MARINE PLANTS: A UNIQUE AND UNEXPLORED RESOURCE*

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Introduction

The seas provided a suitable site for the early evolution of all life. Ever since plants and animals developed structures and mechanisms that enabled them to survive on land, terrestrial and aquatic plants have been exposed to different abiotic and biotic selective pressures. Marine plants, which, unlike terrestrial plants, have evolved and adapted to life in a largely stable but saline environment, have developed many unique chemical structures not found in terrestrial plants.

The photosynthetic plants in the sea represent the foundation of the marine food web. The oceans occupy 70 percent of the Earth's surface, and the marine plants are known to provide at least the same percentage of available oxygen through photosynthesis. Marine plants are represented both by seaweeds, macroscopic forms largely inhabiting the shallow-water coastal zones, and by phytoplankton, free floating, widely distributed unicellular marine plants. Although a few flowering plants (angiosperms) are abundant in shallow waters, the majority of marine plants are algae, typified by their lack of a vascular system which serves for nutrient transport. Although all are classified as algae, these plants have an amazing taxonomic diversity. Marine algae have been subdivided into at least 12 distinct phyla (16):

Macroscopic forms
Rhodophyta . . . the red seaweeds
Phaeophyta . . . the brown seaweeds
Chlorophyta . . . the green seaweeds
Cyanophyta . . . the blue-green algae
Chrysophyte . . . . the yellow-green algae
Haptophyta . . . . *
Xanthophyta . . . . *
Microscopic,
usually unicellular forms
Bacillariophyta. . the diatoms
Prasinophyta . . . *
Eugenophyta . . the green algae
Cryptophyta . . . *
Dinopbyta . . . the dinoflagellates

• No common nomenclature exists for these algal phyla

Because of the highly unique and specific colorations of these groups, the analysis of numerous photosynthetic pigments has become a fundamental feature of algal classification. While no precise estimate is possible, well over 100,000 species of marine algae are thought to exist in various marine habitats.

Biogeographically, marine algae live in all parts of the ocean, from the tropics to the poles. Seaweeds and the phytoplankton frequently are found in extremely high concentrations. Although precise figures are difficult to substantiate, the primary productivity of 1 acre of open, plankton-rich ocean may be twice as large as that of a Midwest corn field.

A Unique Chemical Resource

Marine plants have evolved unique and highly specialized biochemical pathways to adapt to their unique seawater medium and survival pressures (7). The marine environment is rich in halogens, mainly in the form of chloride and bromide salts. Other chemical entities, such as sulfate, are also found in high concentrations. Marine plants use these elements in biosynthetic processes to produce compounds such as halogenated terpenes, acetogenins and alkaloids which are unique to the marine environment (6).

Many marine plants have evolved toxins and deterrents to enhance their survival in the face of abundant and freely migrating predators. Even though the same evolutionary pressures have produced similar responses in terrestrial plants, the defensive chemicals from marine plants are novel and represent interesting new chemical species which are unprecedented in terrestrial sources, even in closely related terrestrial algae.

Other adaptations, such as the development of resistance to wave shock and motion, have resulted in the synthesis of complex polysaccharides (complex sugars) which act to reduce the surface tension of seawater. These constituents, too, are highly specific to marine algae and help illustrate the unique genetic compositions of marine plants in general.

● Another paper on marine plant products was written for the OTA workshop by Ara der Marderosian of the Philadelphia College of Pharmacy and Science. Dr. der Marderosian's paper focused on the early stages of marine pharmaceutical development in the late 1960's and mid-1970's. The constraints that existed then in this field still are present today—namely, problems of procuring and screening plants and extracting, isolating and characterizing their active ingredients; lack of both an adequate number of trained personnel and a multidisciplinary approach; and inadequate patent protection. Dr. der Marderosian advocates increased collaboration between government and industry and more long-term support for marine plant products work.

