Food and Feed Applications of Algae

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Abstract Microalgae and seaweeds have a long history and increasingly important applications as both food ingredients and animal feed. The vast majority of algal species have yet to be evaluated for these applications. However, due to their extensive diversity, it is likely that they will lead to the discovery of many new algal products and processes in the future. This chapter covers algae as food, feed, nutraceuticals, functional food and food ingredients as well as production systems for food from algae.

Keywords Microalgae · Aquaculture · Shellfish · Functional food · Feed

1 Introduction

Algae, including microalgae and seaweeds, have a long history and increasingly important applications as both food ingredients and animal feed. This is well recognized in some countries such as Japan where today, seaweed forms a significant part of many meals (especially as wakame, nori, kombu and hijiki) and accounts for as much as 10 % of the overall nutritional intake (Mouritsen 2013). Japan also observes an annual Seaweed Day (February 6), which commemorates the day in 701 AD that the emperor of the time began to accept seaweed as payment of tax, recognizing its historical and cultural importance. Algae have also been used historically as food in several Asian countries, such as China, Indonesia, the Philippines, North Korea, South Korea and Malaysia (Fig. 1). In China, approximately 4.2 million tonnes of kelp, *Laminaria japonica*, is now cultivated annually, mostly for food (Lüning and Pang 2003). In many countries, there are detailed regulations for harvesting seaweed, highlighting the economic importance of algae as a crop (Chopin and Neish 2014; Mouritsen 2013).

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Fig. 1 *Porphyra* production on the Fujian's mudflats in China. The mudflats also produce oysters in addition to this edible algae, which is used to make nori (seaweed sheets). China is one of the world's biggest producers of seaweed—with seaweed farming being a vital component of China's fishing sector. The algae are farmed in a very similar way on a large scale in Japan where it is used mainly for making sushi. Credit: Wong Chi Keung (Hong Kong)

As most of the world's arable land is already in use or otherwise unavailable, the demand for algae and its importance as a food source is likely to increase markedly over the coming decades to help fulfil the world's food production requirements for projected population growth. Approximately 70 % of the earth's surface is oceanic, representing a relatively untapped resource of potential space to farm seaweed, not only as edible food, food ingredients and animal feed but also for other raw materials such constituents of cosmetics, agrochemicals, biomaterials and as renewable bioenergy feedstocks. The vast majority of algal species have yet to be evaluated for these applications. However, due to their extensive diversity, it is likely that they will lead to the discovery of many new algal products and processes in the future (Chopin and Neish 2014).

2 Algae and Their Constituents

Algae have many characteristics that distinguish them from terrestrial crops. In addition to the information supplied in Chap. 1, this chapter emphasizes the food and feed focus which follows; the simplest description is that algae are aquatic plants. However, this is not entirely accurate, as some microscopic varieties show microbial versatility and can opportunistically live in damp terrestrial environments (e.g., damp soil, mountainous areas and ice-fields). Algae are found in a range of salinities from freshwater to marine and some grow optimally at intermediate saline levels. There are some 350,000 species of algae but only a few species are currently domesticated. The unexploited potential for use as food or in feeds is therefore large. The composition of different types of microalgae and seaweed reflect their different uses as food, food ingredients and feeds.

The term microalgae strictly refer to eukaryotic photosynthetic microorganisms. Eukaryotes are cells that have a high degree of internal organization, including a membrane-bound nucleus (containing genetic material) and several other internal organelles that are also surrounded by membranes. There are many different types of microalgae including dinoflagellates, green algae (Chlorophyta or Chlorophyceae), golden algae (Chryosophyceae) and diatoms (Bacillariophyceae). Most species of microalgae are unicellular and can be motile or non-motile depending on the presence of flagella. Where multicellular or colonial conglomerations exist, very little specialization of cell types occurs, which distinguishes them from seaweeds.

There are about 8000 species of green algae, including micro- and macroscopic varieties. Like most other groups, they contain complex long-chain sugars (polysaccharides) in their cell walls as opposed to cellulose, hemicellulose and lignin which are found in the cell walls of terrestrial plants. These carbohydrate cell walls account for a large proportion of the carbon contained in algae, though many species also contain high levels of various lipids (lipids are fats or oils—the term 'natural oil' distinguishes these oils produced by biochemical processes from petroleum oils that are produced through fossilization). In some species, under certain conditions, the level of lipids may be as high as 80 % by wet weight (Chap. 6) (Chisti 2007; Miller et al. 2009).

Diatoms, which are mostly unicellular marine species, can also accumulate very high levels of lipids. As well as the common triacylglycerol lipids (TAGs), diatoms also store energy in phospholipids and chrysolaminarin, a β-(1-3)-linked glucan molecule. There are estimated to be around 100,000 species of diatoms, which dominate the marine phytoplankton and in contrast to other algal species, have a silicate cell wall.

Often the term microalgae is also used to include cyanobacteria (blue-green algae), which are prokaryotes (cells that lack a distinct nucleus). Some species of cyanobacteria have important food and feed applications (e.g., Spirulina (*Arthrospira* spp.) and *Aphanizomenon flos-aquae*). There are also many species of photosynthetic bacteria, such as purple-sulphur bacteria and green-sulphur bacteria, that are not normally included in the general term microalgae and as currently none of these are used as food or in feed, they are not discussed further here.

Seaweeds (macroalgae or macrophytes), are multicellular algal plants that usually have some specialization of cells into tissues. The degree of specialization, although higher than that of colonial microalgae, is much less than for terrestrial vascular plants and it is partly because of this that the productivity of some species is very high, generally much higher than terrestrial crops (Sect. 4). Around 200 species are used worldwide as food or food ingredients (Carlsson et al. 2007).

Seaweeds are divided into three broad groups, based on secondary photosynthetic pigments contained within them and are referred to as the green (Chlorophyta), red (Rhodophyta) and brown (Phaeophyta) seaweeds. These are not strictly taxonomic groups but are convenient conventions.

Green seaweeds, like their microalgal relatives have a diverse range of polysaccharides in their cell walls. Red seaweeds contain non-fibrillar and sulphated polysaccharides in their cell walls such as carrageenans, agars and complex sulphated galactans. These polysaccharides are well known for their gelling and thickening properties and are used as ingredients in many food products. The main species containing carrageenans include *Chondrus crispus*, *Gigartina* spp., *Eucheuma* spp. and *Hypnea* spp. Brown seaweeds are rich in other sulphated polysaccharides (Chattopadhyay et al. 2008, 2010), such as laminaran, alginic acid and fucoidan, which have been proven to show a wide range of biological activities important to human health (Sect. 7.1) (Cumashi et al. 2007; Teas et al. 2013).

About 200 species of seaweeds used worldwide as food or food ingredients, but only a few are intensively cultivated on a large scale including, the red seaweeds *Porphyra*, *Eucheuma*, *Kappaphycus* and *Gracilaria*, and the brown seaweeds *Laminaria japonica* and *Undaria pinnatifida* (Lüning and Pang 2003). Microalgal species that are commercially produced include *Chlorella* spp., *Dunaliella spp.*, *Haematococcus* spp., *Phaeodactylum* spp., *Schizochytrium* spp. and the cyanbacteria Spirulina (*Arthrospira* spp.) and *Aphanizomenon flos-aquae* (Chisti 2007; Guccione et al. 2014). Microalgae species important for feed applications are described in Sect. 6.

