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BIOTECHNOLOGY OF MARINE ALGAE: OPPORTUNITIES FOR DEVELOPING COUNTRIES

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ABSTRACT

Recent advances in molecular biology provide the means to exploit the unlimited potential of marine resources, especially finfish, shellfish and algae. This is true especially for countries with significant coastal resources, although other countries can also take advantage of the benefits of marine biotechnology. One of the most accessible marine resources of the coastal zone are the macroalgae or seaweeds. The marine macroalgae are comprised of several distinct taxonomic groups typified by a wide range of sizes, pigmentation, chemical composition and physiology. A common feature for most however, is a macroscopic life history stage distinguished by substrate-attached individuals. Historically, these plants have been cultivated with great success.

Seaweeds are used in various ways - from food for humans and animals, primarily in the Far East, to energy production, to a source of the specialty chemicals known as phycocolloids (agar, alginate, and carrageenan). The world market of phycocolloids alone exceeds $250 million per year. This market will continue to expand as the demand for such products increases.

The application of modern biotechnology to the problem of efficient exploitation of algal resources (macroalgae and microalgae) presents developing countries with opportunities to expand existing markets and develop new markets. The potential of marine algae for developing countries and for developed countries is unlimited; this potential can be realized with a concerted effort to employ the powerful techniques of modern molecular biology in conjunction with both historically established mariculture techniques and new developments in aquacultural practices.

Advances are being made in the area of "genetic engineering" of seaweeds and microalgae. Thus, we should soon realize the goal of hybrid strains of marine

algae that have desirable features such as rapid growth rate or "hyper-producers" of valuable compounds (e.g., phycocolloids).

By carefully developing a strategy to take advantage of the results of genetic selection of macroalgal strains and appropriate cultivation techniques, developing countries with favorable climate and coastal resources can make significant gains in their national and international marketplaces. Of primary interest is the potential to establish new industries based upon the production of highly valuable specialty chemicals such as phycocolloids, nutritional supplements, vitamins, fertilizer, and pharmaceuticals.

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Marine waters cover approximately 71% of the earth's surface and harbor a wide variety of highly diverse biological communities. In all probability, the oceans contain more than one million species of animals, algae, bacteria, and fungi. For centuries, humans have depended on harvests of some species of fish, shellfish and algae from the oceans as a staple food. Also, we have relied on the oceans for raw materials for some industries and as a avenue of travel and trade.

Our long-standing dependence on natural stocks of marine life, especially finfish and shellfish, has resulted in the lack of incentives to enhance production of desirable species. The lack of progress in this area is in sharp contrast to our progress in food production on land. We have advanced from hunter-gatherers in exploiting terrestrial food crops to our current stage of producing food supplies from a technologically-advanced agricultural industry. The development of agriculture has included the application of appropriate technologies to maximize production of desirable crops. Those technologies range from developing hybrid strains of plants and animals to the application of molecular genetics in agricultural biotechnology. Thus, we are able to capitalize on the metabolic potential of key crops, livestock and terrestrial microorganisms. We have not made similar accomplishments in utilizing marine resources.

Our awareness of the productivity of the oceans is changing as we become more appreciative of the fact that natural stocks cannot meet the demand for many marine organisms and their products. For example, it has been estimated that the maximum world-wide harvest of wild seafood is between 100 to 150 million metric tons (National Oceanic and Atmospheric Administration, 1977). The current harvests of approximately 70 million metric tons of seafood cannot be sustained in the long-term. In the United States, harvests from natural stocks cannot meet the demand and, as a result, the United States imports billions of pounds of finfish, shellfish, and algae (National Marine Fisheries Service, 1980).

Only in a few countries have there been sustained efforts to apply some of the experience gained from agriculture to cultivating and harvesting marine organisms. China and Japan have been at the forefront of farming coastal waters (Tseng, 1981; 1984). The successes realized in China and Japan as well as increased demand for products from marine organisms are enhancing incentives for adapting successful agricultural practices to farming some regions of the marine environment. Compared to terrestrial crops, the concept of farming the oceans is in its infancy.

