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My sixty years in applied algology

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Introduction

I am greatly honored to present this Keynote address. My focus, even after sixty years, continues to be on the future of phycology, even though I now present mainly from the past. I am delighted to see biological and physical scientists and engineers coming together in the field of Applied Phycology. Our working together will result in many benefits for mankind. There is no doubt that Applied Phycology has a great future because it has the potential for more efficient use of solar energy than conventional agriculture, and because it is poised to reach still unimagined goals through both genetic and ecological engineering. As an engineer I have focused mainly on large algal mass culture systems and the efficient use of solar energy in wastewater treatment (Oswald, 1962, 1963). But now I can envision such future triumphs as the introduction of genes for sulfur amino acids into the presently deficient *Spirulina* genome. I am fascinated by Dr Bailey Green's crusade to minimize energy use and greenhouse gas emissions using algae-based sewage treatment (Green, 1998), by Dr Joseph Weissman's commercial production of shellfish fed mass cultured algae, and by Dr John Benemann's vision of achieving very high productivities through physiological and genetic manipulations of the photosynthetic apparatus (Benemann, 1990), to mention just three examples currently underway by former students and colleagues. All of these and many more advances have resulted from combining biological and engineering knowledge.

As a young civil engineer I was greatly surprised when I learned that the growth of one unit dry weight of algae is accompanied by release of over one and one half times as much dissolved molecular oxygen, a process powered by virtually free solar energy. How to use this low cost dissolved O_2 in wastewater treatment and life support systems has consumed much of my, and many of my students', ingenuity during the past half century. Over these years my main area of research has been the design and operation of large-scale cultures of microalgae that grow commensally with bacteria in rich organic media such as domestic sewage or some industrial wastes. Not only is solar energy and the resulting 'photosynthetic oxygenation' nearly free, but also the nutrients in the wastewaters are free and often ideally suited for algal mass cultures.

In these waste treatment ponds we only exert minimal control over the algal species that grow, but we can impose some limits through pond operations such as residence time, depth and mixing. For reasons best known to the algae themselves, we often find species of *Chlorella*, *Scenedesmus*, and *Micractinium*, although species of *Euglena*, *Chlamydomonas* and *Oscillatoria* may occur in ponds with excessive loadings or long residence times. In these wastewater-fertilized systems the role of algae is primarily for production of O_2 to support bacterial growth, although nutrient uptake, adsorption of heavy metals and, indirectly, disinfection are also important functions of the algae in these systems. In the following I highlight some of the benefits of growing microalgae in wastewaters (Oswald 1978).

Heavy metal adsorption by microalgae

My first encounter with microalgae was the Presidio of Monterey, California where, as a military laboratory technician I identified Asterionella to be the source of taste and odor in the Presidio's drinking water supply and found it could be corrected by applying and mixing small amounts of copper sulfate into the reservoir and by aerating the water before drinking it. Two years later in the midst of World War II as assistant laboratory officer in a 700 bed station hospital in England I identified Synura as the source of a taste and odor so vile that patients and staff alike were nauseated when attempting to drink the water. Remembering my

Monterey experience, we turned to copper sulfate and aeration. These steps improved the water quality so greatly that the Colonel in Charge commended me as algal expert! Far from true but he had no clue as to what algal expertise involved.

After World War II, there was urgent interest in control of radioactivity in the environment, and I had a small project to study uptake of uranium by *Chlorella*. Remembering my experience in the Army with taste and odor control using copper, which I noted adsorbed to the algae cells, we mixed varying concentrations of uranyl acetate with waste grown *Chlorella*. We found that the adsorption (actually ion exchange) capacity of *Chlorella* exceeded 20 mg uranyl acetate/100 mg of dry weight of alga. The Geiger Counter told us that if we did not exceed this ratio all of the radioactivity would be centrifuged out of solution with the algal cells (Oswald & Golueke, 1970). It is of course now common knowledge that actively growing microalgae are highly negatively charged on their surface and hence strongly adsorb polyvalent cations. The ion exchange capacity of growing algae in waste water treatment is not only associated with their potential for removing heavy metals but also their harvestability, either by chemical flocculants or spontaneous flocculation and sedimentation. As there is typically a large excess of algal biomass produced in algal wastewater treatment ponds in relation to the concentration of heavy metals present in such systems, the algal cells can absorb and remove most of the heavy metals in municipal and other wastewaters. Roy Ramani (1974), studying the Napa ponds, found an almost complete removal of chromium from a series of four wastewater treatment ponds.