3 What Drives the Interest in Algae as Food, Food Ingredients and Animal Feed?

The use of algae as food ingredients and animal feed can be traced back several hundred years in some countries. More recently, the interest in algae for food and feed products has been sparked by the appeal of producing algae as renewable energy (such as for biodiesel) in response to global economic drivers such as the fossil fuel shortages in the late 1970s and the mid-1990s. The nascent peak after 2000 was blunted by the onset of the global financial crisis. Over the last decade, many surviving enterprises are exploring higher value products from algae including biotechnology products and foodstuffs or food ingredients. This has allowed momentum in the field to continue to the point where both food and fuel crops are seen as having large-scale commercial development potential.

Algae have several characteristics that distinguish them from terrestrial crops as sources of food or feed. Microalgae often combine the flexible metabolic repertoire of microorganisms with higher level eukaryotic sophistication, such as post-translational modification and partitioning 'products' within or exporting them out of the cell. This results in their actual and potential utility as self-replicating biochemical processing factories with high efficiency (Briggs 2004; Packer 2009).

The high productivity of microalgae compared with terrestrial crops is a feature shared with many seaweeds; this is further discussed in Sect. 4.

In addition, other characteristics of algae, or attributes of their use that are desirable for commodity-scale production include (Benemann 1997; Chopin 2012; Mouritsen 2013; Pulz and Gross 2004; Spolaore et al. 2006):

- Simple growth requirements; including nutrients—a nitrogen and phosphate source; trace metals; water; CO_2 and sunlight.
- High efficient productivity with comparatively low water use (Brown and Zeiler 1993; Chelf et al. 1994). Note that leaching from farmland, soil erosion and sewage contribute eutrophying phosphates, nitrates and other limiting nutrients to rivers, lakes and the sea where algae consume them thus enhancing growth in these areas.
- It is easy to provide optimal nutrient levels in a well-mixed aqueous environment of algal growth medium as compared with complex matrices such as soil.
- Absence of non-photosynthetic supporting structures (roots, stems, fruit): Single-celled and colonial microalgae are self-contained, meaning they do not have to spend energy moving storage molecules like starch around between tissues, almost the entire biomass is productive and no other tissues have to be supported. Seaweeds too are predominantly all productive tissues compared with terrestrial crops that require extensive above and below-ground structures such as roots and stems to support their productive components (leaves). Algae have few leaf-like structures, and are relatively efficient producing little inedible matter.
- Ability to be grown continuously: Although many species of microalgae undergo sexual cycles under certain conditions, most often they reproduce vegetatively through simple cell fission. Continuous harvest rates can be adjusted to maintain optimal culture density. This is especially so with continuous culture systems such as raceway ponds and bioreactors, where harvesting efforts can be modulated to match productivity. Continuous production also enables constant processing, unlike terrestrial crops that have seasonal cycles of planting, growing, harvesting and processing.
- Ease of moving and handling and automating harvest. One can simply pump microalgae whereas the handling of terrestrial crops is more difficult often requiring expensive crop specific equipment. These characteristics result in the industrial suitability of microalgal crops for a variety of uses, particularly for food and feed products (Chap. 4).
- Suitability as an aquaculture feed. Algal culture may support more valuable organisms like shellfish and fish. This can be achieved directly (lab cultures) or in-direct (bulk culture or natural blooms), e.g. in integrated multi-trophic aquaculture (IMTA), algae form part of the diet of cultured fish and/or shellfish, by absorbing and growing from animal waste products. The result is less expensive fish and shellfish, with less pollutive waste from farming them intensively as monocultures (Sect. 4).
- Algae can grow in environments like non-arable land, lakes and offshore oceanic waters that are unsuitable for other crops.

- The high reproduction rate of microalgae allows research and development to proceeds several orders of magnitude faster than with terrestrial crops. Furthermore, there is substantial evidence that the results of small-scale, cost-effective experiments can be translated effectively to commodity scale for food production.
- Learning and leveraging microalgal research and development from other fields including wastewater treatment and aquaculture.
- There is a niche societal aspect of food production from algae. Traditional farming and harvesting of microalgae and seaweeds has benefited communities and specific groups within those communities such as the coastal fisher women described in (Periyasamy et al. 2014).

Chopin coins the term "aquanomy" (in Greek, "the laws of the aquatic fields"), and suggests that seaweed production can be an ecosystem-responsible aquaculture. Seaweed farming has been identified as a "responsible aquaculture practice" by the UN Food and Agriculture Organization (FAO), providing high levels of employment with very low environmental impact (FAO 2012). The same can be applied to the production of microalgae. In the future, as large amounts of algae are grown as crops so must our understanding of how to efficiently grow them and manage this new farming activity. This includes its environmental, economic and societal impacts (Chopin 2012). Policies, scale-up trajectories and technological advances will be important for the future of the growing world population (Chopin and Neish 2014).

4 Production of Food from Microalgae and Seaweeds

As described in Chaps. 1, 2, 3 and 4, algae can be grown in a variety of different ways each with various trade-offs and suitability as fit for purpose (Fig. 2). In early 2000, Pulz and Gross indicated the largest closed commercial system for microalgal culture was a 700 m^3 tubular photobioreactor operated by Roquette Klötze GmbH & Co. KG (Klötze, Germany), producing about 100 tonnes of high-quality *Chlorella* biomass annually for the health food market (Pulz and Gross 2004).

In addition to microalgal culture in dedicated raceways and closed photobioreactor systems, open ocean systems, especially for seaweeds, are also important. These systems have developed from traditional wild harvest of seaweed, via family or craft-scale seaweed farming (Hurtado and Agbayani 2002). Several red seaweeds such as *Eucheuma* sp. are grown in tropical regions, and *Porphyra* sp. in temperate shallow sheltered sea areas (Fig. 3). These favourable natural locations support development of craft-level industries with simple equipment. The nori industry has grown to be approximately one third of the total seaweed market by value, extending well past its traditional craft basis. This has notably occurred via gaining an understanding in the 1940s of the complex life cycle of *Porphyra* sp., a genus that grows in cold shallow sea water, and undergoes an alternation of generations

Fig. 2 Raceways ponds for microalgal food production. Raceways are a pond style for suitable for microalgal growth that optimizes light utilization in a given unit area, in a cost-effective manner. Open ponds are managed for continuous production of microalgae. The technology has been developed over the last 40 years resulting in a well-understood industrialized production method for many species. The commodity-scale is demonstrated by the size of the figure walking between raceways in the centre of the image. Credit Cyanotech Corporation, Hawaii, USA

Fig. 3 Seaweed farming ropes for *Eucheuma* sp. in Bantaeng South Sulawesi Indonesia. Systems for growing seaweeds have developed from family or craft-scale practices and subsistence farming to a wide-spread industry. Over 95 % of world seaweed supply now comes from aquaculture sources rather than wild harvest. Credit Saipul Rapi, PT Mars Symbioscience Indonesia on the seaweed farm owned by Daeng Karim

with microscopic and macrophyte life stages (Drew 1949). Though cultivated since the seventeenth century, this new scientific understanding has allowed the industry to manage all aspects of production and move from a subsistence farming practice to an investable industry (Fig. 1). The importance of seaweed farming as opposed to wild harvest is demonstrated by the fact that 95.5 % of world seaweed supply now comes from aquaculture sources (FAO 2012). Since 2004, seaweed has constituted the largest group of organisms cultured at sea, representing 50.9 % of the total world mariculture production by mass (Chopin 2013).

