis* was much higher than for any land vegetables as well as for other edible seaweeds (Rao et al. 2007). *P. vietnamensis* has potential as a spice to improve the nutritive value in the omnivorous diet. Due to its high nutritive value, Guil-Guerrero et al. (2004) compared *P. cruentum* biomass with those of soybean flour.

3.3.4 *Asparagopsis* sp.

Asparagopsis is local seaweed that belongs to the red algae group (Paul, 2006). Very little scientific information is known about its nutritional composition and health benefits. It was reported to have high levels of iodine (which is beneficial) and bromine (which can be deleterious) (Edgar, 1997). These genera may be of more interest for extractive bioactive compounds, but not much for whole food.

3.3.5 *Grateloupia* sp.

Grateloupia is also belongs to the red algae. Very little information is available on its nutritional composition and health benefits. No detailed chemical analysis was found. One recent study has demonstrated its antiviral activity of a sulphated galactan present in *Grateloupia indica* against herpes virus (Chattopadhyay et al. 2007). This suggests implications for nutraceutical development.

3.3.6 *Gelidium* sp.

Human consumption of *Gelidium* is restricted mainly to *G. divaricatum* in China and to *G. amansii* in Japan, Indonesia, China, Borneo (Santelices, 1987). A few early studies (reviewed in FAO, 1987) have demonstrated that *Gelidium* contains 2.01% nitrogen, 12.5% crude protein, 23.7% galactan, 2.03% pentosan, 23.2% reducing sugar, 0.93% methyl pentosan, 17.89% fibre, 0.52% magnesium, 0.28% lime and 4.23% ash. A high content of vitamin B12, cholesterol, essential oils and lipids have been also reported (Santelices, 1987). The identification of vitamin B12 may be of interest in vegetarian cuisines, given that this vitamin is almost exclusively sourced from animal foods.

3.3.7 *Ecklonia* sp.

Ecklonia is probably the most abundant local brown algae. Species of *Ecklonia* are mostly used as a fertiliser and soil conditioner because of their high content of nitrogen and potassium. The large amount of insoluble carbohydrates in this seaweed makes it ideal for soil conditioning.

3.3.8 *Sargassum* sp.

Sargassum belongs to the group of brown algae which has been traditionally consumed in East Asian countries, and the functional food aspects of this genus were reviewed by Plaza et al. (2008). The different species exhibited good nutritional values as sources of proteins, carbohydrates, minerals and vitamins. The major components of *S. vulgare* are high level of carbohydrates (67.80%), very low

lipids (45%) and a high percentage of fibre (7.73%) and proteins (15.76%). It has been demonstrated that the proteins of *S. vulgare* have a high nutritional value since they contain all the essential amino acids in significant amounts, particularly leucine (8.2%), alanine (6.8%), glutamic (17.4%) and aspartic acid (10.6%). Anti-bacterial and anti-viral properties have been documented in this genus. For example, had described polysaccharides with potential antiviral action formed principally by alginic acid, xylofucans and two varieties of fucans. *S. macrocarpum* is a good source of zosterdiol A, B, zosteronol, zosteronediol and new toluquinol derivatives which demonstrated some antibacterial properties. Further research may be warranted, again in the medicinal area.

3.4 Commercially important polysaccharides from seaweeds

Polysaccharides produced by marine macroalgae (seaweeds) form the basis of an economically important and expanding global industry (Renn, 1997., Pandey et al. 2005., Broderick et al. 2006., Leung et al. 2006). Major commercially important seaweed polysaccharides are described in Table.5, particularly with reference to the eight genera of seaweeds in this review.

Table 3-5 Seaweed polysaccharides: sources, compositions and applications¹

Polysaccharides	Source (genera)	Composition	Application
Agars and agaroses	<i>Gelidium</i> , <i>Gracilaria</i> , <i>Porphyra</i>	1,4-linked α -D-galactose and 3,6-anhydro- α -L-galactose backbone substituted with varying percentage of methoxyl, ester sulphate and ketal pyruvate groups	Baking icings, jelly candies, canned meats, laxatives, microbial culture media, matrices for electrophoresis, immunoassays, microbial cell culture etc (agarose).
Algins/alginate	<i>Laminaria</i> <i>Sargassum</i> <i>Ecklonia</i>	1,4-linked α -L guluronic acid and β -D-mannuronic acid subunits in GG, MM and MG domains	Baking icings, salad dressings, frozen foods to maintain structure on thawing, tableting agent for faster release (Salofalk [®]) ² , dental impression media, textile sizing
Carrageenans	<i>Porphyra</i> , <i>Gelidium</i> <i>Grateloupia</i>	1,3-linked α -D-galactose and 1,4-linked 3,6-anhydro- β -D-galactose backbone substituted with varying percentage of ester sulphate	Frozen desert and chocolate stabilizers, low-calorie jellies, toothpaste binders, air-freshener gels, personal care products, pet foods

