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Controlled photosynthesis may have its potentially greatest applications in meeting the needs of an expanding human population: the need for waste purification, nutrient recovery, and increased rates of food production. These possibilities and the problems which must be dealt with first are considered here.

THE COMING INDUSTRY OF CONTROLLED PHOTOSYNTHESIS

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ALL but the most minute amount of energy used to drive our transportation system, heat and light our homes, power our industry, and, indeed, supply the energy which we obtain from the food we consume, comes from the sun by way of photosynthesis. Furthermore, all of this energy, whether it be fuel or food, comes from the nonliving to the living world across a single bridge known as the chlorophylls—the pigments of photosynthesis. Controlled photosynthesis involves the bringing of sunlight energy across this chlorophyll bridge at a regulated rate and with a higher efficiency than normally occurs in nature.

Applications of the process are already in use and its potential for solving many of mankind's fundamental problems both old and new is exciting widespread recognition. Therefore, the time is appropriate for a review of the process itself and a discussion of its use in the solution of a few of the more interesting and significant problems facing civilization.

As used in this paper, the term "controlled photosynthesis" refers to those processes in which photosynthetic organisms are produced continuously under partially or completely controlled environmental conditions. Two processes developed during the last decade can be classified as "controlled photosynthesis." The first is the continuous production of grasses on irrigated, continually grazed or harvested pasture land, according to the procedure described by Pirie.[1] The second is the continuous culture and harvest of microscopic algae. Although continuous grass production has an important potential in present food production, the scope of its future application does not appear to be as broad as that of continuous cultures of algae, with which this paper is primarily concerned.

A number of processes for culturing algae under controlled conditions has been devised. In these processes, algae are grown in shallow ponds designed to permit a maximum exposure of the surface to sunlight, in which nutrients are supplied continuously. Provision is made for the mixing required to prevent sedimentation of the algal solids. Culture is withdrawn continuously for separation of the algal cells.

In one process originally studied in the United States,[2] and then more extensively in Japan,[3] algae were grown

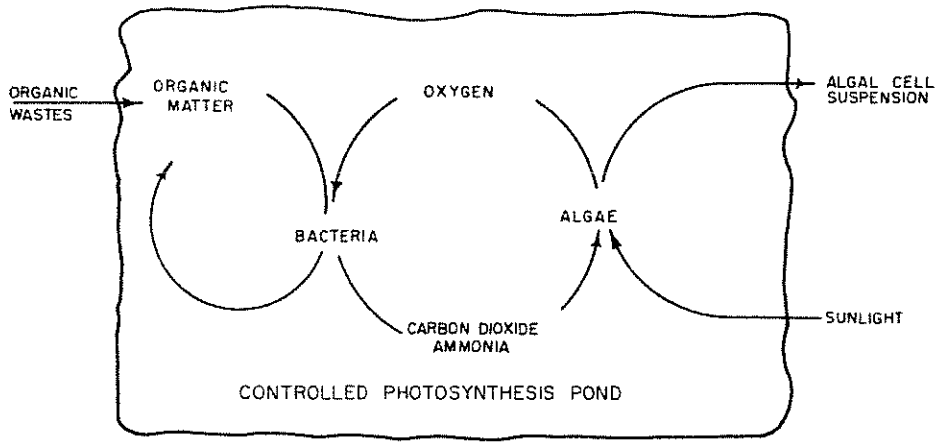

Figure 1—Cycle of Controlled Photosynthesis in Organic Wastes

in solutions of inorganic chemicals which included inorganic nitrogen, phosphorus, trace elements, and gaseous carbon dioxide. In Japan, this process is now employed to produce a pure form of the alga, Chlorella, which is suitable for direct human consumption. The retail cost of the product is estimated to be from 25 to 50 cents per pound.

A second process, which involves the culture of algae in waste waters, has been studied extensively in the United States[4] and in Germany.[5] In projects sponsored jointly by the University of California, the Public Health Service, and the Rockefeller Foundation, this process has been carried on successfully through a two-acre plant, with the production and harvesting of more than a ton of algae. It is estimated that the net cost of the algae thus produced will be only from three to five cents per pound, mostly because it is produced in waste waters, which normally must be treated prior to disposal. This price makes the process extremely attractive as a method for producing protein concentrates for use in animal feedstuffs. The low cost of sewage-grown algae will make its production commercially feasible long before algae can be produced economically for animal feed on inorganic media.

