PLANT PROCESSES AND APPLICATIONS[1]

by C. H. Ward

Introduction

Green plants are a highly diverse group of organisms that function as the nucleus of the earth's food chain. Present and past plant life provide the energy requirement for maintenance and balance of the multi-organismal ecology that has evolved on earth. This elevated position has been attained through the unique process of photosynthesis combined with, what now appears to be, almost unlimited genetic and physiological plasticity. While green plants have evolved into varied morphological forms, ranging from microscopic algae to the giant redwood, their gross physiological and biochemical characteristics are remarkably similar. Although minor qualitative variations undoubtedly provide for selective advantages of certain species over others in a particular environment, differences between most species are largely quantitative. Indeed, with the exception of photosynthesis (where oxygen is evolved as an end product), the counterparts of most plant physiological and biochemical functions are found in one or another microbial or animal species.

The field of plant physiology has a vast and intriguing literature from which I will attempt to select and condense some of the salient points to convey to an audience composed mostly of engineers primarily interested in water and waste management. Water (and its contaminants) is intimately associated with land, people, and their food supply. Since green plants serve as the base of the food chain, it seems appropriate that those interested in water problems should also attempt to place plants in their proper context in relation to water, i.e., characteristics and processes that could serve to advantage or cause disadvantage in the solution of water problems. Let us then look briefly at some of the basic principles of plant physiology with the understanding that *you* will make whatever interpretations are warranted, since, at the time of this writing, my knowledge of the problems of water and waste management

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are lamentably fragmentary.

If I were to attempt to cover all of the known plant physiological processes I could hardly do more than give definitions in the time allotted. Suffice it to say that such processes as absorption, translocation, accumulation, and even respiration differ perhaps only in detail from like processes found in other organisms such as bacteria, yeasts, molds, and even higher animals. The previous paper dealt with the biochemistry of heterotrophic metabolism and covered such topics as enzyme action, electron transport, and respiratory pathways. The information given on these processes is in most cases directly applicable to green plants. It would appear then that major emphasis should be given here to gaining a better understanding of processes that distinguish green plants from the rest of the biological world and then turn to applications. However, before doing so, a brief review of "how a plant grows" might be instructive.

Growth of Plants

Plants can be photolithotrophs, using light as energy and water as the hydrogen donor, or chemoorganotrophs using sugars or other organics (mostly acids) both for energy and a source of reduced carbon. Some plants are obligate for one mode of metabolism. Examples are the colorless algae that grow only with a source of reduced carbon and other algal forms that grow on no known exogenously supplied carbon source. Numerous plants demonstrate both types of metabolism and it is probable that most have the capability for true heterotrophic metabolism provided the proper environmental conditions are known and are made available.

Physiological processes are closely associated with both structure and function and should be discussed with these factors in mind. The seeds of higher plants are reproductive storage organs. When seeds are exposed to the proper environmental conditions of temperature, moisture, light, atmospheric gases, etc., they imbibe water. Complex storage products are mobilized (solubilized) and used as energy and a source of reduced carbon. The energy derived through respiratory metabolism is used to support growth of rudimentary tissues destined to be shoot and root. Germination occurs and shoot and root growth continue, for periods of hours to days, supported solely by the energy obtained through the breakdown of stored materials. After the first true leaves are formed, photosynthesis begins in illuminated plants and they become self-sufficient, no longer requiring stored or exogenously supplied reduced carbon. Photosynthesis normally proceeds at ten to twenty times the rate required to support basal metabolism. During the seedling and juvenile stages, excess photosynthate is used to support growth of leaves, stems, and roots. At some stage in time, depending on the plant, sufficient leaf surface is attained to support the remainder of the life cycle. Subsequently, excess photosynthate is translocated and stored in asexual reproductive structures such as tubers, corms, etc., and/or directed toward the production of sexual reproductive structures such as seeds, fruits, etc., depending on the horticultural definition. At this stage the plant is considered mature and the photosynthetic rate declines and senescence follows. Perennial plants go through this cycle repeatedly, using the stored materials to promote growth in the spring. Leaves form and excess photosynthate supports the current year's growth and seed formation and is stored as a reserve energy supply. Plants without sexual cycles (both higher plants and algae) may store excess photosynthetically reduced carbon in specialized structures or simply store it as undissolved constituents in the cells. Survival under adverse conditions is accomplished through hardening of tissues or other specialized dormancy mechanisms or merely by reduction of respiratory activity.

I have given a greatly oversimplified and condensed version of plant growth. However, it should be remembered that the basic "purpose" of the plant is to produce more plant. In doing this the plant is subject to the same, or similar, limiting factors as other biotic forms. Optimization of limiting factors is subject to mathematical and experimental analysis using methods discussed in a later paper. Since the primary distinguishing factor between green plants and other forms is photoautotrophic metabolism, optimization generally deals with factors affecting photosynthesis. In most instances, total synthesis as evidenced by growth closely follows the course and rate of photosynthesis.

Photosynthesis

Classically, photosynthesis has been described by the equation

$$CO_2 + H_2O + \text{light energy} \rightarrow (CH_2O)_n + O_2 + H_2O$$

wherein light energy activates the combination of CO_2 and water to form organic material (sugars) and molecular oxygen. Note that aerobic respiration is essentially the reverse of this reaction in that organics are burned in presence of oxygen to yield energy, CO_2, and water. This equation approximates the overall process which is now known to proceed in stepwise fashion. The primary energy receptor or machinery of the process is chlorophyll. This reaction represents the world's most extensive chemical (synthetic) activity.

