Algolculture

Margaret Caswell
Economic Research Service, USDA

David Zilberman
Department of Agricultural and Resource Economics, University of California at Berkeley

1. INTRODUCTION

U. S. agriculture is at a crossroads. The value of traditional agricultural exports has fallen while imports have increased. Concerns about the environmental impacts of current agricultural practices threaten profitability. As O'Connell (1989) pointed out in *Choices* , one answer to U. S. farm problems might be found in the "development of nontraditional farm products." This diversification will probably require "joint efforts among government, academia, and industry." In recent years, it has been recognized that aquaculture was a natural part of agriculture, and research funding for the development of a commercially viable aquaculture industry has increased. Research has focused, however, on the culture of fish and shellfish. The production of algae and the development of algal-derived products have the potential to become an increasingly important part of the agricultural sector and should be actively pursued.

Autotrophic algae synthesize their organic requirements from the same basic oxidized substances required for all plant life, so much of what we have learned about agricultural production will be transferable to these new "crops." Also, algae is a production unit that removes CO_2 from the air, produces oxygen, useful chemical products and feed, and leaves no polluting residue requiring disposal. Algolculture would complement traditional agriculture and should be welcomed as a development that will strengthen the agricultural sector.

Algae can be differentiated as either macro-algae (i.e., basic seaweeds) or micro-algae. The harvesting of macro-algae for consumption has a long history, and the world harvest of macro-algae currently has a value of hundreds of millions of dollars per year. Many types of dried seaweed are used directly as food products, mainly in salads and for seasonings. The economic value of the macro-algae derivatives, however, is much greater than the direct use of seaweed as food. Agar is a class of vegetable gum that was first extracted commercially around 1900, and it is the most diversely used macro-algae derivative. Agar is a very strong gelling agent with unique properties: it is not poisonous to humans, has no nutritional content, does not rot, and can absorb liquids and swell. In addition, agar gel may survive a wide range of temperatures, is indigestible by most bacteria, and is very elastic, resilient, and clear. Agar can be used as an emulsifier, a gelling agent, a preserving agent, an impression material (especially in dentistry), and in microbiological genetic-engineering applications. Carrageenan and algin are two other macro-algae derivatives that are used as gums, emulsifiers, and gels.

Even as demand for macro-algal products grows, the pollution of coastal waters threatens the natural supply of the macro-algae. Research is underway to use mariculture techniques to "domesticate" the seaweed. However, the commercial culture of macro-algae is far less developed than for micro-algae.

Micro-algae are a group of photosynthetic micro-organisms comprising several thousand species. These species can be divided into four types: cyanobacteria (blue-green algae), rhodophytes (red algae), chlorophytes (green algae), and chromophytes (all other algae). Only a small fraction of these varieties have been studied for possible beneficial use. Therefore, there is great uncertainty regarding the behavior and properties of most micro-algae species. These microscopic organisms make up the world's phytoplankton, and they can form rapidly-growing populations in water when supplied with the necessary nutrients for their culture. The commercial utilization of many micro-algal-derived products is experimental, so that there is still uncertainty regarding the economic potential of these products. The focus below is on micro-algae products. The appendix provides a more detailed discussion of both micro- and macro-algae products.

2. MICRO-ALGAE PRODUCTION

The growing of suitable micro-algae requires an abundance of solar radiation and warm temperatures. Algae can be grown in either an open or a closed system. An open culture system is usually a pond containing a single dominant organism (alga). Algal ponds are generally shallow (less than 1 meter) to ensure the penetration of light into the culture, and they are kept continuously mixed by gentle stirring.

Algal farming can be accomplished with the use of saline and brackish water so that a soil quality requirement need not be met. Even when algal production requires good quality water, the water requirements are likely to be less than those of many agricultural crops because algal production does not involve evapotranspiration. Algae "feed" comes from a supply of CO_2 (carbonation). Since many algae grow in a high salinity, completely inorganic medium, few, if any, natural competitors and predators interfere with large-scale cultivation.

Research is also being conducted on the culture of algae in closed systems. Plastic tubes are used to promote autotrophic or phototrophic growth. Sunlight is a major energy source, although CO_2 and nutrients have to be supplied exogenously and the algal culture still has to be kept agitated. It will be many years before a large-scale closed system culture of algae will be commercially viable.