The benefits of the development of new and, perhaps, high technology marine-based industries will be many, especially in developing countries. One benefit to societies in all countries will be to reduce (or eliminate) threats posed to sensitive habitats and organisms by harvesting natural stocks of marine life. In many instances, the genes which code for a particular product or process can be cloned into a microorganism amenable to laboratory cultivation and, as a result, eliminate the need to harvest organisms from the wild.

The application of techniques of modern molecular biology and molecular genetics to marine organisms presents many unique opportunities and unlimited potential for many facets of society (see review by Colwell, 1983). Indeed, through marine biotechnology we can exploit the genetic diversity of marine organisms to obtain particular products while promoting economic development. Concomitantly, the development of marine biotechnology-based industries will require efforts be directed toward basic studies on commercially-important marine species. An investment in studying the basic biology and ecology of marine organisms will ensure increased productivity of mariculture-based industries and, equally important, that there will be an continual influx of innovative ideas to stimulate new marine biotechnology initiatives.

In order for any country to expand existing industries and to develop new industries based upon marine biotechnology, it is essential to institute policies which are sound ecologically as well as economically. Countries with abundant coastal resources should benefit most from marine biotechnology and, as such, they must ensure that the development of this field does not harm their coastal resources. Considering this, we must evaluate which strategies have the greatest probability of success.

The potential of marine biotechnology can be considered in terms of the **genetic potential** and **crop potential** of marine organisms. Genetic potential includes an organism's metabolic products (i.e, pharmacologically-active compounds, fine chemicals, etc.) and the processes it mediates *in situ*. The crop potential of marine organisms includes their use as food and food supplements and, perhaps, in applications of their biomass (i.e., as a substrate for methane production).

Marine organisms possess a remarkable phenotypic diversity and, therefore, an even more varied genotypic diversity. Of the hundreds of thousands of species of marine organisms, only a relatively few have been studied in any detail. Fewer still have been examined at the genetic level; of those, only a very limited amount of information has been obtained. Compared to what is known about the molecular genetics of *Escherichia coli*, we have, at best, only a rudimentary appreciation for the genetic diversity of marine life. However, on the basis of the very limited amount of information available, a great deal of knowledge is to be gained from studies on the genetics of marine organisms.

Marine organisms survive and grow in habitats characterized by physico-chemical environmental parameters not encountered by terrestrial or freshwater organisms. As a consequence, marine organisms must cope with habitats characterized by seemingly harsh conditions. In addition to high salinity, many species of marine organisms must contend with high hydrostatic pressure and low temperature (typical of the deep sea) or high hydrostatic pressure and high temperature (typical of deep sea hydrothermal vents [Baross, and Deming, 1983; Deming and Baross, 1986]). Much of the biota of tropical marine waters possess specific traits for survival in highly diverse and competitive habitats; because of this, they are subjected to strong selective pressures from biotic and abiotic factors in their environment.

In order to survive and grow in highly competitive habitats marine organisms must compete for limiting resources. A variety of offensive and defensive mechanisms have evolved to allow organisms to gain a selective advantage and to cope with competitors. The physiological manifestations of offensive and defensive abilities of marine organisms are in the form of bioactive metabolites (i.e., toxins) (Martin and Padilla, 1973; Scheuer, 1973; Hashimoto, 1981). Many marine animals produce specific toxins that are used to capture prey or to deter predators. Many marine algae produce metabolites that function as feeding deterrents (Burreson, et al., 1975; Targett, 1979; Faulkner and Ghiselin, 1983; Tachibana et al., 1984, 1985). These and other bioactive metabolites are excellent candidates for a variety of applications in, among others, the pharmaceutical, agrochemical, and food industries (Scheuer, 1973; Baslow, 1977; Cardellina, 1986).

Compounds produced by marine organisms, especially marine algae, represent a variety of (potentially) lucrative markets. An increasing appreciation for the unlimited potential of food and products from the sea is stimulating the development of marine biotechnology-related industries in many countries. This is true for products with pharmacologic activity and those that have applications as fine chemicals. The momentum to capitalize on the potential of marine biotechnology should increase dramatically in the future.