When waste waters are used as a source of nutrient, bacteria and green algae are cultured together in the wastes and no chemical additives are provided. Major reactions in the process are shown schematically in Figure 1. Aerobic bacteria break down the organic matter in the wastes to carbon dioxide, ammonia, phosphate, and other decomposition products. These products are then employed as nutrients by the algae, which with sunlight as a source of energy transform them into algal cell material. Oxygen is liberated in the process and is used by the bacteria to oxidize additional waste material. In practice, the cycle, which is depicted in Figure 1, is carried out in a physical plant of the type shown schematically in Figure 2. Here raw waste is pretreated and injected into a shallow pond consisting of earthwork lined with an insoluble and impervious material. The pond is equipped with facilities for mixing, recirculation, and withdrawal of effluent. When the effluent is passed through a separator, suspended algal cells are removed and purified water is discharged. The algal cells are then treated to remove additional water prior to grinding and storage. The net result of the process is that the elements in organic wastes are transformed into green algae.

The harvested algal material, because it has been grown in waste waters, contains a limited amount of bacterial cell material and detritus, some of which could have pathogenic significance. However, since such material is destined for animal, rather than human consumption, the heat sterilization which normally occurs during drying of the product may be adequate for health protection. This facet of the problem is under current study by the author's associates.

The potential of controlled photosynthesis in the form of algal culture on wastes to hasten transfer of solar energy to a form of value to mankind is perhaps best illustrated by comparing it with conventional agriculture. We shall compare the two on the basis of yield per acre and briefly examine the reasons why the yields differ so significantly between the two processes.

In making the comparison, in every case on a dry weight basis, several agriculture crops are considered. One of the most prolific grains, wheat, may have a bumper-crop yield of two and one-half tons per acre per year, but normally it yields less than one ton per acre per year. Corn may yield thrice this amount as ensilage. Sugar beets may yield as much as 12 tons of organic matter per acre per year under best conditions.[6] At Richmond, Calif., on the other hand, the yield rate for algae grown in sewage ranges from a minimum of five tons per acre per year, in December, to as much as 60 tons per acre per year, in July. The average yield rate is about 30 tons per acre per year. Thus, controlled photosynthesis yields from two and one-half to ten times the peak yields of the more prolific conventional agricultural crops.

When protein alone is considered, even greater yield differences prevail. The most prolific plant protein producer, the soybean, yields up to one ton per acre per year. Cultures of the alga, Chlorella, yield an average of about 12 tons of protein per acre per year—more than tenfold the rate for soybeans. Farm animal protein rarely exceeds 100 or 200 pounds per acre per year, dry weight. Euglena, a motile alga having animal-like characteristics and which may contain proteins more similar to animal protein than to plant protein, has been grown with yields of ten tons per acre per year, 100 times the rate of animal protein production. Thus, rates of protein production in controlled photosynthesis are from ten to perhaps 100 times those of conventional agriculture.