Large-scale open cultures should be sited where both light and temperature permit growth outdoors during a major portion of a year. Although algae can be grown almost anywhere during the summer season, biomass production would be limited in many locations. Despite warm temperatures, much of the tropics has sustained cloud cover which also diminishes net production of biomass. Also, tropical rains can dilute the production ponds. Ideal locations may be temperate and semi-tropical deserts, where cloud cover is minimal and rare, and nights are generally cooler than days. There is, however, a high rate of evaporation for desert areas, so clean makeup water is needed for such areas.

Harvesting is a major cost of a micro-algal mass culture system. In most cases, production of micro-algal products involves their separation from their growth medium (exceptions are for applications in waste treatment, fish food, and nitrogen fixation). Harvesting is often difficult because algae have a density just slightly greater than that of the water in which they grow and because they have a strongly negative charge on their surface. It will be important to find algae strains with natural properties favorable to harvesting even at the expense of lower yields to offset high separation costs.

Although existing well-designed micro-algal systems can outyield the biomass of any known crop, the cost of algae from man-made ponds is, at present, not competitive with most other plant protein resources. Reliable information on costs of algal production systems is hard to come by. Operational costs include production, harvesting, and drying. Currently, labor costs are high, but as experience is gained, labor costs will decline. Feed costs are the big cost item in the long run, especially the CO_2 cost. The cost of repair and maintenance will decline with time as more efficient production technologies and machinery are developed. Energy efficiency is likely to increase, but energy consumption may rise as production becomes more automated. Although experiments in Israel had operating costs that ranged from $15,000 to $24,000 per dunam, it is believed that operational costs can be reduced to $10,000 per dunam. Reducing CO_2 and feed costs is a major challenge. Capital costs were also high (up to $30,000 per dunam) in the Israeli experiments, but they may be reduced over time as experience is added.

3. CURRENT ALGAL PRODUCTS

There are several algal-derived applications that have already proven to be of value: wastewater treatment, the production of fine chemicals, and the supply of food and feed products. Many studies and several commercial facilities have demonstrated the viability of micro-algae in sewage treatment. Oxygen production by micro-algae aids waste oxidation by bacteria in ponds, and algae enhances sedimentation, disinfection, and the removal of nutrients, heavy metals and organic toxins. In addition, the algae biomass produced in sewage pools can be used to produce energy by fermentation for alcohol or methane gas production. The latter would suggest advocating more research funding from the Department of Energy than the U. S. Department of Agriculture.

From the standpoint of agriculture, however, the cultivation of algae for the production of marketable products is a potentially profitable venture. Algal products vary substantially in price and value, according to their use and refinement. Two chemical products currently produced commercially are beta carotene and phycobiliproteins.

3.1 Chemicals

Beta carotene is a metabolite with a wide range of commercial applications. It is used as a food coloring (with a major application in providing the yellow color to margarine), as an additive to enhance the color of the flesh of fish and the yolk of eggs, and to improve the health and fertility of grain-fed cattle. Early commercial production of beta carotene was synthetic, but during the 1970s, researchers realized that, under nutrient-stressed, high salt, and high light conditions, the micro-algae, *Dunaliella salina*, would accumulate up to 14 percent of dry weight as beta carotene. This discovery led to a growing industry in the derivation of natural beta carotene.

The introduction of natural beta carotene will likely have many impacts on beta carotene uses and markets. Today, the price of extracted and purified natural beta carotene is much higher than that of synthetic beta carotene ($1,000 to $2,000 per kilogram for natural versus $400 to $800 per kilogram for synthetic). The price difference reflects the preference consumers have for natural products and that natural beta carotene has physical properties that make it superior to the synthetic form. In particular, natural beta carotene is fat-soluble which would make it a more effective anticarcinogen and anti-heart disease agent than synthetic beta carotene. Diffusion and substantiation of the knowledge about the desired medical properties of natural beta carotene will increase the demand for the product.

Algal-derived phycobiliproteins can be used in medicine as a diagnostic tool. Specifically, biliproteins from micro-algae are used as fluorescent markers for genetic screening. It is relatively easy to produce phycobiliproteins, and there is much competition. The case of phycobiliproteins represents a fast response time between research discoveries (1982) and commercial applications associated with algal utilization.

3.2 Food

Many micro-algae have a high nutritional value since they contain proteins, vitamins, minerals, and nonsaturated fats. Moreover, they can yield higher outputs for the same levels of water and land than many conventional agricultural products. Still, there has not been much commercial utilization of this food source for human or animal feeding. *Spirolina* is a unique exception. It is one of the two micro-algae that grow isolated in a monocultural setting (the other one is *Dunaliella salina),* and it is available in Mexico and other Central American locations in large quantities. *Spirolina* is a component of many health food products. In the late 1970s and early 1980s, it reached a peak in popularity and prices soared, but current demand for *Spirolina* is more stable.