¹Adapted and modified from Renn, 1997
²Tugcu-Demiroz et al. 2007

The above polysaccharides from seaweeds underpin a well-established and growing ingredients industry. Algins, carrageenans and agars have all achieved commercial significance because of their food and industrial applications. The majority of the commercial polysaccharide-based products have been in the market for a long time without any major innovation, probably because of the strict regulatory requirements and highly competitive industrial pressure to minimise cost.

3.5 Health benefits

Bioactive compounds, either from synthetic or natural sources have been linked to health and wellbeing. They may also alter the genetic expression of a number of cellular events by influencing different metabolic pathways (Milner, 2004). However, increasing numbers of commercial health claims on bioactives have been found to be misleading. Health claims regulations in different countries are evolving notably to address proper scientific substantiation. This must be a component of any health oriented R&D activity.

Over 15,000 novel bioactives have been chemically isolated from a diverse range of algae and the prospect of commercial application is enormous (Cardozo et al. 2007). Seaweeds have caused an emerging interest in the biomedical area due to the presence of potent pharmacologically bioactive substances with wide arrays of potential health benefits (Table 6) (Blunden, 1993, Ireland et al. 1993, Smit, 2004). Of the substances, the bioactives most used by pharmaceutical companies for developing new drugs are the sulphated polysaccharides (anti-tumours and antivirals), the halogenated furanones (antifouling compounds) and the kahalalide F (anticancer and anti-AIDS compounds) (reviewed by Smit, 2004). Wide arrays of bioactive compounds found in seaweeds await a major breakthrough for a variety of food/medical applications as natural antioxidants in different food/pharmaceutical products (Cardozo et al. 2007).

Table 3-6 Functional ingredients and possible health benefits of eight selected seaweeds

Algae	Functional ingredients	Possible health benefits
<i>Ulva</i>	Sterols Dietary fibre (glycosaminoglycans) Acidic polysaccharides	Reduce total and LDL cholesterol Gut healthy effect Anti-tumour Immunomodulation
<i>Gracilaria</i>	Sulphated polysaccharides (galactan/hyprins A) PGE ₂	Antiviral and anticoagulant Antihypertensive
<i>Porphyra</i>	PUFAs Sterols Soluble fibre Sulphated polysaccharides Mycosporine-like amino acids	Reduced risk of certain heart diseases Reduce total and LDL cholesterol Reduce total and LDL cholesterol Anti-tumour Anti-apoptotic Anti-thrombotic Protection against solar radiation
<i>Asparagopsis</i>	Sterols Fibre	Reduce total and LDL cholesterol Gut healthy effect
<i>Grateloupia</i>	Carnosadine Sulphated polysaccharides	Anti-inflammatory Immunostimulant Antiviral
<i>Gelidium</i>	Sphingosine derivatives	Contraceptive agent
<i>Ecklonia</i>	Phlorofucofuroeckol A Alginic acid Laminarin	Antithrombotic Antiviral Satiety Antiinflammatory
<i>Sargassum</i>	Alginic acid Sterols Xylofucans Laminarin	Satiety Antitumor Antiviral Antibacterial Anti-inflammatory

The research published to date mainly provides an alternative structure for further R&D, but a strategic approach is required to define the types of commercial outcomes (food/nutrition,

complementary medicines, supplements, nutraceuticals, pharmaceuticals, etc). There are well defined procedures for developing the required science program (pharmaceutical model), which may be seen as a 'pipeline' or staged process to market.