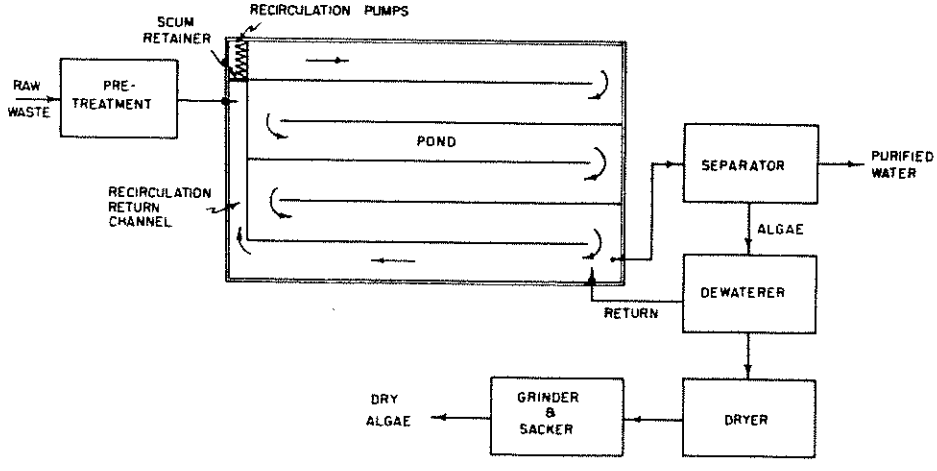

Figure 2—Controlled Photosynthesis Plant

The high yields of food resulting from controlled photosynthesis may be attributed to several factors. Algae are maintained in their most rapid stage of growth continually throughout the growing season; while field crops grow rapidly only for a brief time, and then cease growing as they mature. In properly designed ponds, algae occupy the entire area of growth unit many layers thick and completely absorb the available light energy. Field crops, on the other hand, cover only a part of the ground when young. They are frequently subject to drought and soil nutrient deficiencies; while algae, since they are maintained completely submerged in nutrient solution, have unlimited access to nutrients and water. A large portion of the total growth of field crops goes into roots and stems, which comprise photosynthate that does not contribute to the measured yield; whereas the unicellular algae are composed entirely of photosynthate which can be harvested and used.

In conventional agriculture, the average yield of a given crop differs from the peak yield for that same crop. For example, the national average yield of wheat is approximately 15 bushels per acre, while the peak yields of wheat are about 100 bushels per acre. Thus, the national yield for wheat is only 15 per cent of the maximum. Consideration of the probable factors which influence this percentage, indicates that the most significant is the time lag between planting and harvest. The farmer may plant in the spring and harvest in the fall. During the intervening time his crops are vulnerable to insect and animal damage, malicious mischief, blight, drought, freezing, flood, hail, wind and fire. Any one of these has a high probability of occurrence and may reduce—or wipe out—a given crop. Each danger makes strong inroads on the ratio of average to maximum yield for every crop.

What may be expected with regard to the ratio of average to maximum yield in controlled photosynthesis? The process is subject to few of the hazards of field crops. The time interval between "planting" and "harvesting"—called the detention period in continuous systems—is but three to five days. Freezing, fog, and predation by microscopic rotifers and crustacea appear to be the main problems. Freezing, of course, halts algal production, as does intensely foggy weather. Predation of algae by microscopic animals is readily controlled by chemical methods. Thus, the average crop should be at least 50 per cent of the probable maximum crop in controlled photosynthesis.

Although food production has been used to illustrate the potential value of controlled photosynthesis, it may also be applied in other important problems. In the next generation, the lines of development of controlled photosynthesis are expected to include waste disposal, water reclamation, food production, and, perhaps, power production. Use of controlled photosynthesis for maintaining the environment of space ships suitable for human habitation is an interesting application which is now under intensive study at the University of California and elsewhere.

Aerobic sewage disposal processes are vital to our civilization, since these are the major processes having the capacity rapidly to remove from solution the soluble organic compounds, which comprise at least half of the weight of water-carried wastes and which place the principal burden on our streams. Because it is only slightly soluble in water, oxygen is an important limiting factor in aerobic waste disposal. Many familiar and relatively costly devices, such as the trickling filter and the aeration chamber, are employed to improve oxygen availability and accomplish waste oxygenation. Oxygenation of wastes is accomplished economically

through controlled photosynthesis in the process shown in Figure 1. The principles of photosynthetic oxygenation have been described in several technical publications[4,7] and, hence, are only briefly recounted here. Essentially, there exists a relatively constant production ratio of 1.6 pounds of dissolved oxygen per pound of algae grown. Once produced, this dissolved oxygen is readily available to bacteria for oxidation of additional wastes. Under average conditions, controlled photosynthesis will supply about 200 pounds of oxygen per acre per day, a quantity sufficient to oxygenate completely the wastes of from 800 to 1,000 persons, and to produce a stable effluent.

Controlled photosynthesis may have an important bearing upon future water supplies in several respects, namely, direct treatment and reclamation of waste water quality improvement, and utilization of sea water for crop production. In the process shown in Figure 1, it has been found that over 90 per cent of the biologically available dissolved organic matter orginally present in the sewage is rendered insoluble and hence removable from waste waters.[8] The major part of this insoluble material consists of algal cells which may be separated with the use of natural precipitation or of small amounts of water treatment chemicals. The residual water is clear, sparkling, stable, and useful as a water resource.