3.3 Feed

Algae produced as a by-product of waste-management plants can be used for animal/livestock and fish feed. It is also recognized that, for long-term sojourns in space, micro-algal bacterial cultures are likely to be an essential part of regenerative life-support systems. However, much research is needed to develop large-scale food and feed production from algae.

4. FUTURE ALGAL PRODUCT LINES

Much of the algal research has been directed toward increasing biomass to be used as a fuel source. More research is needed for identifying and developing production techniques to obtain commercial products from micro-algae. Micro-algae contain many useful chemical compounds that can be used in cosmetic and skin products, food and feed supplements, vitamins, and fertilizers. At this time, micro-algae is less productive than bacteria, and our ability to manipulate the genetic structure is not as advanced, but micro-algae contain unique and complex products not available from other sources. Therefore, there is a great deal of research potential regarding the use and manipulation of micro-algae. The development of several product lines seems very promising. Algae can be the source of fatty acids, polysaccharides, organic food coloring, osmoregulators, vitamins, and several other important chemical compounds.

4.1 Omega-3 Fatty-Acids

Micro-algae can be used to produce unsaturated oils which have desirable therapeutic properties. Research has shown that omega-3 fatty acids reduce cholesterol and fat levels in the blood and "cleanse" the lining of the blood vessels. They also have effective therapeutic properties dealing with rheumatoid arthritis and immuno-deficiency diseases. Currently, the source of such fatty acids prescribed for patients is fish oil, but cod and other fish are not the direct producers of omega-3 fatty acids—the fish extract the acids from the micro-algae found in their natural environment. A product extracted directly from the algae is likely to be superior to the cod liver oil because (1) it will not have the "off" flavor of cod liver oil, (2) it will be more of a "pure" product, and (3) it will have a lower cholesterol content. Omega 3 fatty acids extracted directly from micro-algae can also be used as feed for chickens and dairy cows which will then introduce omega-3 fatty acids to eggs and milk. The application to eggs may be especially useful since it will tend to combat the contribution of eggs to cholesterol buildup.

4.2 Polysaccharides

Polysaccharides are chemicals that are used as viscofiers (thickening agents), flocculating agents, and lubricants. The value of polysaccharides varies according to the end use, availability, and purity. Polysaccharides can be derived from bacteria, fungi, macro-algae (e.g., carrageenan and agar), and micro-algae. Bacteria and fungi are much more productive than algae at this time, but algae generate complex and unique polysaccharides. Under the right conditions, 15 to 55 percent of the weight of the micro-algae can be extracted as polysaccharides.

4.3 Food Color

There is a growing demand worldwide for organic food coloring. Regulating agencies constantly limit the range of permissible chemical food coloring, and the regulatory process will be even stricter if and when organic substitutes are available. Micro-algae can be used as a source of many organic food colorings. Some micro-algae contain substantial amounts of Carotene (besides beta carotene). Other types of coloring appear in micro-algae as well. The potential of micro-algae as a source of food coloring is limited, however, because algal-derived food coloring is not photostable and the color tends to bleach with cooking. Nevertheless, in spite of this limitation, the potential market for micro-algae-derived food coloring is vast.

4.4 Osmoregulators

Certain carbohydrates can affect osmotic processes, and micro-algae compete with bacteria and animal fat as sources of osmoregulators. Up to 50 percent of the dry weight of *Dunaliella salina*, can be transformed to osmoregulators under the appropriate conditions. Research is likely to discover valuable osmoregulators that can be produced uniquely from micro-algae.

5. RESEARCH DIRECTIONS

There are three main types of research essential for the development of an agricultural sector based on the production of micro-algae-derived products. The first type of research would attempt to discover new species and to study the behavior of micro-algae in the natural environment. The second type would be aimed at analyzing the properties of micro-algae, optimal growing conditions, and the chemicals and metabolites that can be generated. The third type of research would be designed to define mechanisms and procedures for producing algal products commercially. We are at the early stages of the economic utilization of micro-algae, and the first two types of research are setting the direction and much of the agenda.

With limited budgets, it will be essential to design public and private research strategies carefully. Some productive lines of research could include: research to increase productivity with respect to both an increase in algae yields and an increase in content of desirable product; research to design better facilities and machinery which would be aimed primarily at reducing capital and operational costs; research aimed at reducing feeding and energy cost; research in disease control which is crucial for any monoculture; research aimed at environmental control; and research into the marketing of products. State Agricultural Experiment Stations and the Agricultural Research Service will be important contributors to the development of the algolculture industry as will researchers from the academic and industrial communities.