3.5.1 Antioxidant Properties

Among the compounds found in seaweed, those with antioxidant activity have attracted major industry and consumer interest. As photosynthetic organisms, seaweeds are exposed to a combination of light and high oxygen concentrations that induces the formation of free radicals and other oxidative reagents. The absence of structural damage in the seaweeds suggests that these organisms are able to generate the necessary compounds to protect themselves against oxidation. Thus, algae can be considered an important source of antioxidant compounds that could also be suitable for protecting human bodies against the reactive oxygen species formed, for example, by the normal processes of cell metabolism or induced by external factors (as pollution, stress, UV radiation, etc.). There are common and unique antioxidant substances in algae, including fat-soluble vitamin E (or α -tocopherol) and carotenoids and powerful water-soluble polyphenols, phycobiliproteins and vitamins (vitamin C). The α -tocopherol is the principal tocopherol in brown algae and has shown potent antioxidant activity both in vitro and in vivo. In this regard, a type of carotenoids called xanthophylls obtained from *U. pinnatifida* have demonstrated some activity against cerebrovascular diseases (Ikeda et al., 2003) through antioxidant pathways. The 7% dietary supplement of Nori seaweed significantly affected total and reduced glutathione, glutathione reductase activity and total antioxidant activity in rats (Bocanegra and Benedi, 2006). In an in vitro study, Ganesan et al. (2007) demonstrated that antioxidant activity of three selected Indian red seaweeds, particularly *Gracilaria edulis*, which had higher phenolic content (16.26mg gallic acid equivalent/g extract). Besides polyphenols, many constituents of the fibre also show antioxidant activity as well as immunological activity (Plaza et al. 2008).

3.5.2 Anti-cancer/anti-tumour properties

The fucoidans (a group of sulphated polysaccharides enhance immunity and assist with joints, blood function, digestion, liver and stomach function, and improve skin and cellular growth) have demonstrated an anti-tumoral effect in rats with mammary carcinogenesis (Plaza et al. 2008). On the other hand, the red algal genus *Porphyra* spp. contains a sulphated polysaccharide called porphyran that has shown some potential apoptotic activity of the human carcinogenic cells (Plaza et al. 2008). One study showed that the Ulvans (from *Ulva lactuca*) constitute a dietary fibre structurally similar to the mammalian glycosaminoglycans with cytotoxicity or a cytostaticity effects on normal or cancerous epithelial cells (Kaeffer et al. 1999). In other studies, *Sargassum* sp. demonstrated significant anti-tumour and immunomodulatory properties (Fujiihara et al. 1984, 1992, De Sousa et al. 2007).

3.5.3 Anti-inflammatory properties

Steron is the compound of great antiinflammatory potential that can be found in most seaweed. Diverse clinical studies showed that diets with sterols (from plants and seaweeds) might help to reduce cholesterol levels in blood (Plaza et al. 2008). Carnosadine identified in *Grateloupia carnosa* has been described as an antiinflammatory and immunostimulant agent (Wakamiya et al. 1984). In a recent animal study, laminarin, a polysaccharide extracted from brown algae has demonstrated immunostimulatory and antiinflammatory activity (Neyrinck et al. 2007), similar to *Sargassum* sp. (Alves Sousa et al. 2007). The authors proposed the effects could be due to the direct effect of laminarin on immune cells or to an indirect phenomenon through fermentation of fibre in the gut.

3.5.4 Immunostimulatory/immunomodulatory properties

Water-soluble acidic polysaccharides from the wall of *Ulva rigida* have shown immunomodulatory effects on murine macrophage cells by increasing expression of several cytokines and chemokines (Leiro et al. 2007). The result suggests that this component can be used as an experimental immunostimulant in inflammation where macrophage function is impaired. Laminarin from most of the brown algae has shown excellent anti-inflammatory activity in animals (Neyrinck et al. 2007).

3.5.5 Antiviral/antibiotic properties

The alginic acid and sulphated polysaccharides have demonstrated a powerful antiviral activity against herpes type 1 virus (HSV-1), HSV-2, and cytomegalovirus in humans (HCMV). For example, *S. vulgare* contains alginic acid, xylofucans and two species of fucans, whereas *U. pinnatifida* (brown alga) contains high levels of sulphated polysaccharides, specifically, sulphated fucans (fucoidans) and sulphate of galactofucan (Plaza et al. 2008). Diet supplementation with cellulose from Nori (*Porphyra* sp.) to rats was associated with significant decrease of bacterial enzyme activity in stool samples (Gudiel-Urbano and Goni, 2002).

