Algae

Algae are a tremendously diverse group of organisms that have shaped the evolution of our planet. Commercial food products, goods used in food processing, and health products are obtained from algae, and they represent important markets for countries all over the world. With the continuous growth of human populations, the demands of these algal products have increased. As a result, new technologies and innovative approaches for algal research and utilization have been developed recently.

Algae (singular alga), from the Latin for "seaweed," are a highly diverse group of organisms generally composed of simple photoautotrophs (organisms that get energy from the sun). Algae occur mostly in aquatic habitats worldwide and in many different types of ecosystems and habitats. They range in size from microscopic forms (i.e., phytoplankton) to meters in length (giant kelps). Algae can also be found in terrestrial habitats, and they are especially abundant in tropical rain forests (Lopez-Bautista, Rindi, and Casamatta 2007). One of the most striking landmarks of our planet is the land plant, which evolved from an ancestral green alga millions of years ago. Several endosymbiotic events (where an organism becomes a part of another organism in a mutually beneficial relationship) during the long evolutionary history of our planet have resulted in a wide variety of present-day algae, and these algal groups are represented across the main branches of the tree of life. The chloroplast and the mitochondrion, two parts of most eukaryotic (with a true nucleus) cell machinery, are believed to have once been organisms that became components of cells via endosymbiotic events.

The major groups are classified into three algal phyla: Chlorophyta (*sensu lato*) or green algae, Rhodophyta or red algae, and the diverse Ochrophyta. Another group, the prokaryotic (without a nucleus) cyanobacteria or blue-green algae, are bacteria, which makes them very distinct from the rest of the algae. But cyanobacteria are studied by botanists as algae both for convenience and tradition. Algae have been a major changing force in our planet by providing oxygen to a primordial atmosphere devoid of oxygen and thus changing the face of our planet forever. Nowadays algae and their derived forms provide the oxygen we use for breathing and keeping our biosphere as it is. They are also responsible for more than 250 billion metric tons of sugars produced annually (Raven, Evert, and Eichhorn 2005). Both microscopic and macroscopic forms of algae have been used by humans in a variety of ways throughout history and in the present day; people first collected them from the wild and eventually developed large-scale farming and culture operations.

As Food for Humans

The oldest and simplest use of algae is as a food for humans. Marine macroalgae, colloquially called seaweeds, have been harvested for human consumption since at least 600 BCE in China (Guiry 2010). In the Western world, algae are generally regarded as a specialty or health food, but in Asia algae comprise an important fraction of people's diets; *kombu*, *wakame*, and *nori* are the Japanese names for three types of seaweed that are highly important on both cultural and economic levels (Guiry and Guiry 2010). Kombu refers to kelp, primarily *Saccharina japonica* (formerly in the genus *Laminaria*), a brown alga. This seaweed is the most widely cultivated marine organism in the world (Bixler and Porse 2010).

S. japonica has been harvested primarily in China, where it is called *haidai*, after new methods of farming were developed in the mid-1900s (McHugh 2003, 4). Wakame is a specific brown alga under the scientific name of *Undaria pinnatifida*, and it is harvested in a similar manner to that of *S. Japonica*. In China, both brown algal species are cultivated on hanging rafts. In France, however, the wakame's cultivation requires a different approach including partial cultivation in laboratory conditions. Due to a different temperature tolerance and local food preferences, *U. pinnatifida* is cultivated primarily in Japan and also in Korea, where the alga is called *miyeok* (McHugh 2003). Nori is the name given to various species of the red alga *Porphyra*, which is cultivated and consumed mainly in Japan, though *Porphyra* species in the past have been harvested in the wild in northern Europe as "laver" (Guiry and Guiry 2010). For centuries, nori was considered a luxury food because it was difficult to find in the wild or cultivate (McHugh 2003), but in 1949, Kathleen Drew (1949) discovered that *Porphyra* requires mollusk shells for part of its life cycle. She discovered that a cryptic filamentous form previously thought to be a completely different alga (called *Conchocelis*) was part of the nori life cycle. Since then, nori cultivation has grown, nori is more widely consumed, and it is harvested on an industrial scale. The economic impact of Drew's investigations was so significant that even to this day nori farmers celebrate the Drew Festival on April 14.