In the Advanced Integrated Wastewater Pond System (AIWPS®) (Oswald, 1990, see also below) we have a primary 'Advanced Facultative Pond' in which sewage solids settle, followed by a high rate pond for photosynthetic oxygenation of the settled sewage. A fraction of the high rate pond liquid, containing suspended microalgae is continuously re-circulated to the primary pond where the freshly grown algae can contact heavy metals in the incoming sewage, and typically settle out with the other sewage solids. This reduces contamination of the algae in the high rate ponds, which are destined for harvest, drying and use as fertilizer or possibly fish or animal feeds.

Disinfection of wastewater pond effluents: coliforms and parasites

Although the most obvious organisms in wastewater treatment pond effluents are the microalgae, the major health concern is and must be the disease transmission potential of treated sewage, as typically indicated by the presence of the bacterium *Escherichia coli*. The presence of microalgae in the pond effluents makes economical disinfection difficult, in particular as we suspect that *E. coli* can be accumulated by protozoa and other zooplankton that thrive in these ponds. In 1965, my graduate student (now Professor) Leonard Hom undertook a study of the mechanism(s) of chlorine disinfection of wastewater pond effluents. He found (Hom 1970) that a chlorine residual of 1 mg L^{-1} is sufficient to destroy *E. coli*, whereas microalgae themselves appear to survive a chlorine residual of 5 + mg L^{-1}. This has important implications regarding the disinfection of algal pond effluents as, according to Hom's findings, it may be possible to use 'differential chlorination' to destroy *E. coli*, while leaving microalgae metabolically active. This concept remains to be developed to a practical stage, as it has been hampered by the concern of regulators that algae may harbor pathogens. The sophisticated biochemical and genetic tools now available may provide a scientific basis for the differences observed between algal and bacterial vulnerability to disinfectants and open the way to take advantage of this finding.

Pond effluent disinfection is indeed a major issue, and alternatives to chlorine are avidly sought in light of concerns about the formation of chlorinated compounds during chlorination. Because of their light absorption microalgae must be removed from water that is to be disinfected with ultraviolet lights. Little work has been done regarding the use of ozone in pond effluent disinfection, although it is known that, again, algae are not as vulnerable to this disinfectant as is *E. coli*. Even without chemical disinfection, a decline of one, two or more orders of magnitude in *E. coli* numbers is typically observed in a series of ponds protected from short-circuiting by proper design. Microalgae growth and CO_2 assimilation typically raise the pond pH to above 9.0 and dissolved O_2 concentrations to well above twice that of saturation for several hours or more each day. High coliform removal in high rate ponds is likely to be due to the high O_2 concentration, light intensity and pH typical of waste treatment ponds generally and high rate ponds in particular. Clearly much more information on pond effluent disin-

fection is required for the design of improved sewage treatment processes.

Another major problem with wastewater borne diseases are the parasites such as, and in particular, the large roundworm *Ascaris lumbrcoides* which is responsible for the mortality of large numbers of children around the world. The ova of these common parasites can remain alive and infectious in sewage and even moist soil for more than two years. Although simple deworming medicines can remove these parasites, relief is often only temporary as re-infection is inevitable where there is inadequate water and waste treatment. Conventional primary and secondary sewage treatment is generally ineffective in removing helminthes ova because residence times in settling tanks, aeration basins and even anaerobic sludge digesters are typically too short for their destruction. Also, the overflow velocity in conventional settling tanks is greater than the settling velocity of most ova, which are thus carried through the treatment process into the receiving bodies of water and the water supplies of people drawing from them.

Even anaerobic digester residence times are typically too short to permit die-away of most ova. When the sludge from digesters is applied as fertilizer on land, infection of people may again occur. The very long retention times required for ova die-off, typically up to 100 days, cannot be met economically using concrete and steel structures, but can be accomplished with earthwork reactors, namely ponds, which are more efficient and cost effective for such purposes. Recent evidence suggests that high rate ponds are particularly effective in destroying ova of these parasites, I suspect due to the high dissolved oxygen (DO) in such ponds. This important topic deserves further study.