It has been estimated that the majority of people inhabiting developed countries have some daily contact with products originating in marine algae (Abbott and Cheney, 1982). These products are present in toothpaste, shampoo, many dairy products as well as many other consumer goods. As such, marine algae are the most obvious candidates for enhancing the development of marine biotechnology-based industries in developing countries.

Marine algae have many features that make them ideal organisms on which to base initiatives in marine biotechnology. Although other organisms (i.e., finfish, shellfish and microorganisms) hold great potential for marine biotechnology, marine algae may represent the greatest market potential due to the diversity of products that can be obtained from them (see Waaland, 1981; Abbott and Cheney, 1982; Tapie and Bernard, 1988). Also, industries based on exploiting marine algae have a long history (Waaland, 1981). As technology advances, those industries will expand to meet an increasing market, and new industries will be formed to satisfy new markets.

Many types of marine algae, both macroscopic and microscopic forms, can be used in marine biotechnology industries. However, significantly different types of technology and facilities are required to capitalize on these very different groups of organisms. Representatives from both groups have been used as a food for humans and animals and for a variety of useful products (Abbott and Cheney, 1982; Tapie and Bernard, 1988). Compared to macroalgae, there has been remarkably little exploitation of microalgae. Borowitzka (1988) has estimated that only 60 of over 22,000 strains have been screened for vitamins, pharmaceuticals or biochemicals. Only a relatively modest effort has been directed toward commercial cultivation of a few species of microalgae. These include producing algae as a source of food or food supplements or for fine chemical production. However, the market potential of these organisms has not been exploited to any significant degree. This should happen in the future as improvements are made in the technology required for their cultivation and as more strains with highly desirable characteristics are isolated or developed in the laboratory. For instance, we now have the capability to culture *Dunellialla salina* in such a manner that over 50% of its dry weight is glycerol (Borowitzka, 1988; Borowitzka and Borowitzka, 1988; Moss and Doty, 1987). Currently, glycerol production is petroleum-based but it is reasonable to assume that current production can be supplemented by utilizing algal products.

The economics of microalgal production of specific chemicals will improve as technology advances (see Hartig et al., 1988). For example, cells of some strains of microalgae comprised of as much as 72% lipid have been isolated. These lipids can be converted to a high quality energy source. However, this fuel is still far more expensive than conventional fossil-derived sources (McIntosh, 1984). The application of techniques of molecular biology and molecular genetics to these organisms may result in strains with faster growth rates and increased production of lipids and other biochemicals. Additional research is required if we are to capitalize on these organisms.

Metabolic products of marine algae, especially microalgae, have significant potential as pharmaceutical compounds (see Baslow, 1977). The pharmaceutical industry is very large (multi-billion in the United States) and requires a constant influx of new compounds. Marine algae have yielded many natural products with unusual structures and activities (see reviews by Fenical, 1982; Faulkner, 1984, 1986, 1987). The reported activities of natural products isolated from marine algae range from antimicrobial to antihelminthic to cytotoxic to anticoagulant to, among others, hypocholesterolemic (see Scheuer, 1973; Baslow, 1977). Thus, these organisms are excellent candidates for use in developing industries in marine pharmacology.

Bioactive metabolites from marine algae may also have applications in agriculture. "Agrochemicals" have a multi-billion dollar market. Marine natural products from algae have great promise in this market and emphasis should be placed on developing this potential (see review by Cardellina, 1986). Because relatively large percentage of food crops is lost to insect pests, there are urgent needs for effective and environmentally-safe pesticides.

Studies have demonstrated that plant growth-promoting compounds are common in marine algae (Bentley, 1958; Abe, et al., 1974; Augier, 1978; Kingman and Moore, 1982). More work is required to determine the chemical structures of the growth-promoting substances as well as their specific role(s) in the developmental biology of marine algae. Likewise, studies are needed to evaluate the feasibility of exploiting the applications of these compounds (see Cardellina, 1986).