3.5.6 Protective properties against cardiovascular and related disorders

Seaweeds can also be a source of polyunsaturated fatty acids, in the form of eicosapentanoic acid (EPA) described in *Ulva* sp. and *Porphyra* sp. These omega 3 fatty acids have demonstrated their effect on the reduction of coronary diseases, thrombosis and arteriosclerosis (Simopoulos, 2004). In a relatively recent rat study, consumption of a mixture of brown and red seaweeds resulted in significant reduction of blood lipid levels and also prevented thrombosis (Amaro et al. 2006), an effect attributed to the presence of polysaccharides. In addition, the fucoidans could be used as anticoagulant and antithrombotic agents (Lee et al. 2004), eg. Phlorofucofuroeckol A, an antiplasmin inhibitor isolated from *Ecklonia kurome* (Fukuyama et al. 1990). One innovative and recent industry product, HealSea (Diana Naturals, Phytonutrice) has had clinically proven effect on atherosclerosis.

3.5.7 Antihypertensive effects

Antihypertensive activities of seaweed extracts have been investigated in several in vitro and animal studies. It was reported that peptides with Angiotensin Converting Enzyme (ACE)-inhibiting activities were isolated following peptic digestion of Wakame (*Undaria* sp., brown kelp in the same family as *Ecklonia* sp. (Sato et al. 2002, Ikeda et al. 2003). ACE-Inhibitors inhibitors are used for controlling blood pressure, treating heart failure and preventing kidney damage in people with hypertension or diabetes. Short term and long term oral administration of these peptides decreased the elevated blood pressure of spontaneously hypertensive rats (Suetsuna and Nakano, 2000, Sato et al. 2002). Prostaglandin E2 from *Gracilaria lichenoides* has shown antihypertensive properties in hypertensive rats (Gregson et al. 1979).

3.5.8 Antilipemic/hypocholesterolaemic/hypoglycaemic effects

In few animal and human studies, bioactives, particularly sulphated polysaccharides from wide varieties of seaweeds have demonstrated antilipemic/ hypocholesterolaemic/hypoglycaemic activity (Goni et al. 2000, Vaugelade et al. 2000, Pengzhan et al. 2003). One animal study suggested that Ulvan dietary fibre plays a protective role in the rat to modulate the stimulatory effect to secrete mucin from goblet cells (Barcelo et al. 2000). The results from Pengzhan et al. (2003) indicated that sulphated polysaccharides from *Ulva* have positive effect on total and LDL-cholesterol through high molecular weight and triglyceride and HDL-cholesterol by low molecular weight polysaccharides.

Thus, there are diverse potential health benefits from seaweeds consumption and extracts, but there are also major gaps in the information available to substantiate the benefits of individual seaweeds products, at least from the point of view of the evidence base required for health claims on foods.

3.6 Consumer perception of seaweed-based product

Due to increasing human migration, consumers' acceptance of seaweeds as a food is changing across the globe. Traditionally, South-East Asian countries were major consumers of seaweeds and seaweeds-derived products, but areas such as California, Hawaii, some parts of France have an increased interest and acceptance due to increasing proportions of Japanese immigrants (FAO Technical Paper, 2003). Three major groups of seaweeds, i.e. *Porphyra* (Nori), *Laminaria* (Kombu or Hidai) and *Undaria* (Wakame) dominate the seaweed consumer market. One recent sensory analysis was conducted (Blouin et al. 2006) to determine the consumer acceptance of three species of *Porphyra* to select appropriate types for commercial aquaculture in Maine (USA).

They found that the American palate will accept nutritious, native species of *Porphyra* more than exotic species (*P. yezoensis*) in food products. Particular growing conditions, species, seasonality, product handling, and free amino acid composition (particularly for flavour) are generally regarded to affect the taste preference of Asian consumers (Nisizawa and Oofusa, 1990). Fresh, dried or chilled seaweed markets are steadily increasing in Australia. This observation is supported by import data which shows almost 30% growth rate per annum for the last five years (see Chapter 1.1, see Fig.1.1, and FAO, 2006). Consumers, nutrition and health are still the primary market drivers of this industry in Australia.