History of the Early Use of Marine Algae

Many societies, particularly those in the Indo-Pacific region and Asia, have developed important uses for marine algae (2). The most significant example is the use of various benthic seaweeds, such as *Porphyra* spp. and *Laminaria* spp,, as food or food supplements. Such delicacy items as "Nori," and "Wakami" have become integral features of most diets in Japan. Shortages of these seaweed products have spawned intense aquiculture activities; for example, well over 18,000 MT of "Nori" are produced each year. A unicellular phytoplankton is harvested in several coastal regions in Thailand and used as the basis of a thick fish broth. The algae generally are not considered highly nutritious foods, but provide a broad base of mineral nutrition and roughage in the diet, and perhaps are most important for flavoring fish and rice dishes.

The classical use of marine algae as animal fodder and soil manure in northwest Europe has withstood the test of time. Marine algae, particularly that stranded on the beach after a storm, is collected and fed directly or after drying to sheep and cattle or applied on fields at rates of 56 to 67 MT/ha (25 to 30 tons/ac) as manure. This green manuring has been particularly useful on potato fields in the British Isles.

As man has become more aware of the unique chemical composition of marine algae, numerous additional products have been developed. A classical use for seaweeds has been the extraction of halogens and potash. Brown algae were used for several decades as the major source of iodine, and the red seaweeds were used on a few occasions for the derivation of bromine. The Pacific coast of America between 1910 and 1930 was the site of a flourishing potash industry based on the high potassium concentrations found in local brown algae.

It is not surprising that a wide variety of lesser known uses of marine algae also evolved. Numerous species of marine algae are used in China as herbal medicines to treat many maladies, ranging from intestinal problems to sunstroke, In addition, the gelling properties of aqueous extracts of numerous algae have been used in a host of food-related applications,

Modern Use of Marine Algae

The classical uses of marine algae as sources for elemental halogens, potash, and crude food thickeners largely were curtailed by the mid-1900's as other, more cost-efficient sources were developed. But also during this period, many currently used algal products, particularly algal polysaccharides, became established. A well-established industry in the United States now harvests marine algae (seaweeds) and extracts agar, carrageenan, and alginate. Agar is a sulfated polysaccharide (a polymer of the simple sugar galactose) found in many species of the red algae Gelidium, *Gracilaria,* and *Pterocladia*. This product is used mainly in the specialty food industry as a gelling agent and thickener, but also is used, among other things, as a biochemical adsorbent and as a culture and nutrient medium for bacteriological research, Agar is also a major nutrient medium for the industrial production of antibiotics.

Another specialty polysaccharide, carrageenan, is extracted routinely from red algae of the general *Chondrus, Gigartina,* and *Eucheuma*. This product also is a polymer of the simple sugar galactose, and its major applications resemble those of agar but are more widespread within the food industry. A complete description of the diverse applications of agar and carrageenan are given by Chapman (2). Polysaccharides derived from red algae support worldwide industries that produce about 18,000 MT per year at a total market value of about $200 million.

The brown seaweeds are also prized for their polysaccharide components, particularly alginate, Alginate is a mixed mannuronic and guluronic acid polymer comprising 20 to 30 percent of the overall composition of numerous brown seaweeds (particularly the so-called "kelps"), This polysaccharide represents a major worldwide industrial product generally prized for its thickening properties (e.g., in paints), emulsion stabilization properties, and gelling characteristics, Agar and carrageenan are far superior to alginate for use in foods, but alginates are particularly valuable for incorporation into industrial products and processes,

Even though the majority of the products derived from marine algae come from the readily collected macroscopic forms, several products are being produced by the culture of unicellular forms. The green alga *Dunaliella,* for example, recently has been established in mass culture as a commercial source for glycerol (glycerine) and the orange pigment beta-carotene. Glycerol is used industrially for numerous purposes, including in the manufacture of solvents, sweeteners, printing ink, antifreeze, shock absorber fluid, etc. Leffingwell and Lesser (12) have cited 1,583 different uses for glycerol, including the production of dynamite. Beta-carotene, the precursor to vitamin A, is used to impart color and provide vitamin A in animal feeds and human foods such as margarine, It is also used as a sunscreen agent.

Several algal species have been used consistently in the biomedical sciences. In particular, the red algae *Digenia simplex* and various *Chondria* species have been exploited in Asia for their content of effective anthelmintic drugs *(to* control intestinal parasites). The seaweeds' active components, kainic acid and domoic acid, were found to be relatives of simple amino acids, and they now are extracted, purified, and marketed as drugs in Asia. No other examples of successfully algae-derived pharmaceuticals exist, but there certainly is a great potential for further development in this area.