Although bioactive metabolites and other specialty chemicals have significant potential in markets that will develop in the future. In all probability, they may be minor in comparison to existing and future markets for other compounds from marine algae, especially from seaweeds. In Western cultures, emphasis is placed on using those marine plants as a source of useful chemicals (e.g., phycocolloids) but in Eastern cultures, the culinary aspects of seaweeds are exploited.

All three groups of macroalgae (Chlorophyta, Phycophyta and Rhodophyta) can provide digestible proteins, essential vitamins and trace minerals when consumed by humans. Indeed, in many cultures, these plants are considered delicacies. Macroalgae have been utilized to supplement both human and animal diets (Waaland 1981; Hansen et al., 1981). Certainly, the greatest use of seaweeds is found in the Orient. However, there is a long tradition of regional harvesting of macroalgal stocks in Europe and North America as well.

Macroalgae have been used as food in the Orient and in some Pacific cultures for centuries. Representatives of the three types of macroalgae are consumed, although consumption of the red and brown seaweeds is more common (Stickney 1988). The seaweed industry, including uses and cultivation techniques, was summarized recently by Tseng (1984).

Of the red seaweeds, *Porphyra* spp. are the most widely utilized (see Dawes, 1981). These species have been recognized as a delicacy for more than 1000 years. *Porphyra* (or "nori" in Japan and "zicai" in China) is harvested, dried and processed into thin sheets (Hansen et al. 1981). The processed *Porphyra* is then used in a variety of manners in cooking. Its majors uses are as flavoring in soups and as wrappers for sushi. Many species of seaweeds other than *Porphyra* are consumed directly as vegetables, in soups, or in jellies and puddings. More than thirty types of red algae were consumed by early Hawaiian cultures (Hansen et al. 1981).

In comparison to Oriental cultures, the amount of seaweeds consumed in Western cultures is relatively small. *Chondrus* and *Gigatina* are consumed in the largest amounts. In general, the consumption of seaweeds tends to be a localized phenomenon. For example, *Porphyra* (or "laver") is eaten in the British Isles (Hansen et al. 1981). Similarly, along some coastal areas from Scotland to Alaska, *Palmaria palmata* (or "dulse") is consumed as a snack in taverns or as a vegetable with meals, used in cooking breads and puddings, or chewed like "chewing-tobacco".

Whereas the historical basis for the use of macroalgae as food can be traced back for centuries, industrial uses of chemicals extracted from them is a more recent development. It is apparent, however, that the role played by biochemicals extracted from these plants is far more pervasive in modern societies than is the direct utilization of the plants themselves.

Estimates of the world market for macroalgae vary. However, in general terms, the wholesale value of chemicals extracted from macroalgal sources was approximately $500 million in 1983 (Moss and Doty, 1987). This, combined with a estimated value of over $1.2 billion for seaweeds used as food sources in Japan and China, demonstrates the potential world market size for marine algae (Moss and Doty, 1987). It has been predicted that these markets will continue to expand in the future. An interesting development which may have potential for developing future markets is the use of macroalgae as sources of biomass to be converted to fuels such as methane gas. However, the feasibility of this remains to be established (Ryther, 1984).

The structural polysaccharides (phycocolloids) of marine algae are in the most demand. Phycocolloids from seaweeds are nearly ubiquitous in Western households and in a variety of industries (Waaland, 1981; Abbott and Cheney, 1982). Alginates, carrageenans, and agar all comprise the three general classes of phycocolloids. They are utilized predominantly as gelling agents, stabilizers and emulsifiers. Alginates derived from brown algae (*Laminaria, Macrocystis, Ascophyllum*) are found in milk products and baked goods as well as toothpaste, and shampoo. They are also used in dyes and paints. Over 60% of the world's supply of alginates is utilized in the paper and textile industry. Carrageenans isolated from red algae (*Chondrus crispus, Gigartia*) can be found in a variety of processed foods.