3.7 Seaweeds in a global cuisine

Uncooked vegan food (prepared without any animal products, dairy, or eggs) has become increasingly popular recently (Link and Jacobson, 2007). Some observational (Link and Potter, 2004) and anecdotal reports (Meyerowitz, 1998) suggest that raw food is healthier than cooked food, but no convincing clinical trials have been reported. Traditionally, seaweeds have been used as food in various forms, such as raw as salads and vegetables, pickles with sauce or with vinegar, relish or sweetened jellies, as ingredients in sherbets, ice cream, chocolate milk, cheese, instant pudding, mayonnaise and also cooked for vegetable soup. Some 21 seaweeds species are used daily in food preparation in Japan.

On an average the Japanese consume 4kg of seaweeds per capita per year (FAO Technical Paper, 2003). In Hawaii also, seaweeds are considered as the people's spices instead of pepper, oregano, mustard, or curry (Fortner, 1978). Although Asian countries are the lead users of seaweeds in their food preparation, in the recent years a strong movement has been developed in France to introduce seaweed into the European cuisine (FAO Technical Paper, 2003). Table 7 describes major uses of seaweeds in different food application. Seaweeds are also referenced in numerous cookbooks (Major, 1977, Fortner, 1978).

Table 3-7 Seaweed in food application¹

Food use	Seaweeds type	Seaweeds used
Main dishes	Brown	Sargassum spp.
Main dishes	Green	Ulva spp.
Salads	Green	Ulva spp.
Salads	Red	Gracilaria spp, Porphyra spp.
Soups	Green	Ulva spp.
Soups	Red	Gracilaria spp, Porphyra spp.
Dessert	Red	Gelidiellia spp, Gracilaria spp.
Powders for flavourings	All	Various
Food supplements	Red	Asparagopsis, Grateloupia (Limu spp.)
Food supplements	Green	Ulva (Limu spp.)
Condiments	Red	Food supplements (Limu spp.)
Ritual foods	Red	Gracilaria (Limu spp.)

¹ Adapted and modified from Cordero, 2006, Nisizawa 2006

The Australian seaweed industry is small, localised and largely supported by imported seaweeds. The annual import volume is over 5,000 tonnes in 2006-07 and an approximate value of A\$14 million. The current and potential applications for seaweeds and seaweed-based products in Australia are as marine vegetables, functional foods/nutraceuticals and non-food products.

3.8 Risks associated with seaweed consumption

Due to the increased consumer interest in functional foods, particularly the health benefits of seaweeds, consumption of macroalgae is increasing steadily not only in Asian countries, but also in Western world. Therefore the recommended quantities and risks associated with seaweed consumption should be identified, as seaweeds are known to contain some of their own toxic compounds, and they are efficient at absorbing toxic compounds in polluted environments. Toxins from microalgae have been well publicised, but the most notorious seaweeds toxins are kainoids (α -kainic and domoic acids), aplysiatxin (manauaealide A and manauaealide B), polycavernosides (complex glycosides) and sometimes prostaglandin E₂ (Smit, 2004).

The contents of the food items that can be purchased such as vegetables, are generally not subject to chemical analysis and their composition does not have to disclose even if these were actually known. It has been well documented in that scientific literature that certain types of marine algae have a high affinity for heavy metals (Volesky, 1994), and radioactive isotopes (van Netten et al. 2000) through food chain accumulation. Thus, the algal toxins are a serious threat to public health system and therefore, can affect the economy in many aspects (Table. 8). A high dose consumption of carrageenan and subsequent toxicity is also documented (Cohen and Ito, 2002), despite the FAO/WHO allowable daily intake recommendation. Gastroenteritis caused by *Vibrio parahaemolyticus* is strongly associated with seaweeds consumption (Vugia et al. 1997, Mahmud et al. 2007).

With little research in the area, it is still unclear whether seaweeds can act as a reservoir for bacteria throughout the year or only during a certain period. One recent study (Mahmud et al. 2007) found a correlation between gastroenteritis due to *Vibrio* from seaweeds and season (higher in summer) and highlighted the potential risk of seaweed consumption. The heavy consumption of the seaweeds poses a potential human health risk by bioaccumulation and bioabsorption of toxic elements, such as arsenic, cadmium, iodine and lead. However, due to the low to moderate consumption of seaweeds in Western countries, the level of risk is not alarming yet, but continuous and systematic program of monitoring regarding inorganic pollutants is necessary. Some traditional practices, such as washing and soaking of seaweeds overnight significantly reduce the level of inorganic pollutants.