6. SUMMARY AND CONCLUSIONS

Commercial utilization of micro-algae is economically viable, and there is a worldwide market for algal derivatives. The growth of micro-algae is an agricultural activity and much of the U. S. farming experience would be transferable to the large-scale culture of micro-algae. The diverse product lines that can be derived from algae would strengthen the agricultural sector. The production of fine chemicals such as beta carotene and phycobiliproteins is currently underway, and there is promise of future production of fatty acids, polysaccharides, carbohydrates, vitamins, and organic food coloring. These products would not compete with current agricultural products and, in several cases, the algal-derived products would complement the production of products such as eggs and meats.

The production of food and feed directly from algae could also be a benefit to the agricultural sector because of the lower land and water quality requirements of algae ponds. Algal production is particularly suited for areas with hot and dry climates, access to saltwater resources, and high manpower quality. Marginal or erodible soils could be retired from traditional agricultural cultivation in these areas and be devoted to the growth of algae.

Even though large-scale cultivation of algae is possible, a great deal of research needs to be done to increase our understanding of the species, optimal growing conditions, and characteristics of the products that can be derived and to lower costs of production. Such a research effort will require cooperation among the public, private, and academic entities that are committed to strengthening U. S. agriculture.

7. APPENDIX

7.1 Current Commercial Uses of Algae

Commercial use of algal products is not a vision for the future--it occurs substantially now. Existing patterns of use are insightful and useful for future projections. Still, present success stories are only the tip of the iceberg.

Much more research and knowledge are needed for full societal gains from the economic potential of algal products.

One has to distinguish between two major algae types--macroalgae and microalgae. Macroalgae are basic seaweeds; microalgae (which are our main concern) are microscopic organisms which are observed in groups rather than individually.

7.2.1 Uses of Macroalgae

Nori

Many types of dried seaweed are being used as food products, mainly in salads and for seasoning. Sales of one of the dried kelp, called Nori, are estimated to be in the tens of millions of dollars. While Nori is consumed mostly in Japan and the Far East, its consumption is spreading to the West and is now being produced and consumed in California. Much of the Nori in the market is harvested from the sea, but there are substantial efforts in cultivating it through mariculture (Glazer).

Agar

But the economic value of the macroalgae derivatives goes much beyond their usefulness as food products. Agar is the most diversifiably used macroalgae derivative with substantial worldwide sales. Agar is a class of vegetable gums that is derived from two varieties of seaweed--Gelidium and Gracilaria. It is a very strong gelling agent with unique properties. Agar is not poisonous to humans, has no nutritional content, does not rot, and can absorb liquids and swell. The gel it generates may survive a wide range of temperatures, is indigestible by most bacteria; and is very elastic, resilient, and clear (Chapman, 1970; Renn, 1984). Agar and its derivatives have a wide variety of uses. The value of agar products varies substantially according to their quality.

The relatively low-value agar is used in the food industry (as an emulsifier, gelling agent, and preserving agent), as a component of many laxatives and as an impression material (especially in dentistry). The 1985 price of food and industrial quality agar was between $14 and $30 per kilogram. The medium-value use of agar is in bacteriological and microbiological applications. The 1985 price of agar in these medium-value applications ranged between $30 and $120 per kilogram. The highest-value derivative of agar is called agarose and is used in a microbiological genetic-engineering application. The 1985 price of agarose varied between $200 and $1,500 per pound. A good ballpark figure for its price today is $1,200 per kilogram.

The 1985 volume of sales of dried seaweed for agar products was around $25 million. The retail volume of sales of agar products was around $250 million. The 1985 annual sales of retail microbiology-quality agar were estimated to be around $140 million; annual sales of food-quality agar were estimated to be around $108 million; and agarose sales were estimated to be around $2 million in 1985 (Forget, Vreeland, and Neushel).

The demand for agar and agarose is continuing to grow, and there is much interest in alternative sources of agar and some experimentation with domestication of it. Agar serves as an example to the large market for algae derivatives and versatility of products of different quality that can be produced from individual algae. It also serves to emphasize that this is a time where domestication of seaweed production attracts much interest.

Carrageenan and algin

Carrageenan and algin are two other macroalgae derivatives much used as gums, emulsifiers, and gels. Annual sales of these products are in the tens of millions of dollars.