Agar, extracted primarily from *Gelidium* sp. has a perhaps the longest history of use as a gelling agent (Marine Algae Text). Several different types of agar with differing chemical purities are now being used. Lesser grades find applications in foods while more purified forms are chiefly used in microbiological culture media. As an indication of the demand for agar, consider its retail price during the 1980's. From 1981 to the present, the retail price for laboratory agar has increased by approximately $70 per pound (from $14 to $84 per pound). During the past year alone, the price has risen by approximately 55%.

Dramatic increases in the price of agar has an impact on research related to biotechnology. Gel electrophoresis, a cornerstone technique in biotechnology requires the use of a highly purified form of agar, agarose. The price of agarose has increased proportionately to that of agar during the past few years. Indeed, the current retail price of agarose ranges from hundreds of dollars to thousands of dollars per pound, depending on purity and other properties. Such high prices may restrict some research efforts.

The inherent demand for algal products provides a powerful incentive for development of industries based on macroalgal resources. In a simplistic sense, success or failure will depend upon how well appropriate technologies can be applied to cultivating this biological resource in what is essentially a hostile environment. Given this, it is necessary to consider "biotechnological innovation " in a broad context. The two facets most applicable to this case are the engineering of ecologically sound, efficient culture systems and, secondarily, the genetic manipulation of macroalgal stocks to produce plants with physiological and chemical characteristics most beneficial to the nascent industry.

To begin to appreciate what will be required to farm marine macroalgae, it is necessary to understand that these plants are very different from terrestrial plants. Macroalgae do not form seeds; they rely upon dispersal of fragile spores for reproduction (see Dawes, 1981). The life cycles of algae require two or three generations which alternate between sexual and asexual forms. The diploid, asexual generation (sporophytes) typically produce motile haploid spores. After release, the spores must settle onto a suitable substratum so they can attach and begin growth. They then develop into male or female plants (gametophytes). Fusion of the gametes produced by the gametophytes yields diploid zygotes. The zygotes mature, forming the sporophyte generation. In general terms, the sporophyte generation is macroscopic, whereas the gametophytes may be macroscopic or microscopic and spores and gametes are microscopic.

An understanding of their life history is essential to cultivate macroalgae on an industrial scale. This is exemplified by the success of the Chinese seaweed industry which is based, in large part, on an understanding of their basic biology and ecology (see review by Tseng, 1984). Currently, several varieties are under cultivation, especially in China. However, improvements in technology are required in order to enhance the continued development of the burgeoning industry. Certainly, efforts must be directed at increasing productivity of the seaweed mariculture industry as a means of making it more profitable and less labor intensive.

Mariculture techniques can be broken down into two general patterns: 1) outplanting and 2) growth in closed systems. Outplanting can be accomplished by either of two approaches. The first takes advantage of the alternating stages of macroalgal lifecycles and the second involves vegetative propagation of mature plants.

Historically, the best examples of outplanting are found in the Pacific. *Laminaria japonica*, a, phaeophyte, is grown attached to weighted cords suspended from floating rafts (Tseng, 1981). Zoospores are attached to cords and allowed to develop under ambient conditions. As they grow, the kelp plants are raised or lowered in the water column in order to maintain them under appropriate light intensity for maximum productivity. Scientists determined in the mid 1950's that reproduction was linked to ambient water temperatures (see Dawes, 1981). The natural reproductive cycle starts in the autumn and culminates with spore release in the early winter. However, studies demonstrated that if warm-adapted plants (i.e., "summer sporelings") were exposed to cold temperatures for short periods during the summer, sporulation could be induced artificially. Thus, reproduction and setting could be controlled. The technique not only excluded unwanted sets of weed species from the culture ropes, but the production of the young kelp was increased by 50% because the effective growing season could lengthened by several months.