Methane fermentations in wastewater treatment ponds

Methane fermentation together with algae cultures to control odors are a powerful approach to using the full potential of low-cost earthen ponds in wastewater treatment. Bronson et al. (1963) were the first to demonstrate methane emissions from domestic sewage ponds, although this was already apparent in industrial waste lagoons, were gas emissions made this an unavoidable assumption. For methane fermentations to take place O_2 must be excluded from the fermentation zone. However, although methane is odorless, anaerobic fermentations will also result in sulfate reduction and formation of organic acids and other breakdown products, creating the potential, indeed almost inevitability, for vile odors. Mechanical aeration of sewage, as widely practiced, is not only expensive but also results in the creation of large amounts of bacterial biomass and sludges that will decay and create odors once removed from the system. To escape this quandary, I have long advocated direct anaerobic treatment of sewage, with methane fermentations of all settleable solids. Anaerobic treatment minimizes the amount of subsequent aeration required and, thus, greenhouse gas emission from generation of the energy required. The key concept is to use relatively deep ponds where the sewage is introduced, with the surface of the ponds kept aerobic by action of algal growth or by re-circulation of the algal cultures from following high rate ponds, preventing breakthrough of odors from the pond depth. This concept was first applied in St. Helena, California, where an algal high rate pond is preceded by a deep pond receiving the influent sewage. This system was originally studied by my student Meron (1970) and later by Green and Lundquist (Green et al., 1995). It has not needed primary sludge removal up to the present. Later designs include settling and digestion chambers allowing for methane capture from a small area of the ponds (Green, 1998). Studies of such systems indicated sustained removal of suspended solids and BOD exceeding 80%. More definitive studies are needed to quantify removal of nitrogen, heavy and toxic metals and chlorinated hydrocarbons, and to further study of retention of parasite ova.

Animal feeds from wastewater grown algae

The first studies of microalgae mass cultures (see Burlew, 1953) were inspired by a vision that the productivity of microalgae cultures would exceed that of conventional food plants by several-fold. This lead to a period of euphoria in microalgae R & D, suggesting that mankind would never need to be hungry again and allowing for enormous populations using recycled wastewaters and nutrients. Neither of these visions has yet been realized: microalgae cultures turned out not to be as productive as initially expected, nor has wastewater recycling into algal food and reclaimed water found much favor among the public. However, progress is being made. As mentioned in the introduction, new genetic approaches promise to greatly

increase microalgae culture productivities. And the recycling and reuse of wastewaters is already a fact of life, and becoming more necessary.

One of the more attractive approaches is to use the algae harvested from waste treatment ponds as animal feeds, the limiting factor in animal husbandry. The first test of this concept was carried out by another of my students, now Professor, Dugan (1972), who raised baby chickens up to full grown laying hens using 20% algal fortified mash The algae were grown on pasteurized chicken manure. Because microalgae are near fifty percent protein and most animal feeds are twelve to fifteen percent protein, the protein in algae can, indeed must, be diluted several fold with low cost carbohydrates and/or lipids to attain the correct protein percentage. One observation was that during pelletization of an algae-barley feed, the heat of the process caused the pasteurization of the feed, allying fears of disease transmission from the waste grown algae to the animals and later humans. At least no transfer of disease from humans to animals or birds to birds has been reported during feeding trials of waste grown algae with chickens, pigs and cattle. Many more long term production and feeding studies are needed. It is also possible to envision algal feed production using fertilizers and CO_2, rather than wastewaters. This method is already the case in aquaculture, where algae cultures are used to feed bivalves and in some fish aquaculture systems (Benemann, 1992). *Spirulina*, used as a traditional food around Lake Chad and other areas, is also sold as animal feed in some applications, particularly those requiring pigments. In brief, microalgae for animal feeds has significant potential in the future.

Microalgae in space life support systems

With Sputnik the era of space exploration started, and with it also a new chapter in algal technology. Because algae release oxygen from water and utilize light energy with high efficiency, there was early interest in algal life support systems (Oswald & Golueke, 1965). Space scientists had to confront the problem of waste recycling and atmosphere regeneration, and it was natural that there would be great interest in our systems. The U.S. Air Force's School of Aviation Medicine (SAM) in San Antonio, Texas, conducted extensive experiments on closed systems supported by oxygen produced by microalgae, guided by two pioneers in the fundamental studies of algae cultivation, Professor Jack Myers at the University of Texas at Austin and Professor Herb Ward at Rice University. Later SAM supported our research on closed systems for several years, until the Space Program became part of the newly formed National Aeronautics and Space Administration (NASA), which abandoned microalgae R&D in favor of physical and chemical processes for recycling water and air for short-term sojourns to the moon and the Space Station. Little thought has been given to the types of systems needed for manned vehicles that must recycle everything to sustain life for trips of several years and even decades. We all know that our earth is such a vehicle and that it has sustained a complex biosphere for over a billion years, in spite of periodic disruptions by planetoid collisions. Our objective was to create a miniature earth (a 'Terrella') that could sustain a crew of two humans indefinitely without any inputs other than sunlight, used directly or first converted to electricity with solar cells.