Table 3-8 Heavy metal ($\mu\text{g g}^{-1}$ dry wt) contamination of seaweeds^{1, 2, 3, and 4}

Algae	Arsenic (As)	Cadmium (Cd)	Iodine (I)	Lead (Pb)
Ulva	4.50	0.58	25	1.16
Gracilaria	N/A ^a	N/A	N/A	N/A
Porphyra	28.33	3.15	17	<0.5
Asparagopsis	N/A	N/A	N/A	N/A
Grateloupia	N/A	N/A	N/A	N/A
Gelidium	N/A	N/A	N/A	N/A
Ecklonia	N/A	N/A	N/A	N/A
Sargassum	N/A	157 ^b	N/A	N/A
¹ Perez et al. 2007 ² Van Netten et al. 2000 ³ Rose et al. 2007 ⁴ Ahluwalia and Goyal, 2007 ^a Data not available ^b Absorption capacity (mg g^{-1})				

3.9 Regulatory position of seaweeds safety and consumption

Regulation is an important consideration in functional food innovation because it governs the means by which health benefits can be communicated to the consumer. Food regulations and standards differ significantly between countries and also across larger jurisdictional organizations, such as Codex Alimentarius, USA FDA, and FSANZ. In Australia and New Zealand, all nutrition and health claims on food will have to be scientifically substantiated. Safety is a paramount importance in food regulations and standards in all most all countries but there is some variation. For example, there is no regulation for arsenic in food in Europe (Rose et al. 2007).

In the UK, the amended Food Regulations (SI 1959 no. 831) recommended a general limit of 1mg/kg for total arsenic in food, but this does not apply to fish and edible seaweed where it is naturally present. Following a Canadian Food Inspection Agency report on consumption of hijiki seaweed owing to its high inorganic arsenic content (CFIA, 2001), the UK Food Standards Agency (FSA 2004) conducted a survey of seaweeds available in the UK markets. Still there is no formal global regulation on arsenic levels in seaweed for human consumption. Food Standards Australia New Zealand (FSANZ) advice people to avoid eating hijiki, a black variety generally used in soup and salad, due to its high level of naturally occurring arsenic. However, this advice does not apply to other varieties of edible seaweeds found in Australia and New Zealand.

Monitoring of algal toxins in freshwater and seafood is required in many countries and is recommended by World Health Organisation (Hungerford, 2005). Food safety issues will require particular attention in commercial R&D plans.

4 Culture methods for seaweeds

Seaweed is currently cultured at laboratory scales, to pilot systems and extensive and intensive commercial systems (Critchley 2004, FAO 1990). Although much can be learned from the protocol of culture systems used elsewhere, local species differences and climate and environmental conditions means that the protocol will differ. Also, there are many potential species for culture in Australia that have not been attempted elsewhere, and in addition, the concept of culturing combinations of seaweed species can be more efficient at removing nutrients from water and complement each other in culture (Bracken and Stachowicz 2006).

Both extensive and intensive culture of seaweeds has potential in Australia depending on the situation and resources at hand, including sea, pond and tank based culture. Seabased culture of seaweed has the potential to offset nutrient output from land sources as well as seabased aquaculture cages (Chopin et al. 2006). Pond based culture in saline affected areas also has potential (Cordova 2007), however there are multiple environmental and logistical constraints to inland saline aquaculture that need to be addressed (eg. overcoming wide temperature fluctuations and varying ionic composition of the saline water sources) (Cordova 2007, Partridge 2008). The most strategic direction for the evolution of seaweed culture industries is to address the immediate barriers for ventures that are close to commercialisation; thereby reducing the risk of research and development heading in the wrong direction based on untested assumptions. It is also important that this is done in a controlled environment to quantify the culture conditions used for culture protocols.

Land based, fully controlled tank culture will provide a basis on which to establish propagation and grow out techniques, determine the required proportions and quantities of water nutrient and micro nutrients, as well as environmental or climate requirements. The potential integration with the growing tank based aquaculture industry also lends itself to being commercially viable in the shorter term compared to other culture methods (Metaxa et al. 2006, Neori et al. 2004).