Many other edible algae are also harvested worldwide. These include, among other, dulse (*Palmaria palmata*) and Irish moss (*Chondrus crispus*) in Europe, *aonori* (*Enteromorpha* spp. and *Monostroma* spp.) in Japan, sea moss (*Gracilaria debilis)* in the Caribbean, sea grapes (*Caulerpa lentillifera)* in the Philippines, and *cochayuyo* (*Durvillaea antarctica*) in Chile. Seaweeds in general are a good source of vitamins and minerals and sometimes protein, though the proportions vary between species and harvest times (Noda 1993; Yamanaka and Akiyama 1993).

Microalgae are much less widely cultivated than macroalgae, but several cultures have developed ways to use microalgae as food. The most notable microalgal food source is a filamentous cyanobacterium widely called spirulina; this name comes from the genus *Spirulina*, though the algae in question have since been renamed *Arthrospira platensis* and *Arthrospira maxima* (Kómarek and Hauer 2010). Spirulina has served as a food (*tecuitlatl*) for the precolonial Aztecs (Ortega 1972) as well as several present-day African cultures (Chamorro et al. 1996). Although *Arthrospira* is a microorganism, it often grows in mats that can be skimmed off the surface of water in a wide variety of environments, requiring little in terms of resources. Along with the fact that spirulina is a very good source of protein and other nutrients, the ease of cultivation of spirulina has made it appealing for use in developing countries in which hunger is a widespread problem (IIMSAM 2006). Spirulina and other cyanobacteria such as *Aphanizomenon flos-aquae* (Pugh et al. 2001) are also used as nutritional supplements or food additives, with various health benefits cited as a result of their consumption. In addition to any vitamins present, examples of these purported health benefits include immunostimulatory (Pugh et al. 2001) and antioxidant properties (Wu et al. 2005). Conversely, certain cyanobacteria have been known to produce toxins affecting humans and economically important fisheries. These toxins include beta-methylamino-L-alanine (BMAA), saxitoxin, and microcystin, raising the question of whether the consumption of cyanobacteria is safe (Gilroy et al. 2000). Biomagnification of BMAA in particular has been observed in studies of the Chamorro people of Guam, where the incidence of neurodegenerative disease is fifty to one hundred times the incidence elsewhere (Cox, Banack, and Murch 2003). But recent investigation challenges a correlation between the neurodegenerative disease and the BMAA produced by cyanobacteria (Snyder et al. 2009). Some cyanobacterial toxins have been proven useful in pharmacology, such as tolytoxin produced by the cyanobacterium *Tolypothrix* (Graham, Wilcox, and Graham 2009). Besides cyanobacteria, some green microalgae are used in industries; the alga *Dunaliella* is harvested to synthesize beta-carotene (Mojaat et al. 2007) to be used in supplements, and *Chlorella* is sold as a supplement similar to spirulina (Pugh et al. 2001).

Phycocolloids: Gels from Algae

Cell walls of red and brown seaweeds contain thick polysaccharide gels (substances made of carbohydrates that give the cell structure) that have become useful in food processing and in other industries. These gels, called phycocolloids, are extracted from different types of algae to manufacture three primary thickening agents: alginate from brown algae, and agar and carrageenan from red algae (McHugh 2003). An entire industry surrounding mass production of these gels has developed and continues to grow: in 2009, total sales of phycocolloids accounted for 86,100 metric tons (MT), worth over US$1 billion, compared to 1999, with 72,500 MT worth $644 million (Bixler and Porse 2010). All three kinds of phycocolloids are used to help emulsify, bind, thicken, and otherwise improve the texture of foods, such as ice cream and mayonnaise, as well as other products like toothpaste and paint (Guiry and Guiry 2010).

Alginates are extracted from brown algae, also known as kelps. They were discovered in the late nineteenth century in Scotland, and an alginate industry developed in the 1940s. Genera harvested to produce alginate (sometimes referred to as algin) have changed dramatically since 2000. In 1999, *Macrocystis* from the Americas and *Ascophyllum* from Europe were the most-harvested seaweeds for alginate, but the alginates extracted from these two genera are low in guluronic acid, which results in a less rigid gel (Bixler and Porse 2010). In addition, extracts of *Ascophyllum* are very dark, resulting in a product that must be bleached strongly (McHugh 2003). In 2009 the most important alginate seaweeds had shifted to *Laminaria* from Europe and Asia and *Lessonia* from South America, these two genera accounting for a total of 81 percent of seaweed harvests by weight. Combined, *Macrocystis* and *Ascophyllum* accounted for 58 percent of harvests in 1999, but by 2009 the amount had dropped to only 8 percent (Bixler and Porse 2010). *Laminaria japonica,* also called *Saccharina japonica* (Guiry and Guiry 2010), is easily the world's largest maricultural crop, grown in huge quantities in China, though not all of it is used for alginate. To extract alginate, the seaweed is pulverized and heated with an alkali solution, then diluted and filtered to remove seaweed residue. The solution then is chemically treated to eventually form a paste of sodium alginate, which can be dried and sold (McHugh 2003); the average price for alginate is about US$12 per kilogram (Bixler and Porse 2010). Alginate sales amounted to 26,500 MT and US$318 million in 2009 (Bixler and Porse 2010), representing about 30 percent of total phycocolloid sales value. In addition to food-related applications, alginates are also used in the textile pigmentation (McHugh 2003) and papermaking industries (Bixler and Porse 2010).