Another important commercial species, *Porphyra*, a red alga, is consumed in many countries and, consequently, has a large market. The Chinese have directed efforts at farming *Porphyra* for more than 200 years (Hansen et al., 1981; Tseng, 1984). Initial efforts in *Porphyra* farming were very simple. Rocks in coastal areas were cleaned free of attached seaweeds, barnacles, and other sessile marine organisms in the fall, immediately prior to the natural release of *Porphyra* spores. Because the surfaces of the rocks were clean, the *Porphyra* spores had a substratum to attach to and grow. The local people harvested the crop the following year.

Today, *Porphyra* farming is based on the use of floating rafts (Tseng, 1981). This development was the result of basic studies on the reproductive biology of *Porphyra* by Chinese and Japanese phycologists during the 1950's. Mariculture of *Porphyra* begins in the spring when water temperature increases and it induces development of *Porphyra* carpospores. These spores are isolated from reproductive tissues and suspended in seawater in tanks lined with shells. The carpospores settle on this substrate and the filamentous or conchocelis stage develops over the summer. Autumn cooling induces a second round of spore formation, this time from the conchocelis filaments. The process is easily manipulated so that the released conchospores settle on layered nets which may be suspended *in situ*. Adult *Porphyra* develop from these spores.

The best example of exploiting vegetative growth can be found in the Philippines where *Eucheuma* sp. are cultivated. In this process, fragments from plants are fixed to artificial substrata (typically monolines) and grown suspended just below the mean low tide level. Approximately two months are required before a harvestable quantity of biomass is produced. Maintaining the crop is very labor intensive. This type of mariculture can be improved by employing new approaches to growing the crop and by developing new strains of *Eucheuma* that are more amenable to mariculture. The latter can be accomplished either through strain selection by classical genetics or by employing techniques of recombinant DNA technology. In order to maximize the probability of success, efforts should be directed in both directions.

In all three of the examples given above, the culture systems rely upon very simple technologies coupled to an understanding of the ecology and reproductive biology of the species. In addition, by employing the process of outplanting, coastal resources are used directly, thereby eliminating the need for expensive land-based cultivation.

The labor intensive nature and unpredictability of ocean farming are major obstacles that must be overcome in order to ensure the continued development of this industry. The advent of intensive, enclosed culture techniques helps to alleviate these difficulties. Western mariculturalists have been cultivating the red alga *Chondrus crispus* for many years (Hansen et al., 1981). Large scale suspension cultures maintained with flowing seawater and nutrient enrichment are required. By manipulating nitrogen loads it is possible to shift the alga's physiology towards growth and biomass production, or alternatively, to the synthesis of the desired biochemical, carrageenan.

In Taiwan, cultures of *Gracilaria* are successfully raised for the production of agar. Vegetative cultivation of the plants is done in tidal enclosures, of approximately one hectare. The cultivation of *Gracilaria* requires fresh seawater and, in most situations, addition of fertilizer. Usually, fertilizer is added in the form of urea or manure. In most situations, fertilizer is required to meet the demand for the limiting nutrient, nitrogen. The crop is then harvested at 10 day intervals over a 6 month long peak growing period.

The addition of fertilizers can also be used in outplanting techniques. Typically, additional nitrogen is applied directly to the crops. This practice enhances growth of the mature plants, thereby increasing productivity and yield of the crop.

Natural stocks as well as mariculture crops of *Gracilaria* and other agar-producing seaweeds cannot meet the demand for agar. This has resulted in a variety of commercial initiatives directed toward the cultivation of *Gracilaria* sp. in the West (see Waaland, 1981). Certainly, developing countries with appropriate coastal features and climate should take advantage of the opportunity presented by the market for agar and its derivatives.

The harvesting of natural algal stocks is conducted on a worldwide basis. *Geledium* sp. (and many other species) are taken in Japan, while in the Northeastern U.S. and Canada natural populations of *Chondrus* are collected. Chondrus or "Irish Moss" is typically collected by raking shallow beds from small dories. On the California coast of the United State, the giant kelp *Macrocystis pyrifera* grows in forest-like stands rising from the sea floor to form an algal canopy. This canopy vegetation is harvested with specially designed boats equipped with cutting blades (Jackson and North, 1973). Harvesting macroalgae in this manner is not lethal to the plants, thus permitting a sustainable crop.