The primary target for research and development towards culture of seaweeds in Australian tank based systems is to learn the biology and culture requirements of local species. In particular, the culture of seaweeds requires optimisation of a range of parameters which can affect the viability of a seaweed culture system both in terms of production, and financial viability. These parameters can be tested and controlled in tank based systems, after which there is better potential to extend culture into sea-based or inland saline areas where control is not as easy. The parameters that need to be considered in culture systems include:

- flow rates
- light:dark cycles
- light wave length
- inorganic carbon levels (potential for integration with CO₂ emitting industries)
- macro-nutrient concentrations and ratios
- micro nutrients (implications for culture in inland saline culture)
- stocking density
- water exchange rates
- light intensity
- salinity
- temperature
- pH
- feeding regimes (pulse vs. constant)
- epiphyte control

5 Future directions

5.1 Why Australia should pursue this industry?

There is a strong case that Australia is missing an opportunity to become a world leader in sustainable technologies, as integrated production systems and seaweed culture technology in particular, is a growing and well funded field of research in many industrialised countries. For example, the Seapura project was funded by the European Union between 2001-2004 at an investment of \$1.5MEuro (app. AUD\$2.4M) (SEAPURA 2004), and recently the EU continued their commitment to this industry by funding a collaborative university and industry research and development program to improve integration for seaweed culture with fed aquaculture (app. AUD \$370,000) (Biopuralg 2007).

Seapura was a collaboration between universities in Germany, Spain, the UK, France and Portugal that developed culture technology for a range of seaweed species, as well as identified some important anti-bacterial properties (Bansemir et al. 2006). The anti-bacterial properties of seaweed are hugely significant, as the management of bacterial pathogens in primary production of livestock in land and water can no longer rely on traditional antibiotics. For example, *Vibrio anguillarum* is a major fish pathogen in the salmon industry, and Norway developed expensive vaccination technology to overcome reliance on anti-biotics. Obviously, the costs saving that may be realised by simply adding seaweed to fish feeds, or by reducing pathogens in recirculation systems with seaweed culture modules are very attractive. The technology for this particular research is currently being patented in Spain.

The expansion of the aquaculture industry overseas, (currently 50% of global seafood production) and the ambition (Fig. 5-1) and recent trends for this industry in Australia (ABARE 2007, Knapton 2008, Nicholas 2008, Stensholt 2008), indicates that commercialisation of seaweed culture technology is in a good position for private investment. Of importance is the timing, as this development coincides with an increased demand for healthier and more environmentally sustainable produce. However, the technology needs to develop in close partnerships with the respective government research organisations, and quickly within Australia to make up for lost time in research and development as technology is quickly patented. Australia requires a research and development effort comparable to that in other industrialised countries if it is to realise the potential of a new seaweed culture industry, and take advantage of the current investment in aquaculture as an industry.

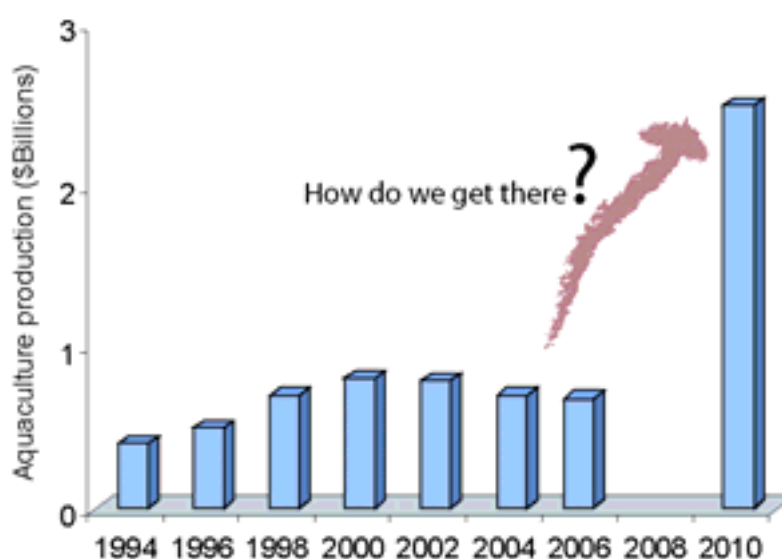


Figure 5-1 Australian aquaculture production value from 1994 – 2004, and the prediction set for 2010 by the Department of Agriculture Forestry and Fisheries.

5.2 How to get there?

This document highlights the range of potential products that a seaweed industry could deliver, and has focused on the most promising development opportunities in the short term; food products from integrated multi-trophic aquaculture systems.