Agar is produced almost exclusively from two genera of red algae, *Gracilaria* and *Gelidium*. Agar was first discovered in Japan before the seventeenth century. The agar extracted from *Gracilaria* is used in foods, but *Gelidium* produces a high-quality agar that is crucial in bacteriology as the basis for culture media. To extract agar, the seaweed is heated in water for several hours, dissolving the agar in the water. After filtering, a jelly is produced with around 1 percent agar, which is then concentrated and dried (McHugh 2003). In 2009, 80 percent of manufactured agar was agar powder from *Gracilaria* (Bixler and Porse 2010), and most agar is produced in Asia, followed by the Americas. Of the three phycocolloid industries, the agar industry has the smallest sales volume—only about 15 percent of the total, having increased from 7,500 MT in 1999 to 9,600 MT in 2009—and the highest average price, worth about US$18 per kilogram (Bixler and Porse 2010). Agarose, the isolated gelling component of agar, is highly important in biotechnology and can reach prices upwards of US$5,000 per kilogram (Guiry and Guiry 2010). The market for agarose is small, consisting of less than 10 percent of the overall market for agar (Bixler and Porse 2010), and agarose producers usually buy agar rather than processing seaweed for their starting material (McHugh 2003). Besides its scientific applications, agar can be used as a vegetarian alternative to gelatin or in baking.

Of the various carrageenans, three are commercially useful based on their chemical properties: lambda, kappa, and iota (McHugh 2003). Kappa carrageenan forms firm gels, while iota forms elastic gels; lambda carrageenan does not form a gel but thickens solutions. Carrageenans are extracted from different red algal species, and the chemical composition of the extracts varies based on the algal species used. For example, *Chondrus crispus* produces a mixture of kappa and lambda carrageenans, *Kappaphycus alvarezii* produces mainly kappa, and *Eucheuma denticulatum* produces mainly iota (McHugh 2003). The carrageenan industry has grown from a sales volume of 42,000 MT to 50,000 MT since 2000. In addition, the average price of carrageenans has risen from US$7 per kilogram to US$10.50 per kilogram, resulting in the total sales value of carrageenans increasing from US$291 million to US$527 million (Bixler and Porse 2010). The majority of seaweeds (80 percent) harvested for carrageenan belong to the species *Kappaphycus alvarezii* (commonly harvested in the Philippines), while *Chondrus crispus*, although historically important as a carrageenan source, only represents 2 percent of 2009 harvests (Bixler and Porse 2010). Carrageenan is used in processed meats to increase product yields or replace fat, in dairy products as a stabilizer, and in canned pet foods to prevent separation of fat. The Food and Agriculture Organization/World Health Organization (FAO/WHO) Expert Committee on Food Additives determined that adding carrageenan is not a health hazard and is acceptable for daily intake (Guiry and Guiry 2010).

Algae as Environmental Indicators

Algae have proven useful as environmental bioindicators and bioassays. *Bioindicator* refers to the practice of directly examining an environmental sample, while *bioassay* refers to adding nutrients, like nitrogen and phosphorus, to different samples and examining any effects. Based on a variety of environmental factors, the types of algae present in a water sample, or the number of algal cells of some species in a sample, can be a source of information reflecting the chemical content of the environment (Graham, Wilcox, and Graham 2009). While it is possible to analyze water samples using chemical means, these methods can over- or underestimate the biologically available amount of the chemical. Round (1981) discussed many different species that can be used to measure different properties of a water sample, including

Selenastrum capricornutum. This species is a unicellular green alga that is the most widely used alga in bioassays (Graham, Wilcox, and Graham 2009); more recently it has been established that *Pseudokirchneriella subcapitata* is the correct name for *Selenastrum capricornutum* (Guiry and Guiry 2010). Many other studies use multimetric analyses of the phytoplankton (i.e. microalgae), based on abundance of different groups of algae or the presence of certain algal molecules, like chlorophyll *a* (Lacouture et al. 2006). With recent advances in genomics, the concept of an "ecogenomic sensor" has arisen, which is a device that can be placed in an environment and continuously take samples, analyzing the DNA present to detect organisms or genes over time (Scholin 2010). New technologies may soon be used regularly to remotely detect certain algae that have been shown to produce harmful algal blooms (HAB), toxins, or other deleterious environmental effects (Scholin et al. 2009).