Where conditions are favourable, microalgae too can be farmed inexpensively. For example, Spirulina (*Arthrospira* spp.) is grown in a relatively hands-off manner in natural soda lakes in Africa (it thrives at high pH) and there are several large ponds ($\sim$50 ha total area) in Australia for mass culture of this cyanobacterium. These are essentially very shallow ($\sim$20 cm deep) artificial lagoons constructed either on the bed of a hypersaline coastal lagoon, or formed by artificially expanding a lagoon (Belay 1997). The green microalga *Dunaliella salina* is often a by-product of large-scale salt producing evaporative ponds and is used as a health food and to produce β-carotene extract (Beuzenberg et al. 2014; Borowitzka and Borowitzka 1990; Oren 2005). To cultivate algae other than in these precious natural localities requires considerably more investment. This is currently only economic for higher value products, but costs are decreasing rapidly as new technologies develop.

Another possibility is the development of intermediate-scale freshwater microalgal production as an integrated waste water treatment system in sheltered marine bays and estuaries, but these, such as the OMEGA project of floating photobioreactors (Trent 2012) are unlikely to be used for food and feed production in the near or intermediate term because of the potential for contamination (Sect. 8 and Chap. 13).

Integrated food-waste systems have gained acceptance in India and throughout South East Asia. In the simplest of these systems, vegetarian fish such as tilapia are grown in ponds where algal growth is encouraged with nutrients derived from terrestrial animal or human waste with various levels of prior treatment. Such traditional systems have developed into the modern concept of IMTA which can be either marine or freshwater and can involve microalgae, seaweeds and animal species such as molluscs in addition to finfish (Holdt and Edwards 2014). In an increasingly resource-constrained world and with good understanding of contamination control, acceptability for this kind of process is likely to grow. Some aquaponics systems, a term used to describe the freshwater variation of IMTA (Chopin and Neish 2014), rely entirely on algae within the system to capture energy as sunlight using this to fix carbon into biomass and are thus not dependent on external food sources or waste utilization. Here, the animals in the system, consume the algae or seaweed. Bacteria present convert their nitrogenous waste to nitrate, along with other waste such as carbon dioxide, for use by the algae. Therefore, an efficiency is gained with greater quantities of algae, fish and/or shellfish produced.

As mentioned previously, an attractive feature of algae as food crops is their comparatively simple structure and biochemical efficiency which results in greater productivity than that of the terrestrial crops. There is a wealth of information on the productivity of microalgae in the literature (Banerjee et al. 2002; Benemann 2008; Carlsson et al. 2007; Chisti 2007; Huntley and Redalje 2007; Murakami and Ikenouchi 1997; Sheehan et al. 1998; Usui and Masahiro 1997; Weissman and Goebel 1987).

Generally, biological systems double in activity with a 10 °C rise in temperature, up to different limits for individual organisms/species. Microalgae are a broad group with varied requirements and limits. Some species can cope with temperatures approaching 40 °C. Thermophilic species thrive at even higher temperatures with some able to grow at temperatures approaching boiling water. Likewise, there are cold water adapted (cryophilic) species that can be equally productive at very low temperatures. Most of the species suitable for food and feed are grown at temperate through to tropical temperatures.

The photosynthetic efficiency of algae results in approximately 9–12 % of incident solar energy being converted to biomass. This is about 25 % of photosynthetically active radiation (PAR) (the band of wavelengths of visible light that can be utilized by plants) which is about 45 % of total full spectrum of sunlight (Carlsson et al. 2007; Melis 2009; Stephens et al. 2010).

Under optimal laboratory conditions, many microalgal species can double their biomass in a few hours. Maximum biomass productivity occurs under nutrient-sufficient conditions including the availability of light. Actual growth rates vary greatly depending on the growth method employed. Year round productivity in large-scale open ponds is generally accepted to be somewhere between 25 and 300 t ha^{-1} $year^{-1}$ of biomass (6.85–82.2 g m^{-2} day^{-1}) (Benemann and Oswald 1996; Heubeck and Craggs 2007; Ratledge and Cohen 2008).

For seaweeds, there is more variation in productivity data and less data available. This variation reflects not only different methods and units of reporting growth but also the variation in the ways it is being farmed, which differ in intensity. It is also important to consider that the growth and environmental conditions can significantly alter algal composition and performance of the crop as a feedstock (Chynoweth 1987).

Kappaphycus sp., (or *Eucheuma cottonii*, there has been some confusion over its taxonomy due to morphological plasticity), may be the fastest growing seaweed with values of 173 dry weight t ha^{-1} $year^{-1}$ reported (Hurtado and Agbayani 2002; Zuccarello et al. 2006) (Fig. 4). It is a red seaweed farmed for carrageenan as food additive. The brown seaweed *Macrocystis pyrifera*, a kelp, has been recorded growing at 15 g $frond^{-1}$ day^{-1} (wet weight) in California (Zimmerman and Robertson 1985) and at 1.3 kg carbon m^{-1} $year^{-1}$ in Canada (Wheeler and Druehl 1986). This equates to about 7 t ha^{-1} $year^{-1}$ if one assumes a value 2 times the amount of carbon needed per unit of biomass (values between 1.8 and 2.88 are commonly used for various algae). For *Gracilaria* spp., a red seaweed grown for relatively high value ingredients including carrageenan, productivity has been estimated at 10–12 t ha^{-1} $year^{-1}$ (Carlsson et al. 2007; Taw 1993) a value that is comparable with the 12 t ha^{-1} $year^{-1}$ for the same species farmed in experimental farming trials in the Philippines, where each plant was measured growing between

Fig. 4 *Eucheuma* sp. attachment on seaweed farming ropes. Also commonly referred to as *Kappaphycus sp.*, this is one of the fastest growing species of seaweed and is grown on a large scale for food products in many tropical and temperate parts of the world. Credit Southeast Asian Fisheries Development Center Aquaculture Department, Creative commons license 2.0, via Wikimedia Commons

6.0 and 11.2 % per day (Taw 1993). The carrageenan industry is large, with the Philippines having a capacity to process 120,000 tonnes of raw seaweed a year. Most producers are small and the economics are marginal for the vast majority of them. The industry structure is one of monopsony, where there are few food ingredient manufacturers buying from multiple tiers of aggregators, meaning that the producers may have little leverage.