When natural stocks of algae are harvested, the plants must be considered in the same context as fish or shellfish in a traditional fishery. Therefore, the effects of over-harvesting, water quality, herbivores (e.g., sea urchins) as well as natural climatic and biological cycles must be considered. It is reasonable to assume that harvesting of natural stocks of algae can be supplanted by mariculture-grown crops.

In most of the cases of macroalgal culture described in the literature, advances in the understanding of the physiological ecology of the plants and the technological innovations required to grow them have spawned efforts to improve production through genetic screening and selection. The Chinese began breeding different strains of *Laminaria* in the 1960's (Neushul, 1981; Tseng, 1981; Fang, 1983). Plants with specific traits were used as sole sources of spores. These were inbred and progeny sporophytes were derived from the gametophytic generation. Strains with variable thallus morphologies and iodine content were selected. A more extensive selection program for plants combining both iodine content and high production resulted in the generation of two *Laminaria* strains for commercial cultivation (see review by Mathieson, 1981).

Spore selection has been practiced within the Oriental *Porphyra* industry for many years. As for other species, emphasis has been placed on selecting strains with desirable growth or chemical characteristics. Hansen et al. (1981) note that additional laboratory based attempts have produced distinct morphological variants which grow much more rapidly and to considerably larger size than parental stocks. Strains selected in these manners have projected yields that are three to five times greater than the wild type.

The most notable example of strain selection in the West can be found in the Canadian *Chondrus* industry. During the 1970's a strain particularly suited to growth in suspension culture was isolated. The strain designated "T4" has a very rapid growth rate and fragments spontaneously, in effect, "re-seeding" itself (Hansen et al., 1981). Both of these characteristics are important in increasing production of *Chondrus*.

In the examples described above, the strains of macroalgae that were cultivated were obtained as a result of selecting from wild stocks those varieties that expressed desirable characteristics. These approaches to strain selection are based upon simple screening for desired characteristics and normal manipulation of plants during the mariculture process. Despite the drawback that this may require a considerable investment of time (i.e., several generations through successive growth cycles), it remains a proven and effective means to increase production.

Given the incentive to speed the selection process as well as develop new hybrid strains with exceptional characteristics, research efforts have been directed toward more direct approaches to strain selection. These techniques are based on inducing mutations, either with ionizing radiation of chemical mutagens. For example, ultraviolet and x-ray irradiation have been used to induce mutations. Exposure to chemical mutagens has also been used very effectively (Neushul, 1981).

An alternative approach to developing new strains of seaweeds involves hybridization of gametes from separate populations. Such intraspecific crosses have been very successful with kelps (Sanbonsuga and Neushul, 1980; Bolton et al., 1983). In addition, there have been reports of success in interspecific crosses yielding true intergeneric hybrids (Lewis et al., 1986). Experiments of this type have been performed on members of the Laminariales (e.g., *Macrocystis* X *Nereocystis*). Unfortunately, the hybrid plants were infertile.

Even though progress has been made in macroalgal genetics in recent years, it is reasonable to assume that, with the techniques of modern molecular biology and molecular genetics, substantially more progress will be made relatively quickly. Efforts are underway to elucidate the molecular genetics of marine alg [illegible] hrough direct manipulation of specific genes (Cheney et al., 1981; Cheney, 1988; Goff and Coleman, 1986, 1988). As the information base on macroalgal genetics increases, the rate of progress should increase also. This has been true for all aspects of modern molecular biology.

On the basis of historical perspectives, current research initiatives, and future potential, the biotechnology of marine algae represents a remarkable opportunity for developing countries. However, in order to take advantage of this opportunity, developing countries should develop strategies that are based on a combination of economic and scientific factors. Whereas the cornerstone of an economic strategy may be an evaluation of the exiting and potential markets for products from marine organisms, production of the product will be based on appropriate scientific principles.