7.2.2 Uses of Microalgae

The uses of microalgae and the research on microalgae are both in their infancy. There are more than 8,000 microalgae species which are divided into four types: cynaobacteria (blue-green algae), rhodophytes (red algae), chlorophytes (green algae), and chromophytes (all other algae). Each of these types contains hundreds of species. Each species may have thousands of genetically distinct strains. Only a small fraction of these varieties have been studied for possible beneficial use, and there is much ignorance and uncertainty regarding the behavior and properties of most microalgae species. Still, during the last three decades, much has been learned about microalgae and several substantial applications have been established. These applications include waste water treatment, chemicals such as beta carotene and phycobiliproteins, food and feed.

Waste Water Treatment

Many studies and several commercial facilities have demonstrated the viability of microalgae in sewage treatment (see the survey articles by Oswald, 1987a and 1987b). Oxygen production by microalgae for waste oxidation by bacteria in ponds is generally recognized. There are also promising results demonstrating algae contribution in enhancing sedimentation, disinfection, nutrients, and in removing heavy metal and organic toxins. Oswald estimates the savings associated with use of algae (in place of electricity) for oxygen production in sewage ponds to be between $3,300 to $14,000 (1985) per hectare (based on an energy price of 10 cents per kilowatthour).

The algae biomass produced in sewage pools can be used to produce energy by fermentation. There has been large-scale experimentation in the combined use of algae for waste management and energy production, and a combined system seems especially appropriate and economical for locations characterized by expensive and scarce energy resources.

The use of algae for sewage oxidation (including use of the resulting biomass for energy production or other economic purposes) is likely to increase substantially as energy prices increase and more knowledge about the technology becomes available through experience. Increased productivity is an important factor in determining the future of the technology and will influence its fate.

There is substantial demand for technologies capable of removing chemicals from bodies of water. For example, there has been extensive search in California over the last few years for technologies capable of ridding water of selenium and other minerals and toxins. The volume of the problem is immense, and hundreds of millions of dollars are allotted to be spent annually in waste treatment. Similar problems occur elsewhere and suggest a good area for future applications for algal use (given that through research algal technologies can provide effective and economical solutions).

Beta Carotene

Beta Carotene is a metabolite with a wide range of commercial applications. It is used as a food coloring (with a major application in providing the yellow color to margarine), as a food additive to enhance the color of the flesh of fish and the yolk of eggs, and to improve the health and fertility of grain-fed cattle (see survey by Borowitzka and Borowitzka, 1987).

Until the early 1980s, commercial production of Beta Carotene was synthetic, and Hoffman Laroche had a virtual monopoly on the production and marketing of Beta Carotene. During the 1970s, researchers (Ben-Amotz and Avron, 1980, and Borowitzka and Brown, 1974) realized that, under nutrient-stressed, high-salt, and high-light conditions, the microalgae, Dunaliella Salina, will accumulate up to 14 percent of dry weight as Beta Carotene. This discovery led to commercial derivation of natural Beta Carotene from Dunaliella Salina, and it is currently a substantial and growing industry.

It is estimated (based on Borowitzka, Ben-Amotz, and Oswald) that worldwide revenue of the natural Beta Carotene producers in 1987 was between $6 million and $10 million. There are two producers in the United States (Crynotech in Viona, Hawaii, and Microbio Resources in California's Imperial Valley) with 1987 sales of $2 million to $4 million. There are three producers in Western Australia with sales ranging from $3 million to $5 million in 1987 and one producer in Israel (Koor Eilat) with about $1 million in sales of natural Beta Carotene in 1987.

Hoffman Laroche is a dominant factor in the natural Beta Carotene market. They market much of the product and have acquired the largest Australian algal production and development firm (with whom Lesley and Michael Borowitzka have been associated) for (about) $25 million (Australian dollars). Hoffman Laroche is attempting to gain as much control of the production of natural Beta Carotene to maintain their hold on the Beta Carotene market. They face quite a challenge because production of natural Beta Carotene is a farming activity which will occur in many locations. Moreover, the users of Beta Carotene would like to rid themselves of a monopoly (Hoffman Laroche) and will gladly buy Beta Carotene from other sources.