Our first system was a 'Microterrella' with a two-mouse crew, supplied with oxygen by an algal culture in the bottom of a large illuminated chromatography jar. The mice lived on a platform (the 'mousenine') above the mixed algal culture, with their feces and urine discharged into the culture. A small fan circulated the air and evaporated water condensed on a cooling coil in the top of the jar, providing abundant fresh water for the animals. The only physical input was a mouse diet of 20% algae and 80% creamed pasta. We maintained the mice for up to six weeks, but O_2 levels eventually began to fall, due to the fan becoming clogged with hair. (All mice returned from these experiments alive.) Even when the crew included a male and a female, the mouse population never increased, perhaps due to the continuous illumination or possibly because, unlike humans, the mice had enough wisdom to know that a population increase would overload the system beyond its carrying capacity.

We next developed the 'Algatron' (Shelef & Oswald, 1966), for which Gedaliah Shelef, now Dean at the Israel Institute of Technology, was mainly responsible for its perfection. This device was a rapidly (300 rpm) spinning plexiglass bowl in which the algal culture (*Chlorella*) formed a thin layer on the inside surface by the centrifugal action of the device. This is, without doubt, the highest productivity and culture density photobioreactor ever developed. Its high productivity due to the rapid spinning of the Algatron, achieving the 'flashing light' effect, first described by Bessel Kok in 1953. We calculated that three 1-m diameter Algatrons would sustain one human on a 1600 calorie per day diet. Dr Shelef (Shelef et al., 1970) also

carried out a fundamental study of the 'Bush Equation', the equation that tells us why algae are not as productive as we would like, as also explained by Kok's flashing light effect.

The final step under our SAM project was the design and construction of a two-man Terrella. This was, however, only operated briefly and then without a crew. The project ceased for several reasons, including the tragic loss of our chief engineer, Mitchell Sabanas, the subsequent shift in funding priorities by NASA and safety concerns by University officials, despite our many student volunteers.

Energy use and greenhouse gas abatement by algal wastewater treatment systems

One of the realities of the 21st century is the increasing cost, both financial and environmental, of the energy required for wastewater treatment. These topics have occupied the attention over the past many years of my current close colleagues, Dr Bailey Green and Tryg Lundquist (Green et al., 1995). In California we have seen large increases in the cost of electricity this past year, almost bankrupting our State. If these trends continue, and they must as fossil fuels become less available, and if we continue to use 20th century sewage treatment processes, fewer people, particularly in poorer countries, will be able to afford adequate wastewater treatment. Even in the U.S., the simple goal, promulgated some 40 years ago, to make our waters again 'swimable' and 'fishable' remains to be met in many, if not most, watersheds today, despite hundreds of billions of dollars on this effort. Part of the reason for this failure is that most engineering firms choose the activated sludge (AS) process for municipal wastewater treatment, because it works reasonably well. However, and perhaps not uncoincidentally, AS is also generally the most expensive option, in terms of construction and operating costs, as well as in energy consumption. The need for disposal of sludges ('biosolids') adds greatly to cost of these processes and requires large land areas for their disposal, or deposition into rapidly filling landfills.

Natural systems using ponds and wetlands have been largely ignored by major engineering firms, despite considerable research demonstrating their superior performance (Oswald, 1990). The evidence is that advanced pond systems provide treatment that is economically and ecologically superior to that of AS. Advanced pond systems cost less than half as much to construct as AS systems of equal capacity, require less than one third as much electrical energy for operations, produce algal biosolids that are less objectionable and more valuable as a fertilizer than the digested sludge typical of AS plants. In the Advanced Integrated Wastewater Pond System (AIWPS®) that our company (Oswald Green, LLC) has developed, we settle and ferment primary biosolids (sludge) to completion, due to the very long, essentially infinite, residence times for the settled solids in the pond, resulting in their almost complete destruction. The primary ponds in the AIWPS® can be designed to capture the emitted methane gas, and this can be beneficially used for electricity production or otherwise. The lack of primary sewage biosolids production by these ponds is a major factor in their attractiveness and economy.