In evaluating the potential of marine biotechnology of marine algae for a country, consideration be given to many important factors such as natural resources, work force, technology transfer, university-industry relationships, and, among others, government funding of basic and applied research. These factors and others that may be considered as country-specific, will determine the success or failure of an initiative in marine biotechnology.

It is difficult, if not impossible, to attempt to prioritize the relative importance of economic, scientific, regional, or other factors that will influence initiatives in this field. However, when a program in marine biotechnology is initiated, a country should not depend on harvesting natural stocks of an organism. Serious consideration should be directed toward crop production in coastal areas or, alternatively, in enclosed systems. The success of this approach will be due, in large part, to an understanding of the biology and ecology of the species being cultivated. Such knowledge is required in order to optimize environmental conditions for growth and reproduction of the species being cultivated. Also, it is essential that appropriate consideration be given to the environmental impact of mariculture initiatives. No initiative that would damage (either short-term or long-term) to the environment should be undertaken.

The coastal zones of all countries represent a resource that is under-utilized (Epstein and Norlyn, 1977). Coastal regions can make significant contributions to a nation's economy, especially in developing countries. In order to do so, efforts must be directed to developing mariculture programs and the supporting industries. Thus, the results of developing coastal resources should extend beyond the primary mariculture industry and into many facets of the private sector.

The economics of some biotechnology initiatives dictate a significant commitment of financial, physical, and intellectual resources. An understanding of the biological principals of a systems will be a significant contributing factor to the overall success of any industry that is based on producing large quantities of an organism. Thus, studies are required on the basic biology and ecology of the species in question. Usually, small companies cannot provide funds or personnel to carryout such studies. However, gaps in our knowledge can be overcome by forming cooperative partnerships between government, industry, and academia. Basic studies on the biology and ecology of organisms, especially commercially-important species, should be government supported. Furthermore, a combination of industrial and government support is required for carrying out applied studies. This is true especially in the early stages of the development of an industry. However, appropriate safeguards to intellectual property rights are required to ensure the success of such cooperative ventures and to guarantee continued support for basic research in academic institutions.

Support for basic research can contribute greatly to a well-trained work force that is required to enhance an existing industry and to develop new markets and new industries in the future. This type of support will also ensure that: 1) society gains an appreciation for the ecology of the species being exploited and for the environmental impact of the industry; and 2) basic research leads to technological advancements that will be available for transfer to industry. In this manner, for most situations, marine biotechnology initiatives can, and should, begin as "low-tech" and then develop into "high-tech". Regardless of the degree of sophistication of a marine biotechnology-based industry, the best efforts of traditional techniques, genetic selection, or even molecular manipulations will be of little use if mariculture techniques are inefficient ecologically or socially.

An understanding and appreciation of their genetic diversity can lead to a realization of the benefits of marine organisms. The potential of marine organisms and the process they mediate can be of profound importance to many aspects of society, both in industrialized and in developing countries. The development of modern molecular biology has provided the foundation for understanding the molecular biology and molecular genetics of marine organisms and the processes they mediate. Thus we can best use modern molecular biology to derive benefits from marine organisms if we understand their basic biology and ecology.

Developing countries can speed the development of marine biotechnology-based industries by forming partnerships with industrialized countries. Also, developing countries should consider pooling resources in order to attain goals that could not be reached otherwise. The latter approach can allow countries without significant marine resources to benefit from this rapidly emerging field. Certainly, agreements between nations can be complicated because of different laws pertaining to patents, international technology transfer, intellectual property rights, etc. However, such differences can, and should be, overcome so that all agreements are mutually beneficial.

The application of the techniques of modern molecular biology and molecular genetics to marine algae is a discipline that is in its infancy. A combination of these powerful techniques and an understanding of the basic biology of marine algae can result in significant economic benefits to developing countries. As such, the impact of farming marine algae on a nation's economy can be analogous to that of some crops in terrestrial agriculture. In order to achieve the goal of realizing the potential of the biotechnological applications of marine algae, nations must develop a strategy that accomplishes specific economic objectives while stimulating both basic and applied research without adversely affecting the environment. Such an approach will ensure the success of this field.

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