Impairment of water quality resulting from uncontrolled algal growth is a problem of increasing importance in inland lakes and reservoirs.[9] The problem is not lessened by conventional methods of secondary treatment. On the contrary, effluents from both the activated sludge and the trickling filter processes produce effluents in which uncontrolled proliferation of algae readily occurs. Having produced one crop of algae, the effluent water from algal growth ponds is usually depleted of algal nutrients and therefore ordinarily will not produce a second crop of algae. Because of this inability to support a second crop, pond effluents from which the algae have been removed are more ideally suited for discharge into natural waters in which algal growth has frequently been a serious nuisance, than are the effluents from conventional aeration processes. Therefore, it is anticipated that in the future, water pollution control regulations will encourage the use of controlled photosynthesis as a method of stripping sewage treatment plant effluents of elements which may cause nuisance growth of algae in receiving waters.

Aside from its ability to deplete waste waters of nutrients essential to algal growth, under certain conditions, controlled photosynthesis may be employed to bring about a significant degree of softening in natural waters containing a large amount of calcium and magnesium—the major elements of permanent hardness. During vigorous algal growth, utilization of carbon dioxide by algae brings about an increase in pH which ultimately results in the precipitation of magnesium hydroxide and complexes containing calcium, ammonium, and phosphate. Frequently, these precipitates enmesh algae, and sedimentation of both the algae and the elements of hardness results in water softening. In experimental work carried on at Concord, Calif.,[8] as much as one-half of the permanent hardness was removed from the pond waters during periods when precipitation and sedimentation occurred as a result of high pH levels.

Utilization of sea water for crop production is another potentially important application of controlled photosynthesis. Mixtures of organic wastes and sea water can produce dense crops of algae of various types. Inasmuch as one of our major agricultural uses of fresh water is for protein production employment of controlled photosynthesis, to

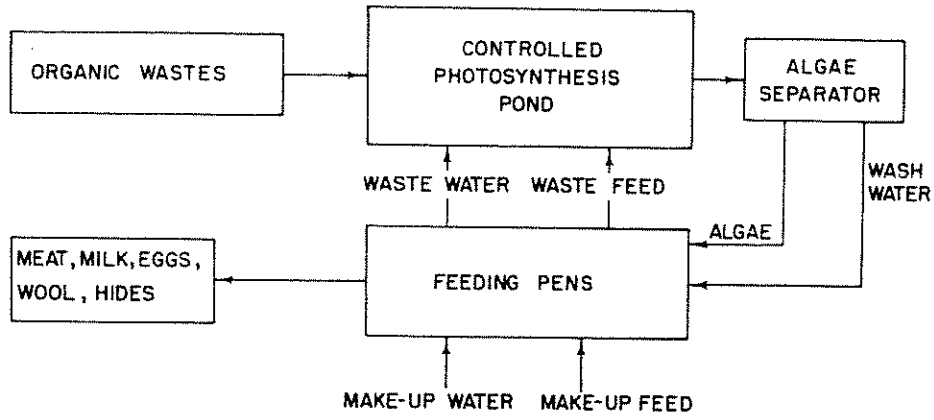

Figure 3—Animal Product Production Complex Using Controlled Photosynthesis and Closed Cycle Conversion of Organic Wastes

achieve protein production in sea water would make possible the diversion of as much as one-third of the sum total of fresh-water resources to purposes other than protein production.

The nutrient properties of the harvested algae are those characteristic of the more proteinaceous higher green plants. The successful use of algae as animal food opens the new possibility of establishing industrialized food production complexes with unusual properties. One such hypothetic system is shown schematically in Figure 3. In the cycle as diagramed in the figure, organic wastes are diverted into shallow ponds in which algae are grown for harvest. Harvested algae, together with supplemental food, are fed to animals, which in turn produce meat, milk, eggs, wool, hides, and other products. Only useful products are removed from the system; and all wastes, such as urine, manures, wash waters, meat trimmings, and dressings, are returned for biological conversion to algae and reuse in the cycle.