The introduction of natural Beta Carotene will likely have many other impacts on Beta Carotene uses and markets. Today, the price of extracted and purified natural Beta Carotene is much higher than that of synthetic Beta Carotene ($1,000 to $2,000 per kilogram for natural versus $400 to $800 per kilogram for synthetic), reflecting the preference consumers and buyers have for natural products. Even though the price difference between natural and synthetic will decline in the future as the supply of natural Beta Carotene increases, the differences will continue and the natural product will always fetch the higher price. Moreover, natural Beta Carotene has physical properties that make it superior to synthetic. In particular, natural Beta Carotene is fat soluble. It was announced recently by the National Cancer Institute that Beta Carotene is anticarcinogenic; other studies have found that Beta Carotene is effective in controlling cholesterol and in reducing risks of heart disease. These new findings make Beta Carotene much more valuable and are likely to increase the demand for the product. By being fat soluble, the natural Beta Carotene is a much superior anticarcinogen and an antiheart disease agent. Thus, the new findings of these desirable medical properties are likely to increase even more the demand and desirability of natural Beta Carotene.

The above analysis suggests that producers of natural Beta Carotene are facing a rosy future, at least in the short run. Diffusion and substantiation of the knowledge about the desired medical properties of natural Beta Carotene will increase the demand for the product. Since it is a new product, with many unresolved production problems, supply will not soon catch up to demand, and one can expect that high prices of natural Beta Carotene will be maintained. Early entry into the market and establishment of productive capacity in the short run are likely to be very profitable. In the longer run (10 to 15 years), supply may catch up to demand, and producers of Beta Carotene will make "normal" profits (equivalent to profits in other industries). In the short run, however, efficient producers of natural Beta Carotene might make substantial profits above the normal. If Israeli producers in the Arava can produce natural Beta Carotene efficiently, we recommend early entry to this line of business.

To guesstimate the economics of Beta Carotene in the Arava, we obtained data from Amit, Borowitzka, Ben-Amotz, and Oswald. For a 5 hecter Dunalliele Salina farm, the fixed setup cost (site preparation, pond construction, production, and harvesting and processing equipment) is estimated to be between 1 million and $1.5 million. Using a five-year return-of-investment period as a criterion to distribute the fixed cost, a conservative estimate of the annual fixed cost per hecter would be $60,000 (.2 x 15,000,000/50). Annual variable cost (labor, CO2, nutrients, and electricity) are estimated to be between $15,000 to $240,000 per hecter. Using a very conservative approach, total costs are estimated to be about $300,000 per hecter. The most conservative estimate of yield we have seen is 500 kilograms of Beta Carotene per hecter Thus, under these conservative estimates, the break-even point is reached when a kilogram of natural Beta Carotene fetches $600 per kilogram.

Phycobiliproteins

Phycobiliproteins is a recent application which uses algal derivatives as a diagnostic tool. Specifically, biliproteins from microalgae (phycobiliproteins) are used as fluorescent markers for genetic screening in cell analysis and imionchemialasis. This application is based on a discovery made by Professor Alexander Glazer of the University of California at Berkeley and published in 1982. According to Professor Glazer, the first application started in 1983 when two laboratories started producing phycobiliproteins. Currently, there are 50 producers, global consumption is 50 grams (1 milligram sells from $6,000 to $12,000), and total revenue to producers is about $1 million annually. The value added, associated with the new application, is estimated to be $50 million annually worldwide. Producers cannot capture much of this value added because it is relatively easy to produce phycobiliproteins, and there is much competition. The market for phycobiliproteins is likely to grow by 20 percent annually in the near future (next 5 years).

The case of phycobiliprotein, like the case of agar, demonstrates the large range of commercial oppportunities algal products are starting to have with sophistication and growth in biological and genetic research, experimentation, and commercial application. The case of phycobiliproteins also demonstrates the strong linkages and fast response time between research discoveries and commercial applications associated with algal utilization.

Food and Feed Products

Many microalgae have a high nutritional value. They contain proteins, vitamins and minerals, and nonsaturated fats. Moreover, they can yield higher outputs for the same levels of water and land. Still, there has not been much commercial utilization of this food source for human or animal feeding. Spirolina is a unique exception. It is one of the two microalgae that grows isolated in a monocultural setting (the other one is Dunaliella Salina). It is available in Mexico and other Central American locations in wide quantities, and it has much nutritional value. It has commercial success as a "health food" and is a component of many health food products. In the late 1970s and early 1980s, it reached a peak in popularity; it had a high demand and got high prices (above $20 per kilogram for the grower). Now, the demand for Spirolina is more stable, its price is around $10 to $15 per kilogram, and the market volume is in the millions (Amit and Borowitzka).

Algae produced as a by-product of waste-management plants are used for animal/livestock and fish feed. They support intensive fish production on a small scale. Much research is needed to develop large-scale food and feed production from algae; one needs to identify species and production procedures, for instance. The food surplus problems in the United States and strong political influence of grain farmers in America prevent development of much research aimed at developing economic viable production of feed from microalgae. Note that, while there is no public support to research on obtaining food from algae, there is much support on fuel production from algae. In any case, large-scale production of food, feed, and fuel from algae will take time; and fine chemicals may be the best category for economic utilization of microalgae.