The current annual global seaweed harvest has been estimated at between 12 and 19 million tonnes (Chopin 2013; Cleland et al. 1990; Mouritsen 2013) with an estimated value of US$5–7 billion (Chopin and Neish 2014; FAO 2009). Of this, approximately 80 % is used for human food (Mouritsen 2013). A large proportion of this is, around US$2 billion, is for a single genus, *Porphyra* that is farmed as nori, mostly for sushi.

The costs of production of algae for food are given in Table 1. The costs are dominated by harvesting expenditure, especially for microalgae (Pulz and Gross 2004). Some of the developing technologies for this are incompatible with food uses of the harvested microalgae (Chap. 5). Regardless, microalgal production for food is commercially viable. Martek Biosciences, Maryland USA, produces algae

Table 1 Example costs of production of algae

Organism	Purpose	Cost range/kg	Basis	Date	Reference
Seaweed	Biomass	$0.28–0.73[a]	Estimate	1987	Chynoweth (1987)
Seaweed	Food	$12–20	Wholesale price	2009	Irish Sea Fisheries Board Seaweed
Microalgae	Biomass	$30–70	Estimate	2007	Carlsson et al. (2007)
Microalgae	Biomass	$5–7.30	Actual	2011	Norsker et al. (2011)
Microalgae	Supplement	$210	Actual	2013	Nguyen (2013)

[a]US$

oil for inclusion in infant formula via a heterotrophic fermentation of sugars, which is a US$200 million per year business. β-Carotene from *Dunaliella* spp. in the health food market sells for approximately US$4000 per kilogram with a total sale of US$100 million per year in Japan & Far East markets.

5 Algae as Food

Algae already provide food and food ingredients for human consumption at both the top and bottom ends of the market. Few seaweeds are inedible; *Desmarestia* species can contain vacuoles of sulfuric acid with a pH as low as 0.44, making it inedible, but this is unusual. As mentioned previously, in many Asian countries algal products form a significant part of the overall nutritional intake and have done so historically. *Chondrus crispus*, commonly called Irish moss or carrageen moss (‘carraigeen’ is gaelic for ‘moss of the rock’ and ‘carraigín’ means ‘little rock’), is a relatively small species of red seaweed which grows abundantly along the rocky parts of the Atlantic coast of Europe and North America. It was most famously used by the Irish during the famine of the nineteenth century. *Caulerpa racemosa*, commonly called sea grapes are found in many shallow sea areas throughout the world and are consumed as part of traditional diet in Pacific Island nations including Fiji, Samoa and Tonga (Morris et al. 2014). In contrast with seaweeds, the difficulty of gathering or growing microalgae makes them an unlikely subsistence food.

Algae have food qualities that are otherwise hard to achieve, and also a potential for commodity-scale production that is almost impossible to realize with terrestrial crops.

5.1 Algal Nutritional Content

There is a multitude of the literature on the nutritional qualities of many microalgae species (Doucha et al. 2009; Fleurence 1999; Garcia-Malea et al. 2005; Pulz and

Gross 2004; Spolaore et al. 2006) and a good deal of quality information on seaweed species such as *Macrocystis pyrifera*, *Durvillaea antarctica*, *Kappaphycus* sp., *Pyropia columbina*, *Caulerpa* sp. and *Callophyllis* (Astorga-Espana and Mansilla 2014; Fleurence 1999; Nagappan and Vairappan 2014; Sjamsiah et al. 2014). The carbohydrates in seaweeds are not readily digestible, but their protein and fat content can provide energy. Despite the diversity there are some themes that can be summarized;

Lipids Algae can be considered masters of lipid metabolism. As mentioned previously, many microalgal species contain high levels of various lipids and this has driven recent interest in them as sources for renewable energy feedstocks for biodiesel and other biofuels (Chaps. 6 and 7), however, many of the fatty acids and lipids synthesized in algae are important for human health (Farzaneh-Far et al. 2010; Wen and Chen 2001a, b). Fatty acids are carboxylic acids with 4–28 carbon atoms in a straight (aliphatic) chain and although humans and other mammals use various biosynthetic pathways to both break down and synthesize lipids, most vertebrates do not possess enzymes to form double bonds at the n-3 and n-6 positions of the fatty acid carbon chain. Therefore, humans must obtain the essential fatty acids linoleic acid (C18:2n-6) and alpha linolenic acid (ALA, C18:3n-3) from dietary sources. Alpha linolenic acid can be extended to eicosapentaenoic acid (EPA C20:5n-3) and docosahexaenoic acid (DHA C22:6n-3) through elongation and desaturation (Kromhout et al. 2012). Most seaweeds, in contrast to most microalgae, contain relatively little total lipid, approximately 1–2 % in dulse (the red seaweed *Palmaria palmata*) and kombu (the brown kelp *Laminaria* spp.) and about 4–5 % in wakame (the brown seaweed *Undaria pinnatifida*). Often a high proportion of those, however, are health-giving polyunsaturated fatty acids (Mouritsen 2013). There is incomplete understanding of the roles of fatty acids in the diet, but it seems likely that there needs to be a balance between the dietary amounts of omega-6 and omega-3 fatty acids. The ratio of beneficial omega-3 fatty acids like EPA and DHA to omega-6 fatty acids is thought to provide health benefits for a variety of human conditions, and the ratio in microalgae and seaweeds is very favourable compared to terrestrial foods. Together with the low overall total fat this makes seaweeds healthy as a food, and microalgae as high producers of 'good oils' for food ingredients and supplements.

Algal-derived n−3 PUFAs, EPA and DHA, possess a range of anti-inflammatory bioactivity and have the potential to be added to foods as functional ingredients (Sect. 7) (Burr 2000; Kromhout et al. 2012; Yates et al. 2014). Currently, most EPA and DHA for human and animal consumption are fish or krill oil derived in unsustainable practices. Wild stocks of the fish supplying these healthy oils are rapidly declining meaning that algae will become increasingly important as a source.

As with other nutrients, the exact levels vary depending on how the algae is grown and, therefore, for wild harvested seaweed, the time of year and the place where the crops is grown can have an influence (Martineau et al. 2013; Miller et al. 2012; Mouritsen 2013; Nalder et al. 2015).

Proteins and amino acids Some algae have a high proportion of proteins and peptides as compared to other basic macromolecules. Many species, again depending on the exact conditions of growth, often include all of the amino acids that are essential to humans or domesticated animals. The protein content does vary considerably, reflecting nitrate levels in the culture water/media and the season in which they are harvested (Beattie and Beattie 2014). Amino acids are amine (containing nitrogen) and carboxylic acid containing small organic molecules that are the building blocks of peptides and proteins. Nine of the 21 amino acids most commonly used in higher organisms are classified as essential amino acids (EAAs) to humans because they cannot be synthesized from other amino acids. They must therefore be consumed in the diet. The ratio of amino acids varies widely between species and marine algae can be relatively low in the sulphur-containing amino acids, leucine and lysine. Seaweed protein is a source of all amino acids and is an especially good source of glycine, alanine, arginine, proline, glutamic, and aspartic acids. Almost a half of total amino acids in algae are EEAs and their protein profile is close to that of egg protein (Černá 2011).