Development of Marine Algal Resources

The potential for developing a wide variety of commercial products from marine algae is great. As the supply of fossil fuels decreases, it will be essential to replace them with living or renewable resources. Even though relatively little basic chemical research has been performed on marine algae, it now seems clear that mass culture techniques, both in the ocean itself and in controlled coastal facilities, have great potential to provide industrially significant quantities of marine algae. As a result of funding from the Department of Energy (DOE) through the Solar Energy Research Institute (SERI) and several other agencies, scientists are learning of the nutrient and light requirements for effective algal growth. Marine algae probably will be a focus of considerable attention over the next decade as we investigate new resources for both energy and industrial product development.

Although relatively few algal products have been developed successfully by industry, the potential for the discovery and development of a plethora of unique new products seems unlimited. A few of the most notable areas for exploitation in the near future are summarized below.

Marine Algae for Biomass Conversion

Work already has begun to assess marine and other euryhaline algae as basic resources for biomass, with the expectation that through fermentation biomass can be converted easily to methane gas, ethanol, and other useful chemicals. A major concern is discovering plant sources that are easily grown in relation to their nutrient requirements, are highly efficient photosynthetically, and will yield readily digestible organic matter. At least the majority of these criteria are met by numerous species of macroscopic and microscopic algae. Algae are efficient photosynthetically and are cultured conveniently in the open ocean, ponds, or controlled (hemostatic) culture vessels. A major problem in algal biomass conversion lies in effective fertilization of cultured seaweeds and in cost-efficient harvesting of unicellular algae, Biomass conversion processes of any type are not cost efficient within the current economic structure. However, technology should continue to be developed so that resources and knowledge will be available for implementation when needed at a future date.

Pharmaceutical Development

The history and development of the modern pharmaceutical industry are based upon the extraction of biologically active substances from terrestrial plants and microorganisms. As human diseases change and pathogenic bacteria become resistant to established antibiotics, it becomes exceedingly important that new pharmaceuticals are available to reduce human suffering. As mentioned earlier, kainic acid, an anthelmintic drug in the Orient, was the first example of a useful drug extracted from marine algae (14), Few complete biomedical investigations have been performed on marine algae. Historically, biomedical applications of alginates and other algal polysaccharides have been clearly emphasized. This subject has been reviewed recently in an edited volume entitled "Marine Algae in Pharmaceutical Science, " by Hoppe, Levring, and Tanaka (10). Although numerous uses for algal polysaccharides have been established, the majority of applications involve use of their physical properties rather than their physiological activities, A surprising percentage of algal polysaccharides, however, show antiviral activity, This area of drug development is of current interest. Extracts of red seaweeds from the family Dumontaceae, particularly the extract of *Constantine simplex,* contain a specific and potent antiviral substance against *Herpes simplex* virus (4). The incidence of disease in the United States attributed to *H. simplex* has reached epidemic proportions,

The macroscopic seaweeds (red, brown, green, and blue-green algae) all possess structurally unusual, biologically active metabolizes. Compounds that show impressive antibiotic activities (5,18), and a number of unique metabolizes that show impressive cytotoxicities have been isolated from algae (9). The brown algal metabolite stypoldione (from *Stypopodium zonale),* for example, is a potent cancer cell cytotoxin which operates through a novel mechanism (11), Few comprehensive studies of microscopic algae have been reported, but there are several reports of antimicrobial activities (1,3). In addition, numerous phytoplankton species, such as *Gymnodinium breve, Gonyaulax catanella, Gonyaulax tamarensis, Prymnesium parvum,* inter alia, are known to produce the powerful toxins brevetoxin-B (13), saxitoxin (17), and prymnesin (15). In general, however, almost no information exists on the pharmacological potentials of the tens of thousands of microscopic plant species in the sea. This is due mainly to the difficulty in purifying a single species of unicellular algae and growing it for biomedical studies. This author is convinced that much could be learned from just such a dedicated effort.