7.3 Future Algal Product Lines

Much of the algal research is in identifying and developing production techniques to obtain commercial products from microalgae. The development of several product lines seems very promising. They include fatty acids, polysaccharides, food coloring and osmoregulators.

Fatty Acids

These are unsaturated oils which have desirable therapeutic properties. Research has shown that omega-3 fatty acids reduce cholesterol and fat levels in the blood and "cleanse" the lining of blood vessels. The medical use of omega-3 fatty acids for prevention and treatment of heart disease is increasing. It is done mostly by prescribing fish oil to heart patients. For example, according to Abuoav, it becomes common practice to prescribe six to eight cod liver oil capsules daily as postoperative treatment for bypass surgery patients (2.1-2.8 grams of omega-3 fatty acids).

Usually, this treatment continues throughout the lifetime of the patient. Moreover, some doctors have started prescribing similar dosages to individuals with high-risk profiles with respect to coronary diseases. As evidence of the effectiveness of this treatment spreads, its adoption is likely to grow. Recent studies (Yetir, 1988) have shown that omega-3 fatty acids have effective therapeutic properties dealing with rheumatoid arthritis and immuno-deficiency diseases, and doctors are considering prescribing pills derived from fish oils to combat these diseases. Cod and other fish are not the direct producers of the fatty acids; omega-3 fatty acids are produced by the microalgae which are ingested by the fish. The fish can be bypassed by direct cultivation of microalgae and extraction of omega-3 fatty acids from the microalgae. The product extracted directly from the algae is likely to be superior to the cod liver oil as (1) it will not have the off flavor of cod liver oil and (2) it will be a more "pure" product and thus more effective. The use of microalgae should not be restricted to direct extraction of omega-3 fatty acids. They can also be used as feed for chickens and dairy cows which will then transfer omega-3 fatty acids to eggs and milk. The application to eggs may be especially useful since it will tend to reverse (and combat) the contribution of eggs to cholesterol buildup.

The recent medical discoveries about the therapeutic properties of omega-3 fatty acids suggest a very large and growing market to algal-derived fatty acids. In the early 1980s, the value of the worldwide sale of cod liver oil is estimated to be between $50 and $150 million annually. The superiority of the microalgae derivative and the continued growth in demand for omega-3 fatty acids suggest a much higher sales potential for fatty acids derived from algae. The global sales potential of algal-derived omega-3 fatty acids is guesstimated to be above $500 million annually.

Obviously, there is a substantial market for omega-3 fatty acids, and they can be marketed through distributional channels of drugs and health products. To assess the profitability of their production from microalgae, one has to use guesstimates based on information available from other products.

Polysaccharides

Polysaccharides are chemicals that are used as viscofiers (thickening agents), fluctuating agents, and lubricants. The value of polysaccharides varies according to their use, availability, and purity. They include macroalgal derivatives such as Carrageenan (with a market value of $10-$15 per kilogram) and agar (with a market value of $1,000 per kilogram). Polysaccarides are derived from bacteria, fungi, and algae. The bacteria and fungi are much more productive than algae, and genetic manipulation and engineering of bacteria is in a much more advanced stage than genetic engineering with algae. Still, algae generate complex and unique polysaccharides, and many algal derivatives are irreplaceable.

Macroalgae are the source of important and commercially used polysaccharides, and the market for these algal derivatives are in the hundreds of millions of dollars.

Microalgae (such as porphyridium) have very promising polysaccharides production potential (as the survey by Borowitzka and Borowitzka (1987) demonstrates), but this potential has not been tapped commercially. Under the right conditions, 15 to 55 percent of the weight of microalgae can be extracted as polysaccharides. Taking a very conservative approach--assuming 15 percent polysaccharides share in weight, low yields (5 tons per dunam), and high cost ($30,000 per dunam annual total cost)--the break-even price for polysaccharides production is $40 per kilogram, which is within the medium range of market value for polysaccharides. Taking a slightly more optimistic view--3 percent polysaccharides share in weight, low yield (5 tons per lunar), and low cost ($200,000 per hecter)--the-break-even price is less than $15 per kilogram, quite a modest price for many polysaccharides. Thus, polysaccharides from microalgae have good economic potential. They are, however, at an early stage of development. Scientists and producers have to determine a small number of target products and concentrate on defining a workable technology for their extraction.