A major benefit of such advanced pond systems is that they require much less energy to operate than conventional technologies (e.g. AS), even capturing energy in the process. Harvesting the algae produced in the high rate ponds and converting this biomass to methane would also actually produce a net output of energy rather than consuming power. By reducing energy consumption, even producing net energy, and by capturing methane gas that otherwise would enter the atmosphere, these systems contribute significantly to the goal of greenhouse gas abatement. Simply put, one kg of BOD removed in an AS process requires one kWhr of electricity for aeration, which produces one kg of fossil CO_2 from the power generation. By contrast, one kg of BOD removed by photosynthetic oxygenation requires no energy inputs and produces enough algal biomass to generate methane that can produce 1 kWh of electric power. Although these figures are only approximate, and depend on local circumstances (such as the fuel used by the regional power plants) overall the AIWPS® could play a significant role in energy self-sufficiency by this vital part of our economy, and microalgae in general could make an important contribution to the global quest for greenhouse reductions (Benemann & Oswald, 1996).

Pharmaceuticals and nutraceuticals from microalgae

The first pharmaceutical from microalgae, the antibiotic 'Chlorellin', was supposed to have been extracted from *Chlorella* in Japan during WWII. This act was the legendary start of pharmaceutical and 'nutraceuticals' (foods claimed to improve health) production

using microalgae. By the early 1960's *Chlorella* production facilities started to appear in Japan, with many claims made for *Chlorella* as a cure for any number of diseases and health problems. As an engineer I have only concerned myself with the production systems for the microalgae, and have worked in this field only with well established algae foods and nutritional products, in particular *Spirulina* and *Dunaliella*.

For example, in 1975 Larry Switzer came to me at the University of California, Berkeley, asking for help in setting up a facility to produce *Spirulina*. This microalga had become world famous as a potential protein source, based on the discovery that native people on the shores of Lake Chad in Africa were harvesting and eating natural blooms of it. At that time John Benemann had been working with a *Spirulina* production plant operating in the bicarbonate lakes near Mexico City. Larry Switzer hired one of my graduate students, Nick Grisanti, to set up a test pond near my home in Concord, California, and later employed another one of my students, Dr Joseph Weissman, when he moved the operation to Southern California, near the Salton Sea, to establish the first *Spirulina* production plant in the U.S. This plant, Earthrise Farms, is now the largest microalgal production company in the world, in terms of acreage, over 10 ha of ponds, and also sales volume. It uses the same paddle wheel raceway ponds that we first demonstrated at our pilot wastewater treatment plant at the Univ. of California Berkeley Engineering Field Station in Richmond, California. Since then many other similar plants have been set-up for the production of *Spirulina*, both in the U.S. and other countries. Nick Grisanti set up his own *Spirulina* plant near Kingsburg, California, but it failed after a windstorm tore up the pond liners, a cautionary tale.

My second go at nutraceuticals production with microalgae was stimulated in about 1980 by two young entrepreneurial recent graduates from Stanford's Business School, Scott Brown and Joe Bottoms, Olympic swimmers with good connections to financing. They wanted to grow *Dunaliella* for glycerol and beta-carotene. For that enterprise I enlisted the help of Dr Ami Ben-Amotz from Israel, who had been studying the production of *Dunaliella*. Their efforts resulted in the establishment of another microalgal production facility near the Salton Sea, although that enterprise is no longer operational. It was first taken over by Nutrilite Co., a division of Amway Co., and shut a few years ago, as the production of *Dunaliella* beta-carotene in Australia became less expensive.

The most successful algal production facility of which I know in the U.S. today is that of Cyanotech Corp., located near Kona, Hawaii, and founded some twenty years ago by Dr Gerald Cysewski, also a graduate of the University of California Berkeley (although not part of my group). Cyanotech produces *Spirulina* and has recently also developed the process for the cultivation of the green alga *Haematococcus pluvialis*, which produces the valuable red pigment and antioxidant astaxanthin. The ability to mass culture such a difficult alga, which grows slowly and is easily contaminated by other species, is a major step forward in Applied Phycology. The success of that facility is in part due to its location in Hawaii, with ideal year-round climate. The climate allows the cultivation of algae without the drastic diurnal and climatic changes experienced near the Salton Sea.