Although a single algae-derived product exists, the slow rate of developing new marine pharmaceuticals clearly can be linked to the limited involvement of the major pharmaceutical companies. U.S. companies do not have a well-defined "entry" into this exploitation, and their lack of confidence is self-perpetuating within industry. Unlike any activity these industries have undertaken, marine explorations involve marine biological and oceanographic expertise, and the proper interface for this education has not existed. In addition, marine biological laboratories in the past have not employed scientists possessing capabilities in biomedical areas. The tide is changing, however, and major programs have developed under the auspices and support of the Department of Commerce's Sea Grant Program. The Sea Grant effort in biomedical development is a perfect blend of academic and industrial (basic and applied) research that is yielding fruitful results. The Sea Grant project, "Marine Chemistry and Pharmacology Program," at the University of California, for example, has discovered over 75 pure compounds with potential biomedical use and they have emphasized a collaborative effort with the pharmaceutical industry. This latter collaboration is the vital link to ensure that basic marine research finds its way to the industry that is *capable* and *interested* in developing new products.

Other governmental agencies have been involved to a more limited extent in marine biomedical development. For example, the National Cancer Institute has dedicated significant resources toward the isolation of new antitumor drugs. Here again, the need to involve basic marine scientists to locate, identify, and quantitate suitable marine species for study was underemphasized, and considerable difficulties (which affected output) were encountered,

The prospect for future development in this area is heavily underscored by the unique nature of marine-derived natural products. Based upon current chemical studies, it is clear that a wealth of novel structures exists in marine plants, and future biomedical studies of these compounds should prove highly productive.

Agricultural Chemicals

The use of naturally occurring compounds to control pests forms the basis of the agrichemical industry. For example, pyrethrins, insecticidal components isolated from pyrethrum, a daisy-like flower of the chrysanthemum family, and their synthetic derivatives continue to dominate agrichemical use. Many synthetic pesticides are halogenated compounds. Since halogenation is a natural process in marine plants, the compounds produced are likely to possess agrichemical activity, Only a few studies have been completed, but initial collaborative investigations indicate considerable promise. Of twelve purified algal metabolizes thoroughly assessed in herbicidal and insecticidal bioassays, nine showed some activity, and one was nearly equivalent to DDT in insecticide activity (8).

Here again, the success in developing marine algal agrichemicals lies in developing a close relationship between academic and industrial research. A limitation on commercial development of marine extracts is that little government funding is available outside of the U.S. Department of Agriculture. Agricultural research funding should be expanded in the United States to include a greater component of academic research.

Food and Food Products

In addition to providing agar, carrageenan, and alginate, marine algae are recognized sources of triglycerides (many species are up to 20 percent triglycerides) which are used as cooking oils, and of numerous useful food products, such as hexose sugars and amino acids. Although seaweeds usually are low in protein, many phytoplankton are rich protein resources. Exploitation of protein-rich blue-green algae already has begun through the increased interest in *Spirulina* as a health food. *Spirulina* clearly is not the only algal species to qualify as a suitable food, and particularly the blue-green algae (many of which are nitrogen fixing) hold great promise for providing new protein resources. The American Medical Association emphasizes that good cardiovascular health can be achieved by reducing one's intake of animal protein, a protein source high in saturated fats. As society becomes more conscious of better health habits, there likely will be a shift toward plant protein sources, and a supplementary resource will be necessary.

Enzymes

The more we learn of the functions and behaviors of enzymes, the more enzyme technology is being applied to industrial processes. Marine enzymes, while almost completely unknown, could be used beneficially. The industrial process of halogenation to produce brominated and chlorinated chemicals is costly, due to the energy needed to activate bromide and chloride salts to their reactive levels. Enzymes perform this process in marine algae naturally; thus in principal, marine haloperoxidase enzymes could be used industrially. Hager and his associates (19) have successfully purified the marine halogenating enzyme and illustrated its behavior with numerous substrates.

Industrial Chemical Feedstocks

As oil reserves dwindle, the concept of seeking industrial chemicals from renewable plant sources no doubt will be considered seriously. We will need to turn to plant species that are readily cultured, have high photosynthetic rates, and contain hydrocarbon resources that somewhat resemble those found in crude oil. While an "oil-analog" will not be found, numerous examples of marine algae (both macroscopic and microscopic) produce mainly linear hydrocarbons. Species are available that could be cultured to yield hydrocarbon mixtures which could be used as diesel fuel without further purification. Linear alkanes and alkenes are virtually ubiquitous in marine algae, and these compounds could be converted (via catalytic cracking processes) to smaller molecules which form the basis of the modern plastic industry. Marine algae also have been reported to contain more unusual substances, such as low-molecular-weight sulfides and amines, as well as industrial precursor molecules, such as acrylic acid used in the production of plastics and in dentistry (1).