Polysaccharides Being plants, algae have complex carbohydrate cell walls. Algal cell wall polysaccharides are more diverse than terrestrial plants. These long-chain sugar molecules are difficult to break down and therefore also to digest. As a result, they have little nutritional value. This means that they are low in food calories but still curb hunger. It is thought that some of these polysaccharides may have prebiotic effects (potentiating gut bacteria as opposed to probiotic which is the inoculation or seeding of gut bacteria), and may bind with cholesterol, causing it to be excreted. The polysaccharides contribute to other characteristics of food products, such as texture and many are bioactive—those that have a function, useful or otherwise, over and above being strictly nutritional (Sect. 5.3 and Chap. 14).

Minerals Marine algae in particular often contain a wide range of minerals (magnesium, selenium, chromium, zinc), some which may be in short supply in places ashore (Mouritsen 2013; Sugimura et al. 1976; Thomson et al. 1996). There is often as much potassium as sodium, which may help balance the higher sodium content of terrestrial food to a ratio that is better for human health. Some minerals may be excessively concentrated by algae. Iodine is often found in algae at levels greater than recommended for human consumption causing thyroid problems in regular consumers (Phaneuf et al. 1999). Caesium is also concentrated in seaweeds, which is of concern only when the water is contaminated with radioactive caesium.

Vitamins Some algal species are good sources of vitamins A, C, E, and some of the B-vitamins—thiamine, B_2 (riboflavin), B_3 (nicotinamide), B_6 (pyridoxine) and B_9 (folic acid).

Pigments Algae produce a range of photosynthetic pigments. Carotenoids are common in algae and cannot be synthesized by humans but are effective antioxidants and may have health benefits including bioactivity (Sect. 7).

Nucleic acids Most microalgae species, being single cells, contain high proportions of nucleic acids. This proportion is even greater when one considers prokaryotic species such as the cyanobacteria *Arthrospira* sp. (Spirulina) and *Aphanizomenon flos-aquae*. Nucleic acids are converted by humans into uric acid, which if present at sufficient levels precipitates into limb joints causing gout. This together with the levels of minerals mentioned above, make microalgae and cyanobacteria unsuitable as whole foods, but they are rarely considered in this way, whereas seaweeds have been used as subsistence whole foods.

5.2 Bio-Available Nutrients

Minerals are normally poorly absorbed in their elemental state. In marine algae, however, they are often chelated and thereby better absorbed. Most species have a substantial fraction of their carbohydrate in the form of indigestible fibre (polysaccharides). Dietary fibre is sometimes thought to reduce the absorption of some minerals and vitamins, but that may be true only where purified fibre is consumed (FAO 1998).

5.3 Attractiveness—Building on Nutrition

Wider than palatability—the attractiveness of a food to the eater—is an important contributor to the value of food and feed. It can be broken down to the following characteristics; (1) **Flavour**; Umami is a word used in Japan from the beginning of the twentieth century to mean a pleasant savoury flavour distinguished from the other four basic tastes (sweet, sour, salt and bitter). Umami is found in a wide range of foods, but is particularly associated with some brown algae because of their high content of the salts of the amino acid glutamic acid—up to 3 % dry weight. (2) **Texture**; Algal extracts are very commonly used to improve the texture of food products. Carrageenans, linear sulphated polysaccharides extracted from edible red seaweed, are often used in prepared foods such as yoghurt and ice cream. It has the EU additive E-number E407 or E407a. In the presence of potassium ions carrageenans bind dairy proteins into a firm aqueous gel, which both thickens the product, making it feel more substantial, and helps to prevent the components separating. One example of this is to prevent water drops forming as ice cream melts slightly during transport from supermarkets and then re-freezing as ice crystals in home freezers. There are many other uses of carrageenan. A *Kappaphycus* extract, containing carrageenan can be added to bread dough to increase moisture content, decrease stickiness of the dough and produce acceptably firmer bread (Mamat et al. 2014). (3) **Colour**; Algae have a wide range of colour, which is derived from the combination of chlorophyll and accessory pigments. The combination and therefore resulting colour is mostly attributable to the latitude,

Fig. 5 Nori seaweed sheets from *Porphyra* sp. for Sushi in Japan. A variety of sushi styles, including this Maki Sushi, rely on nori to provide not only nutrition but also texture and structure aiding presentation. Credit Janet Hudson, Creative commons license 2.0, via Wikimedia Commons

depth and turbidity of the water in which they grow. Some seaweeds are also translucent which when combined with their colour can make them very attractive on the plate. *Chondrus crispus* is a very palatable seaweed which is translucent and can be cultured in green, yellow, pink and purple shades, as a premium accompaniment to dishes in the East and West. (4) **Structure and Aesthetics**; *Porphyra* is attractive as food in several cultures. As previously mentioned it provides the nori in sushi but it is also used as gim in Korea and laver on the Atlantic coast of Europe. Nori provides nutritional qualities and a structural support to sushi and its Korean counterpart gimbap, but the aesthetics are a vital part of the dishes' appeal (Fig. 5). Nori provides a fine glossy coat and a well-defined edge, both of which help make sushi suitable as finger food. The production technique turns a naturally variable raw material into a consistent product with acceptable shelf life that is suitable for commercial kitchen techniques.

6 Algae as Feed

Many of the same characteristics of algae for human food apply with regards to use as animal feed. Algae feed production is important for many aquaculture species and is well established, large-scale and industrialized. This is because algae are often naturally in the diet, or a part of the diet, of many of the species farmed and also because practices have developed from traditional or craft approaches. Many aquaculture species rely on heterotrophic protists, microscopic and near-microscopic organisms such as rotifers and brine shrimp as food which in turn feed on microalgae. For terrestrial animal consumption, the focus is mostly on the ability of algae to supply nutrients in a form that the animal can digest. Algae are rarely a whole food for animals for the same reasons they are not for humans, and are usually a component of a diet created from several sources, which can be balanced by adding components. There are some exceptions though (Sect. 6.3) and algae can also constitute a higher proportion of the diet in animal feed if complete nutrition is met because other factors such as variety and palatability characteristics are reduced to a minor concern (Evans and Critchley 2014).

6.1 Finfish

The most obvious group of animals where algae are used for feed are with various fish species. The IMTA and aquaponics concepts described earlier have evolved from historical practices (Holdt and Edwards 2014). Several fish species widely used in these systems, such as freshwater or brackish tilapia, can feed directly on microalgae growing in, or added to the water. Herbivorous fishes such as the marine butterfish (*Odax pullus* or *Odax cyanoallix*) graze directly on seaweeds (Mouritsen 2013). Such fishes contain a complement of gut enzymes and bacteria to digest a larger proportion of the algal biomass than can other animals, so they can degrade the otherwise indigestible cell wall polysaccharides (Johnson et al. 2012). An advantage of the use of vegetarian fishes versus the carnivorous varieties, which are often used in aquaculture, is that they are a lower trophic level meaning more availability of available energy. This trophic level efficiency arises because there is an energy loss of some 10–25 % at each rise in the trophic level (e.g., primary plant producer to herbivore or herbivore to first carnivore). Thus, overall food conversion ratios tend to be better if vegetarian fishes are farmed rather than carnivorous species (Chopin and Neish 2014).