Integrated systems for wastewater treatment, recycling and eutrophication prevention

'Integrated systems' are here referred to as sewage treatment plants integrated with communities in such a way that maximum benefits are attained by the population at least cost without compromising health or welfare. A growing problem in the world today is that there is not enough useable water, at least not in the right places at the right time. Water recycling technologies are a necessity. However, current engineering practice, favoring large centralized and regional, activated sludge (AS) plants actually make recycling more difficult. This is because such large plants once they treat the water (reduce suspended solids and BOD) cannot easily re-convey the treated water to the producers, resulting in the discharge, often in ocean outfalls, and loss of the scarce fresh water resource. Such discharges from AS with their large amounts of residual nutrients have significant adverse effects whether in marine or fresh water environments. As I predicted long ago, if we continue with large regional plants there will be little money and less water, for effective water and nutrient recycling (Oswald et al., 1966).

Decentralization of plant location is the alternative to regional plants, because it favors water and nutrient recycling and benefits those who produced the wastes to start with. Because of their simplicity, modularity and solar-based operations, microalgae wastewater treatment plants can be built at any scale, from one acre to hundreds. Indeed, most of the thousands of wastewater treatment ponds in the U.S. are only one

to a few acres in size. The 'Advanced Integrated Wastewater Pond System' (AIWPS®) plants that we have developed represent the current state-of-the-art in this field. One of the first such integrated systems was established by the community of Ridgemark, near Hollister, California. Ridgemark's wastewater is treated locally in an series of ponds of my design, recharged into the groundwater and then pumped from wells for watering golf courses, parks and other such uses. The fact that these ponds literally adjoin homes valued at half a million to a million dollars suggest that the NIMBY ('not in my back yard') effect does not apply to such pond systems: they are visually attractive, water fowl and bird friendly, and do not create odors. No hygienic problem has ever been attributed to the use of the recycled water. A similar system is now planned for the City of St. Helena, California, where algae will be harvested with dissolved air flotation and the water disinfected with ultrafiltration and UV. Even with these more expensive add-ons, overall AIWPS® costs are less than half of an AS system.

The term eutrophication is applied to bodies of water that, because of nutrient inputs, accumulate organic matter at a high rate, mainly from aquatic plants and settled microalgae. This may cause anoxic conditions, resulting in fish kills and noxious odors. The term 'cultural eutrophication' is applied to bodies of water enriched by human derived nutrients, typically from wastewater effluents, agricultural runoff, animal wastes and similar nutrient sources. The result is often hypereutrophic conditions, where algal blooms are so intensive as to make any recreational or beneficial use of these waters impossible and severely reducing the value of adjacent lands. Even mild eutrophication can be a major problem: a place of scenic beauty, Lake Tahoe, California, has become surrounded by homes and commercial developments that leach phosphate and nitrate into the lake from septic tanks, runoff and automobile exhausts. Although the wastewater treatment plant effluent is now pumped out of the Lake Tahoe basin, but over the past fifty years, light penetration has decreased by about half, due to increases in algal populations.

In a few more years the legendary beauty of the deep blue Lake Tahoe may only be a memory. The need for nutrient removal and recycling during wastewater treatment becomes ever more acute as our populations increase. If controlled, microalgae are uniquely suited to the task of removing nutrients from wastewaters and preventing eutrophication.

The future

No matter how cautiously we try to predict the future we will always fall short or long of reality. There are two solutions to this problem: avoid predictions, because we are sure to be wrong, or, as I intend to do here, predict anyway, hoping that the predictions will have some small influence on the course of future developments. I predict that the genomics revolution will have major and positive effects in the field of Applied Phycology. Knowing the genomes of commercial microalgae such as *Chlorella, Dunaliella, Spirulina* and *Haematococcus*, may allow us to enhance their nutritional value, their productivity and, perhaps most important, the ability to maintain these strains in open pond cultures. I predict that, although the use of microalgae in sewage treatment is already well established, we will develop more cost-effective harvesting methods, such as bioflocculation (Benemann et al., 1980), that will allow a wider application of this technology. I predict that we will learn how to process better the algal biomass derived from such waste treatment processes, or cultured in their own right, to yield more nutritious animal feeds or increase methane yields. I predict that microalgae will become an important component in global renewable energy production and greenhouse gas abatement. I predict that processed microalgae will become an important source of food, protein and essential nutrients for mankind in the not so distant future.

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