Food Coloring

There is a growing demand worldwide for organic food coloring. Regulatory agencies constantly limit the range of permissible chemical food coloring, and the regulatory process will be even stricter if and when organic substitutes are available. The volume of the market for food coloring is immense--in the billions of dollars annually.

Microalgae can be used as a source of many organic food colorings. As Borowitzka shows, some microalgae contain substantial amounts of Carotene (besides Beta Carotene). Other types of coloring appear in microalgae as well. Borowitzka's company intends to produce Faxaniene--a high-value food coloring aimed at the Japanese market. In pure form it can fetch up to $1,000 per kilogram (Borowitzka). Glazer argues that the potential of microalgae, as a source of food coloring, is limited because algal-derived food coloring is not photostable. Namely, they tend to bleach with cooking. Nevertheless, in spite of this limitation, the potential market for microalgae-derived food coloring is vast.

Osmoregulators

These are carbohydrates that can affect osmotic processes. Glycerol is the most notable member in this compound category, which includes other commercially viable products as well. Substantial weight of the dry weight of several algae, e.g., up to 50 percent (Dunaliella Salina), can be transformed to osmoregulators under the appropriate conditions. Microalgae compete with bacteria and animal fat as sources of osmoregulators. Research should and is likely to discover valuable osmoregulators that can be produced uniquely from microalgae.

Other Applications

Microalgae contain many useful chemical compounds, and its derivatives can be used in the future for many other applications in addition to the ones mentioned above. They include cosmetic and skin products, food and feed supplements, vitamins, and fertilizers.

Microalgae may be less productive than bacteria, and our ability to manipulate it is much smaller. But microalgae contain unique and complex products not available otherwise. Therefore, science potentially can offer much research regarding the use and manipulation of microalgae.

8. REFERENCES

8.1 Books and Articles

Ben-Amotz, A., and Avron, M. "Glycerol, Beta-Carotene, and Dry Algae Meal Production by Commercial Cultivation of Dunaliella." In *Algal Biomass,* G. Shelef and S. J. Soeder, eds. Elsevier North-Holland Biomedical Press, 1980.

Borowitzka, L. J., and Brown, A. D. "The Salt Relation of Marine and Halophilic Species of Dunaliella: The Role of Glycerol as a Compatible Solute." *Archives of Microbiology*, Vol. 96 (1974), pp. 37-52.

Borowitzka, M. A., and Borowitzka, L. J. "Vitamins and Fine Chemicals from Micro-Algae." In *Micro-Algal Biotechnology*, M. A. Borowitzka and L. J. Borowitzka, eds. New York: Cambridge University Press, 1987.

Chapman, V. J. *Seaweed and the Uses*. London: Methuen and Co., 1970, Chapter 5, pp. 89-123.

O'Connell, *Choices*, 1989.

Oswald, W. J. "Micro-Algae and Waste-Water Treatment." *In Micro-Algal Biotechnology*, M. A. Borowitzka and L. J. Borowitzka, eds. New York: Cambridge University Press, 1987a, pp. 305-328.

______, "Large Scale Algal Culture Systems." In *Micro-Algal Biotechnology*. M. A. Borowitzka and L. J. Borowitzka, eds. New York: Cambridge University Press, 1987b, pp. 357-394.

Renn, D. W. "Agar and Agarose: Indispensible Partners in Biotechnology." *ISEC Research and Development*, Vol. 23, No. 17 (1984), pp. 17-21.

Yetir, J. Z. "Clinical Application of Fish Oils." *Journal of American Medical Association*, Vol. 260, No. 5 (August, 1988), pp. 665-670.

8.2. Interviews

It will usually be clear when a reference cited in the text is for an interview.

Amit, Uri. Ein Yahav, Arava, Israel.

Borowitzka, Michael. School of Environmental and Life Sciences, Murdoch University, Perth Australia.

Ben-Amotz, Ami (Professor). Israel Oceanographic Institute, Tel Shikmona, P. O. B. 8030, 31080 Haifa, Israel. 04-515202.

Forget, Ronald D. Manager, Marketing Services, Bio Products, FMC Corporation, Marine Colloids Division, 2000 Market Street, Philadelphia, Pennsylvania, 19103.

Glazer, Alexander N. (Professor). Department of Microbiology and Immunology, University of California, Berkeley, California, 94720. (415) 642-2126.

Neushul, Michael (Professor). Marine Science Institute, University of California, Santa Barbara, California, 93106. (805) 961-2921.

Oswald, William J. Department of Civil Engineering, University of California, Berkeley, California, 94720.