6.2 Non-finfish Aquatic Species

By far the largest group of animals farmed that depend on algae as feed, is the enormous variety of mollusc species that are used in aquaculture worldwide. These include the New Zealand greenshell™ mussel (GSM, *Perna canaliculus*), the blue mussel (*Mytilus edulis*), Pacific oyster (*Crassostrea gigas*), flat oysters (*Ostrea edulis*, *Ostrea chilensis* and others), geoduck, scallop and various species of clam, abalone and snail. Shellfish hatcheries always have dedicated algal production systems to generate feed, especially microalgae (Fig. 6). The Cawthron Institute's aquaculture park in Nelson, New Zealand, has two independent microalgal

Fig. 6 Microalgae production for aquaculture species feed. The microalgae production facility at the Cawthron Institute in Nelson, New Zealand. Hanging plastic bags are used as photobioreactors for the growth of several monospecies of microalgae, which are used to provide high nutritional quality food for both research use and commercial scale shellfish production. At this facility much of the production is continuous where harvested, algae collects in 200 L white bins (*centre*). Algae from these bins are supplied to juvenile shellfish species, such as oysters and New Zealand Greenshell™ mussel, by a computer-control pneumatic pumping system. Some facilities rely on batch cultures of algae, which are less efficient on an industrial scale. The Cawthron Aquaculture Park also has ~1 ha of outdoor open ponds for mixed-species microalgal production as bulk food for developing shellfish species. Credit Cawthron Institute, Nelson, New Zealand

production systems for feeding juvenile shellfish. A plastic bag-based continuous photobioreactor system is used commonly to produce single-species mono-cultures of algae for this purpose—*Isochrysis* affinis *galbana* (T-Iso), *Pavlova lutheri* (Droop), *Chaetoceros calcitrans*, *Chaetoceros muelleri*, *Skeletonema* sp. and *Tetraselmis suecica*. These microalgal species—suitable because of their nutritional content, size and palatability—are grown to feed the smallest most recently hatched shellfish. After a period of development the shellfish are fed mixed algal cultures that are produced in ~1 ha of onshore marine open ponds that are managed to encourage algal blooms representing bulk food. The Cawthron Institute's facility incorporates both commercial and research work, so the algal production systems are flexible and sophisticated. Fully commercial hatcheries employ a range of different methods for their algal production with varying degrees of sophistication. The biggest variation is whether continuous or batch culture is performed for specific species of microalgae and the style of photobioreactor used. Pond styles and management vary also.

Most shellfish can feed by filtering the microalgae out of the water they grow in. Other species such as abalone and some snails graze on benthic algal mats and seaweeds (Fig. 7). A wide range of seaweeds are used depending on the region,

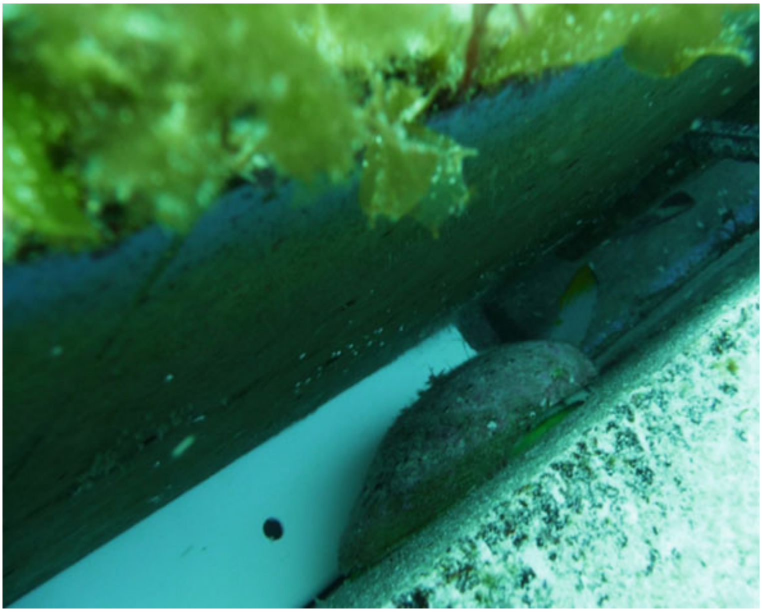

Fig. 7 The green alga *Ulva* sp. used as abalone feed. Many species of seaweeds are either harvested as feed for aquaculture species feed or co-produced in a variety of integrated multitrophic aquaculture systems. Irfan Amas from Curtin University, Australia

season and availability and are rarely grown for this purpose, more often being wild harvested. *Macrocystis* spp, *Ecklonia* spp., *Undariopsis peterseniana* and *Undaria pinnatifida*, *Eisenia arborea* and *Champia parvula*, have all been used for abalone feed in IMTA and commercial mariculture facilities around the world (Bangoura et al. 2014; Hwang et al. 2014; Zertuche-Gonzalez et al. 2014).

Non-mollusc invertebrate aquaculture species include various crustaceans such as crabs and shrimp (Sanchez et al. 2014), and echinoderms (mostly sea cucumbers) that have differing requirements of feed, many, feeding on benthic or planktonic microalgae or seaweeds.

6.3 Terrestrial Livestock

As in the case of human consumption, the high mineral content of marine algae can limit its use for terrestrial animal feed as a whole food. In domestic animals, as little as 10 % seaweed in the diet has been shown to reduce growth (Evans and Critchley 2014). There are some exceptions though. The sheep of North Ronaldsay in the Orkney Islands off Scotland live almost exclusively on a variety of seaweed species as they are confined to graze only at the shoreline for most of the year (NRSF 2014). In parts of Ireland cattle are sometimes taken to graze on wild *Chondrus* *crispus*. Sheep and cattle generally find some seaweed palatable as part of their diet and have been shown to self-regulate intake (Beattie and Beattie 2014).

Algae may be valuable not only as a high-protein feed but can also reduce greenhouse gas emissions because of its low structural cellulose content. Cattle fed on algae emit less methane than those fed with terrestrial feeds as it is the rumen gut microflora digestion of cellulan, the polysaccharide predominant in land plants that leads to methane production. In Australia, James Cook University scientists have evaluated the green seaweed *Ulva* spp. as a low greenhouse gas output high-quality feed for cattle (Cawood 2009).

There are many reports of algae being used for other terrestrial livestock including chickens, ducks, horses and pigs (Moore 2001).