The primary barriers to this industry are:

- 1) Lack of protocols and knowledge of the culture conditions required for a variety of seaweeds
- 2) Development of cost effectiveness studies for integration of diverse production systems
- 3) Laboratory analysis of the health benefits of local species of seaweeds
- 4) Identification of processing and packaging opportunities for seaweed food products
- 5) Detailed scoping of current market opportunities and potential new markets

The Australian research and marketing capacity could easily address these barriers if well coordinated, and the time required to address some of these barriers for some seaweed species is not large.

6 Conclusions

The composition of the different algal genera described in this report, indicates the potential for inclusion of seaweed in the Australian diet, and as a functional food for a range of health benefits. In general, most genera indicate nutritional value and can deliver proteins, carbohydrates, fibre, minerals, vitamins and, good fats, such as omega-3 fatty acids in the diet. Of note are some vitamins and minerals that are recognised as deficient in the Australian and western diets (e.g. iron, folic acid, B12 and iodine). In addition there are potential health benefits to be gained from the antiviral, anti-inflammatory, anti-cancer properties among others. The toxicological aspects associated with some of their components must be considered when developing seaweed-based functional foods. Macroalgae can be considered as effective bioreactors, able to provide different compounds in different quantities as they are influenced by the levels of nutrients and metabolites in the environment in which they grow. This is a significant commercial feature.

Seaweeds have mainly been used in Western countries as raw material to extract food additives such as alginates (from brown algae) and agar and carragenates (from red algae). However, algae also contain a multitude of bioactive compounds that might have antioxidant, antibacterial, antiviral, anticarcinogenic properties. This demonstrates the potential value to food and health and warrants further research, particularly targeted at Australian local species. Of particular interest is the potential for seaweed to address iron and iodine deficiencies in western diets, or the benefits of high quality dietary fibre with a positive influence on several aspects related to health, reducing the risk of suffering colon cancer, constipation, hypercholesterolemia, obesity and diabetes. Also, the continuing scientific investigation of existing bioactives and exploration of new algal chemical compounds is very promising for the functional foods/nutraceuticals and pharmaceutical industries. Fatty acids, particularly PUFA from seaweeds have attracted considerable attention among academics and industry in recent years (Berge and Barnathan, 2005).

Although the fatty acid patterns in different seaweeds are different, they are all rich in PUFA. For example, methoxy fatty acids, which are not very widespread in nature, but have been reported in several species of red seaweeds (Barnathan et al. 1998). These provide direction for new areas of research in seaweed that would be aligned with contemporary health issues and functional food trends. Finally, while it is helpful to look at individual components in seaweed, this must be done with a view to balancing healthful (eg fibre, iodine) and deleterious (eg sodium, heavy metals) components, and with a view to the culinary use of the food in the context of the whole diet.

To this end, further screening of local seaweed species is required to identify the range of health benefits that could be addressed from seaweed products. Barriers to this goal are development of pilot culture systems that can produce enough seaweed for food processing, packaging and marketing trials. Once established, the future technology and applications are limited only by the imagination.

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Seaweed Culture in Integrated Multi-Trophic Aquaculture

—Nutritional Benefits and Systems for Australia—

RIRDC Publication No. 09/005

This review contains a summary of the nutritional analysis and potential health benefits of eight seaweed genera, to support decisions on genera/species that could be cultivated in South East Australia, and integrated into aquaculture production systems.

The health benefits associated with seaweeds are critical in identifying marketable products for a future seaweed industry. By identifying the potential for seaweeds to be marketed as a healthy food, a strategy with which to progress the development of pilot commercial systems of seaweed culture of local species, and integrate these systems with the current developments in the aquaculture industry can be made.

Australia may be just a few years away from becoming truly competitive in the seafood aquaculture industry, if it rises to the challenge of promoting itself as the healthy and environmentally friendly primary producer. Seaweed culture can be a key factor in this challenge.

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Cover photo: *Porphyra* species growing on the south coast of NSW

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Contact RIRDC:
Level 2
15 National Circuit
Barton ACT 2600

PO Box 4776
Kingston ACT 2604

Ph: 02 6271 4100
Fax: 02 6271 4199
Email: rirdc@rirdc.gov.au
web: www.rirdc.gov.au

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