Algae in Biofuel Production

Biofuels are a renewable resource and an alternative to the use of fossil fuels. Currently the primary biofuel industry is based on the production of ethanol from plant biomass, including corn (maize) and sugarcane (Demirbas and Demirbas 2010). Bioethanol is often mixed with gasoline in various concentrations to reduce the need for fossil fuels; in the United States, gasoline is mandated to contain up to 10 percent ethanol (RFA 2010), while in Brazil, 25 percent ethanol or higher is standard. There are several challenges with the production of biofuels from these crops, however, including competition with human food production (i.e., "food vs. fuel"), destruction of natural environments, and differences in greenhouse gas emissions between bioethanol and regular gasoline (UNEP 2009). The use of algae as a source for biofuels could provide a solution for some of these problems (Clarens et al. 2010). The algae used to produce biofuels are not food crops, and they would therefore not be involved in the food vs. fuel debate. Also, algal bioreactors can be built on unused land unsuitable for farming (i.e., deserts), which would not lead to deforestation (Greenwell et al. 2010). Algal bioreactors require large quantities of nitrogen, phosphorus, water, and carbon dioxide added to the system in order to be efficient, but their carbon footprint can be greatly reduced when built in conjunction with a wastewater treatment plant (Greenwell et al. 2010), a residual source of nitrogen and phosphorus. Many different processes can be used to make biofuels from microalgae, including the production of biodiesel, a fuel created from naturally occurring lipids that can completely replace petroleum-based diesel fuel used in transportation. Oil is reacted with methanol to produce methyl esters, which are then used as fuel, and glycerin is produced as a by-product (Chisti 2007). The oils currently used to produce biodiesel can be obtained from several different sources, including large-scale rapeseed farms, waste vegetable oil from food factories and restaurants, and algal bioreactors. Many different kinds of microalgae produce large amounts of lipids naturally; the algae are then pulverized, releasing the oil. In this process, algae yields a high percentage of oil compared to oil crops like rapeseed or soybeans. Combined with the high volume of algae production, as well as the advantages of algal bioreactors, algal biodiesel has great potential as a renewable, carbon-neutral energy source. Due to the limited amount of research on the subject, however, the economic feasibility of mass production of algal biodiesel is uncertain (Scott et al. 2010). Other applications of algae in biofuel production involve hydrogen gas, which can be used as a fuel itself (Hankamer et al. 2007; Kruse and Hankamer 2010) or mixed with carbon monoxide to produce syngas, which is used to produce diesel fuel by the Fischer-Tropsch synthesis (Demirbas and Demirbas 2010).

New Trends and Implications

Algal resources will play a significant role in our planet's welfare during the next decades. Previous and current models of algal utilization have made use of *exterior* conditions in order to improve algal crops and/or harvesting. The new models, however, are instead altering *internal* conditions to permanently modify the algal DNA. Algal transgenics, or the transformation of algal cells using genetic engineering techniques, is a new and rapidly evolving biotechnological field. With the advancements of algal genomes and innovating biotechniques it has been possible to "synthesize" algal cells with desirable traits. These "synthetic organisms" are a reality, and new patents have been already filed (Walker, Collet, and Purton 2005). Depending on the desired commercial product (Hallmann 2007; Cardozo et al. 2007), efforts are being made to create algal cells to function as cell-factories (León-Bañares et al. 2004). Several companies are applying transgenics technologies to improve algal cells and their commercial products (Waltz 2009) and "next generation biofuels" (SGI 2010). The new field of algal transgenics is not without difficulties: biotechnology and genetic engineering problems as well as public awareness and biosafety concerns need to be addressed (Hallmann 2007). But if the promise of "the green gold" becomes a reality in the next years, algae will undoubtedly alleviate many concerns for the near and distant future of the human race.

Juan LOPEZ-BAUTISTA and Michael S. DePRIEST
The University of Alabama

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See also Agriculture (*several articles*); Bioenergy and Biofuels; Food (*several articles*); Hydrogen Fuel

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