7 Algae as Nutraceuticals, Functional Food and Food Ingredients

Nutraceuticals are natural health products (NHPs) including foods and food products which "reasonable clinical evidence has shown to have a medical benefit that its manufacturer cannot claim to the public or the physician under present regulatory policy" (DeFelice 2014). Nutraceuticals are supplements often taken without prescription (Plaza et al. 2008, 2009; Siró et al. 2008). A functional food is "a food that beneficially affects one or more target functions in the body beyond adequate nutritional effects in a way that is relevant to either an improved state of health and well-being and/or reduction of risk of disease. It is consumed as part of a normal food pattern. It is not a pill, a capsule or any form of dietary supplement" (Plaza et al. 2008, 2009; Siró et al. 2008).

Algae can be well suited to NHP use because they contain constituents that are well known to have health benefits with few if any side-effects, and are uncommon in other foods. These include the Omega-3 fatty acids and some pigments, such as β-carotene and astaxanthin (Sect. 7.1).

Governments around the world have regulated NHPs differently and so there is considerable overlap and variability about what constitutes a functional food and what constitutes a nutraceutical. China and Japan have long traditions of NHPs being consumed, with a resulting regime that is supportive of both suppliers and consumers. The USA regime has no such tradition, and seeks to minimize harm much as pharmaceutical regulation does. These differences in outlook result in regimes with little similarity, so what qualifies in one country may be excluded in another.

- **USA**

NHPs are called dietary supplements under US regulation. They are easiest to market if they consist of substances documented as Generally recognized as safe (GRAS), which is based on evidence that the substance has been part of the human diet over a long term with little or no adverse effect. However, this produces a dilemma for suppliers—GRAS marks them as ordinary, so how can they be marketed as having particular health functions?

Any claim made on the package is regulated by the Food and Drug Administration (FDA) and must be supported by data; but if data are generated from clinical studies, the FDA is inclined to classify the product as a drug and the burden for proof of efficacy is extremely high and expensive. Any claim that a product can treat a disease likewise makes the product a drug, not a food.

On the other hand, claims made in advertising (not on the package) are regulated by the FTC (Federal Trade Commission), not the FDA. The FDA has the power to pre-empt sale, whereas the FTC can only order the producer to cease and desist, and can be challenged. A product that can avoid the FDA tests can thus have a substantial market lifetime before FTC can successfully intervene.

Under FDA regulations, claims are permitted provided they are expressed as nutrient content, health, qualified health or structure/function claims. The content of a specific nutrient can be listed, and compared with other foods. Health claims may suggest that the product might reduce the risk of a disease, and if the data are incomplete or inconclusive must be qualified by saying so. The Significant Scientific Agreement (SSA) standard puts the burden of proof on the producer to show that the claims are supported by published studies and opinions from qualified professionals. Structure/function claims can propose an effect of the nutrient on specific body structures or functions, such as joints or eyes, if there is supporting evidence, and the claim does not suggest that it can treat a disease. Such constraints on claims make it particularly difficult for producers to distinguish their product from competitors, except by the amount of a specific nutrient they contain.

- **The European Union**

The EU has a category of Foods for Particular Nutritional Use (PARNUTS) regulated between the categories of Food and Medicine (Coppens et al. 2006). Generally, the test is special preparation to meet the "particular nutritional requirements of certain categories of persons whose digestive processes or metabolism are disturbed; or of certain categories of persons who are in a special physiological condition and who are therefore able to obtain special benefit from controlled consumption of certain substances in foodstuffs." The supplier must notify the competent authority of their intent to market as PARNUTS. Within PARNUTS, the category Foods for special medical purposes requires medical supervision. EU member nations vary in how they interpret the regulations. Suppliers' claims for their product will determine whether it is classified as a Food, a Medicine or as a PARNUTS product.

- **Japan**

Japan has a category of Food with Health Claims (FHC), which is legally distinct from either medicine or food. Most functional food is treated simply as food. Food with health claims may rely on generic claims of nutrient content, or may use the regulated category Foods for Specified Health Uses (FOSHU) which comprises of foods officially approved to claim their physiological effects on the human body.

Positive approval of the claim by the Minister of Health, Labour and Welfare (MHLW), as well as evidence of the absence of harm and of quality is required by FOSHU. Evidence must include human efficacy and safety data generated by trials in Japan, perhaps alongside overseas data. A FOSHU claim can be granted with any of levels levels of compliance, depending upon the quality of evidence provided.

- **Australia and New Zealand**

Food Standards Australia New Zealand (FSANZ) has recently brought in a new food standard (Standard 1.2.7) to regulate nutrition content claims and health claims on food labels and in advertisements. Food businesses must comply with the new standard from January 2016. Nutrition content claims and health claims are voluntary statements made by food businesses on labels and in advertising about a food. Nutrition content claims are claims about the content of certain nutrients or substances in a food, such as 'low in fat' or 'a good source of calcium'. These claims need to meet certain criteria set out in the Standard. For example, with a 'good source of calcium' claim, the food will need to contain more than the amount of calcium specified in the Standard.

Health claims refer to a relationship between a food and health rather than a statement of content. For Australia and New Zealand, there are two types of health claims:

1. General level health claims which refer to a nutrient or substance in a food and its effect on a health attribute. For example, 'calcium is good for bones and teeth'. The claims must not refer to a serious disease or to a biomarker of a serious disease.
2. High level health claims which refer to a nutrient or substance in a food and its relationship to a serious disease or to a biomarker of a serious disease. For example, 'diets high in calcium may reduce the risk of osteoporosis in people 65 years and over'. An example of a biomarker health claim is 'phytosterols may reduce blood cholesterol'.

7.1 Bioactivity of Functional Foods

Some of the constituents in algae that make them good food for people and animals can also be extracted and incorporated as functional food ingredients utilizing their bioactivity in other products. Algal extracts are fully described in Chap. 14, but because functional food ingredients are a rapidly growing area, they are worth mentioning here, especially when considering algal-based ingredients as part of food.

Some of the beneficial properties of algae in food are multiple. For instance, carrageenans though used widely as thickening agents in a range of food products also possess bioactivities that have been ascribed to a variety of health benefits (Chattopadhyay et al. 2008, 2010; Fenoradosoa et al. 2009; Mehta et al. 2010;

Nagappan and Vairappan 2014). As mentioned previously carrageenans are sulphated polysaccharides and marine algae are particularly rich in them (Renn 1997). Carrageenans are found especially in red algal species, such as *Chondrus crispus*, *Eucheuma* spp., *Gigartina* spp. and *Hypnea* spp., but other classes of the sulphated polysaccharides such as alginic acid, laminaran and fucoidan are found in all algal groups (Rocha de Souza et al. 2007; Wang et al. 2008). There is a continuum from the consumption of algae as food for nutrients through to the specific bioactive effects of an extracted molecule from algae. NHPs fall within these two extremes and sometimes the bioactivity is due to the complex matrix of the food consumed itself. For example the Pathway 27 project, a pan-European interdisciplinary group of life and social scientists and high technology food processing SMEs, are assessing the role and mechanisms of action of three bioactives (docosahexaenoic acid (DHA), β-glucan and anthocyanins) as fortifying ingredients in widely consumed food matrices (dairy, bakery and egg products). They are aiming to critically "evaluate the bioactive-food matrix interaction" (Bordoni and Ricciardiello 2014).