Notwithstanding the work on agar, carrageenan, and alginate, phytoplankton, in general, have been virtually unexplored for their polysaccharide components. A great need exists in this field to develop products with specific properties not found in existing saccharides. It is highly conceivable that the thousands of species of unicellular algae would yield new and important products.

Collection v. Aquaculture?

Marine plant development, whether dealing with the derivation of pharmaceuticals or industrial or food-quality chemicals, must be planned in relation to the most effective source of raw algal materials. Massive collections of natural seaweed populations conceivably could be made. While possible, this generally is unreasonable because limited numbers of species are found in abundance. Small volume products, such as a specialty pharmaceutical, could be developed from naturally occurring populations, but, in general, effective use of marine algal resources must be coupled with mass culture technology, unicellular algae, in pure form, could not be collected so must be cultured under controlled physical conditions. Hence, marine algal resources development must be closely aligned with modern advances in algal mass culture.

Mass algal culture and product derivation should also be developed keeping in mind multiple product development. The algal resources that should be considered for development are those that produce more than one marketable product. Such is the case with *Dunaliella;* it yields beta-carotene and glycerol. This can be extended further to include the possible isolation of lipids (hydrocarbons, triglycerides, amines, etc.), the simultaneous extraction of water-soluble polysaccharides (products analogous to agar, etc.,) and, finally, the hydrolysis or digestion of the remaining material to produce either protein supplements or crude biomass for energy conversion. Multiple product use will be imperative from the economic viewpoint to offset the relatively high production costs.

Problems and Approaches Toward Developing Marine Algal Resources

A basic problem in considering development of marine algal resources is that there has been insufficient research on potential products from algae. Although a significant number of chemical investigations have been conducted on seaweeds, there have been few on unicellular algae. Many drug candidate molecules are known, but to date few have been screened as carefully as either pharmaceuticals or agrichemicals.

The cart has come before the horse to a certain degree in this field. Considerable resources are being devoted to developing algal culture technologies in marcroalgae and the unicellular species. However, in most cases these studies are not predicated on a solid knowledge of subsequent product development, but rather on broader concepts, such as algal biomass and energy conversion. The time has come to inititate tedious and costly long-term investigations of the chemical composition of marine algae, particularly the almost chemically unknown unicellular forms. Once a framework of sound composition information becomes available, decisions on what to culture can be made confidently.

A significant problem lies in the poorly developed working relationships between government, universities, and appropriate industries. Government funding agencies have difficulty supporting applied research, particularly as it may benefit a single private enterprise. The university system finds its interface with industry strained by patent and proprietary information problems, Therefore, the proper line of basic to applied research, culminating in real product development, has yet to be achieved.

Renewable resource development with any plant resource will require close collaboration of the agencies mentioned above. This is particularly true in developing marine products because scientists who have basic research interests will need to be involved. Federal funding agencies, such as the Sea Grant Program (Department of Commerce), should be applauded for providing a structural prototype which fosters the university-government-industry interaction.

Biotechnological advance, particularly in the field of marine genetics, can be expected to have a sizable impact on our use of marine resources, Marine products and biochemical processes are unique, and this unique gene pool will be highly useful in future product development. The algal gene for agar synthesis, for example, in principle could be transplanted into a readily culturable nonmarine organism. These concepts, while futuristic, illustrate the value of the marine algae to yield a wide variety of unique products.

Conclusions

Marine algae represent a massive resource for product development based upon their unique genetic adaptations. To foster this development, however, a greater emphasis must be placed on basic research into chemical composition, genetics, nutrition, and reproduction, Further, mass culture technologies must be refined. Collaboration among governmental agencies that provide funding must be developed in a tripartite fashion with universities excelling in marine research and with new industries. As these components gel into a more directed exploration of marine algal resources, it seems likely that marine algal species will become major sources of future products,

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