In Figure 4, the magnitude of nitrogen conservation which could be attained in a protein-producing complex of the type shown in Figure 3 is compared with that obtained with the use of nitrogen in conventional agriculture. In conventional agriculture, five pounds of nitrogen are required to produce one pound of eggs or meat and four pounds are lost as waste. In a controlled photosynthesis complex, two pounds of newly introduced nitrogen are combined with three pounds of reclaimed nitrogen to form five pounds of feed-nitrogen. As in conventional agriculture, after feeding, one pound of eggs or meat and four pounds of waste are obtained. However, of these four pounds of waste nitrogen, three pounds are converted back to feed and only one pound goes to waste. Thus, in such a protein-producing complex, 50 per cent of the nitrogen introduced to the cycle appears as useful products; whereas only 20 per cent is converted to a useful product in conventional agriculture. Similar cycles could be shown for milk, wool, and other animal products.

On a technical basis, there is no question that nitrogen recovery systems of the hypothetical type shown in Figure 3 could be operated, but economic considerations will determine their use. Although it is improbable that they could be used economically on a small scale, the economy of space, water, nutrients, and management resulting from the employment of such a process makes them appear singularly attractive in installations of several thousand acres. Computations show that but five million

acres of algal-animal cultures would meet the entire protein needs of the United States; whereas three hundred million acres are now required with conventional agriculture. The economies resulting from waste disposal and water reclamation would be the incidental benefits of such complex systems.

A system of producing electrical energy through controlled photosynthesis has recently been published by Oswald and Golueke.[10] Those studies showed that through methane fermentation of algae grown on the residues of digestion, power could be produced for 10 to 20 mills per kilowatt hour. This is expensive when compared to the cost of 5 to 10 mills for power generally available in the United States today. However, there are areas of the world where power costing 10 to 20 mills per kilowatt hour would be less expensive than that available from existing systems. However, future use of atomic energy makes power production through controlled photosynthesis appear less attractive than its application in waste water disposal and animal food production.

Summary

In reviewing the present and predicting the future of controlled photosynthesis, those applications have been presented which should have greatest potential value in meeting the ever-increasing needs resulting from mankind's expanding population—the need for waste purification, nutrient recovery, and increased rates of food production. Controlled photosynthetic processes which are within the reach of technical capability of most nations, processes which today could significantly aid in solving the age-old problems of human disease, misery and want, have been outlined. It should be noted that comparatively small amounts of money have been spent on the development of controlled photosynthesis, and many important details require further investigation and refinement. Renewed research efforts, however, will permit more extensive evaluation of the nutrient value and disease-producing potential of algae grown on organic wastes, the study of new or improved methods of culturing and separation, and the development of new applications for the products of controlled photosynthesis. Nevertheless, the fundamental findings of the past ten years of research are unmistakable. It is technically feasible to apply controlled photosynthesis to treat wastes, to reclaim water, to render waste organic matter suitable for use as an animal feedstuff, to obtain unprecedented yields of protein per acre

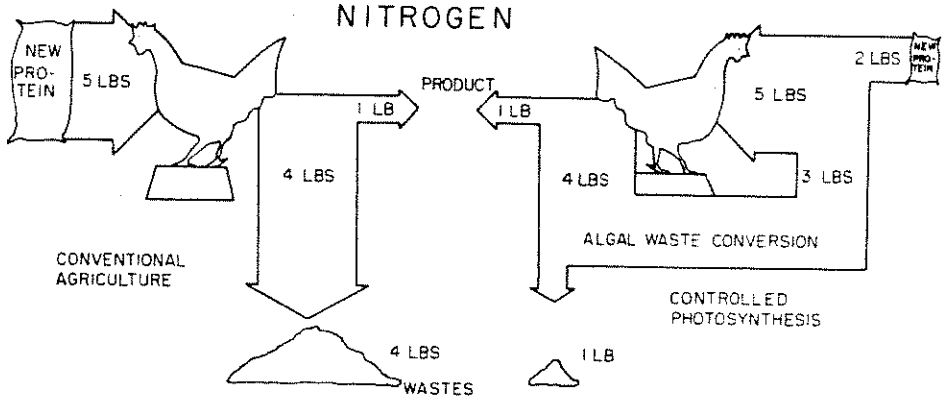

Figure 4—Comparison of Theoretical Nitrogen Balance in Conventional Feeding and in Controlled Photosynthetic Waste Conversion

of pond surface in either fresh or saline waters, and to produce electrical power from sunlight using organic wastes as a medium. By virtue of its simplicity and lack of need for complex machinery, controlled photosynthesis is subject to implementation by much of the world's population. Its successful application could bring people of many underdeveloped countries to a new level of prosperity and human dignity.

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