When algae are used as foods or food ingredients the dose of a particular moiety may not be sufficient for effective bioactivity and this is when extracts from algae play a role. Bioactivity is important to human and animal health and this bioactivity in algal constituents for food products are wide-ranging and include anti-inflammatory, antioxidant antiviral, anti-tumoural, anti-angiogenic, anti-adhesive, antithrombotic and anticoagulant activity (Cumashi et al. 2007) and many of these are potentially beneficial at the low levels ingested in foods incorporating algae.

- **Antioxidant activity**. There are both lipids and polysaccharides from algae with antioxidant activity. Various carotenes are ascribed many health benefits attributed to their antioxidant activity (Lee et al. 2013) (Boussiba and Vonshak 1991; Chou et al. 2010; Lavy et al. 2003; Yang et al. 2013). β-carotene, produced on an industrial scale from halotolerant *Dunaliella* microalgae, is a carotenoid, a relatively small molecular weight lipid with a strong colour. Astaxanthin, another strongly coloured carotenoid that has potent antioxidant activity, is produced commercially from the freshwater green algae *Haematococcus pluvialis* (Boussiba and Vonshak 1991). Astaxanthin has also been shown to be immunomodulatory (Jyonouchi et al. 1991) and a protectant against UV-induced skin damage (Yamashita 2006). These effects are most likely via decreased oxidative stress, bearing in mind the important role of oxidants in inflammation and the immune response (Andersen et al. 2007; Bennedsen et al. 1999; Jyonouchi et al. 1991; Park et al. 2010). The requirement of astaxanthin for healthy growth in finfish, such as for salmon, is an example of dietary intake of effective levels of astaxanthin through consumption of the feed of this important aquaculture species. Another structurally related carotenoid, fucoxanthin that is found in diatoms such as *Nitzchia* spp., *Phaeodactylum tricornutum* (Kim et al. 2012) and other species and the haptophyte *Isochrysis* affinis *galbana* (Kim and Pan 2012) is also a powerful antioxidant. It is thought that it has bioactive effects independent of its antioxidant activity though, such

as for controlling diabetes, obesity and in decreasing dietary cholesterol assimilation (Beppu et al. 2012; Sho et al. 2012) and may have anti-cancer health benefits (Irwandi et al. 2011; Nakazawa et al. 2009). Structurally dissimilar from carotenoids, furan fatty acids (F-acids) are potent free radical scavengers due to an electron-rich furan ring contained within the fatty acid carbon backbone (Spiteller 2005) that have gained a great deal of recent interest. They have been implicated as powerful anti-inflammatory agents (Spiteller 2005; Wakimoto et al. 2011). F-acids also occur in *Isochrysis* sp. and *Phaeodactylum tricornutum* microalgae, but may be in many more species but have not been detected yet because of their low stability.
Fucoidan is another class of sulphated fucan polysacharide that is present especially in brown algae such as the seaweeds *Undaria pinnatifida* (Miyeok), *Laminaria japonica*, *Turbinaria conoides* and *Fucus vesiculosus*, which has been demonstrated to have useful antioxidant effects (Chattopadhyay et al. 2010; Cui et al. 2010).

- **Anti-inflammatory activity**. The lipids n−3 PUFAs, EPA and DHA from algae have a range of anti-inflammatory bioactivity in mammals, which includes reducing eicosanoid, cytokine and adhesion molecule production, enhanced resolving production and decreased leukocyte-EC adhesive interactions (Yates et al. 2014). As described above, in addition or possibly related to, its antioxidant bioactivity, fucoidan also has anti-inflammatory actions (Cui et al. 2010; Cumashi et al. 2007), suppresses pro-inflammatory cytokines (Yoon et al. 2009) and may be useful to prevent neurodegenerative disorders (Kim et al. 2010; Synytsya et al. 2010).
The consumption of various algae as food and as ingredients in food, likely results in significant antioxidant and anti-inflammatory action. There are other bioactivities ascribed to algae, including antiviral (Damontea et al. 2004), anti-cancer (Synytsya et al. 2010) and antibiotic activities (Manivannan et al. 2011) that may not be realized when consumed as foods because of the levels obtained when dietarily consumed. These bioactive products from algae are more fully described in Chap. 14.

8 Algae Food Contaminants

Countries where algal food consumption has been traditional, notably Japan and China, have experienced concern over marine and freshwater environmental pollution. Both ocean-grown seaweeds and microalgae grown ashore in different ways are subject to contamination of various kinds, which can render them less suitable for consumption as food or feed. Spread of infectious disease, contamination with heavy metals, personal care products and hormones are all problematic.

Contamination issues are greater still when recycling of nutrients is used in production such as in ITMA and aquaponics systems. Modern wastewater treatment solutions are able to render recycled nutrients suitable for use, but at a cost. As demand for algal food production grows this will become increasingly important and necessary.

Biological contamination can also occur when other species grow in the same environment as the crop species. As described in Chaps. 2 and 3, one of the trade-offs of open production systems is the risk of contamination. Target species may be contaminated either with non-target algal species or with predators such as zooplankton that consume the algae. Current systems, processes and growth management regimes are designed to provide selective pressure to maximize target species production and discourage and decrease the risk of biological contamination. For instance, two of the most widely grown domesticated species of microalgae are grown under conditions that suit them but few others. Halotolerant *Dunaliella* spp. thrives in high salt and Spirulina in very alkaline water, restricting the growth of competitors and predators (Fig. 8).

Seaweeds are often contaminated with epiphytes—other algae, growing on the surface of their thalli—or with animals, particularly encrusting types such as

Fig. 8 Large-scale food production from microalgae. Spirulina produced as a whole cell food and nutritional supplement from the cyanobacterium *Arthrospira* sp. at a 90-acre facility in Kona, Hawaii by Cyanotech Corporation. This company also grows the microalgae *Haematococcus pluvialis* microalgae in open raceway ponds to produce nutraceuticals. Credit Cyanotech Corporation, Hawaii, USA

bryophytes and sponges. Depending on the ultimate use of the seaweed this can have a big effect on its value as food as commodity-scale processing to remove encrusting non-target species is rarely cost-effect.

Chemical contamination results from the water in which algae grows is being contaminated with substances that may be harmful in excessive concentration.

Seaweeds concentrate certain chemicals; for example, some kelps may concentrate iodine as much as 100,000 times compared with the surrounding water (Mouritsen 2013; Phaneuf et al. 1999). Hijiki (*Sargassum fusiforme*) concentrates arsenic in its tissues, and is poisonous if it is not boiled in large volumes of seawater. As a result, its sale is prohibited in several countries. Nuclear contamination is now also a concern in Japan and surrounding countries since the Fukushima accident. When the March 2011 tsunami damaged the Fukushima 1 Nuclear Power Plant, radionuclides leaked into the sea. Radioactive caesium was taken up by seaweeds. At sites 50 km from the reactor, 2 months after the accident, radioactivity in *Undaria* sp., used for food as wakame) was about 100,000 times higher than before, and after 2 years was still at least 100 times elevated (Kawai et al. 2014).

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