Magnitude of the Process. Each year over 200 billion (2×10^{11}) tons of carbon as CO_2 are removed from the atmosphere and transformed into plant material through photosynthesis. All of man's chemical activities, including the petroleum and steel industries, are dwarfed in comparison. The photosynthetic transformation of 2×10^{11} tons of carbon corresponds to the uptake of approximately 7×10^{11} tons of CO_2 and the production of about 5 x 10^{11} tons of dry plant material. Almost 90 per cent of the earth's photosynthesis is accomplished by marine and fresh water algae. The remaining 10 per cent is performed by cultivated land plants and native vegetation. Cultivated plants vary widely in their mean annual photosynthetic productivity. An average acre of corn with a 120 day annual growing season stores about a ton of carbon per year, whereas sugar cane can store up to 20 tons of carbon per acre year. In contrast, desert shrubs seldom yield more than 0.05 to 0.1 tons per acre year, yet it is interesting to note that in some desert areas halophytic plants transpire almost as much water per unit area as do cultivated crops. The above and other information on the magnitude of photosynthesis is summarized in Table I, where it can be seen that forests are not only efficient photosynthetically (due primarily to year-round dense coverage), but are the single largest contributor to terrestrial photosynthesis.

TABLE I

The Magnitude of Photosynthesis on the Earth's Surface
(From Bonner, 1952.)

Habitat	Area Km^2	Carbon Fixed/yr/Km^2 Tons	Annual Total Carbon Fixed Tons*
Oceans	361 X 10^6	375	13.5 X 10^{10}
Land	149 X 10^6	130	1.6 X 10^{10}
Total			15.1 X 10^{10}
Forests	44 X 10^6	250	11.0 X 10^9
Cultivated	27 X 10^6	160	4.0 X 10^9
Steppes	31 X 10^6	36	1.1 X 10^9
Desert	34 X 10^6	7	0.2 X 10^9
Polar	13 X 10^6	0	— — —
Total	149 X 10^6		16.3 X 10^9

* Values are not corrected for respiratory CO_2 loss.

Mechanism and Materials Turnover. Green plants use light energy to convert carbon dioxide and water into oxygen and organic compounds required for the formation of new plant material or storage products. The first of the syntheses leading to the production of new plant material is photosynthesis.

At one time photosynthesis was believed to consist of two reactions yielding the overall reaction previously given. The first, known to occur only in the presence of light (light dependent), consisted of light-driven decomposition of water into molecular oxygen and hydrogen atoms. In the second reaction, which proceeds with or without light (light independent or dark reaction), the hydrogen is used in the transformation of CO_2 to sugars. Continued research has now shown the essential features of green plant photosynthesis to be light-activated photolysis of water, liberation of oxygen, and production of what Arnon calls "assimilatory power" in the form of adenosine triphosphate (ATP) and reduced puridine nucleotide ($TPNH_2$). ATP and $TPNH_2$ are subsequently used in nonphotosynthetic assimilation (reduction) of carbon dioxide into carbohydrates, lipides, and proteins (Figure. 1).

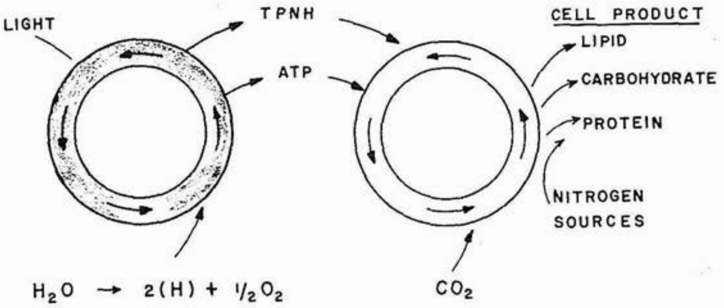

FIG. 1 - SIMPLIFIED DIAGRAM OF ALGAL CELL SYNTHESIS (FROM MYERS, 1964)

Carbon dioxide assimilation is now known to occur in the metabolism of most organisms; however, use of light energy for the production of assimilatory power is unique in photoautotrophic metabolism.

Materials turnover in plant synthesis has been considered in greatest detail using algae. Myers has shown that elementary analysis of algal cells permits estimation of overall metabolism and derivation of equations for cell synthesis. With urea as the nitrogen source, equivalents calculated for 100 per cent recovery of carbon show that for each gram (dry) algae produced, 0.82 liter of carbon dioxide is assimilated and 1.0 liter of oxygen is liberated, resulting in an assimilatory quotient ($AQ = CO_2/O_2$) of 0.82. Algal AQ can be varied between about 0.7 to 0.9, depending on the source of nitrogen used for cell synthesis (Table II). The AQ of higher plants is also subject to some control; however, since carbohydrate makes up such a large portion of the dry weight of most higher plants, an AQ very near 1 is most common.

TABLE II

Overall Metabolism of *Chlorella*
(From Myers, 1964.)

Elementary analysis: 48.7% C, 7.5% H, 9.4% N, 6.4% Ash.
Derived formula for organic composition: $C_{6.0}H_{11.1}O_{2.7}N$
Equivalent weight: 140.7 (organic)
149.0 (total cells)

Equation for cell synthesis:
$0.5\ (NH_2CONH_2) + 5.50\ CO_2 + 4.55\ H_2O$
$C_{6.0}H_{11.1}O_{2.7}N + 6.68\ O_2$

Equivalents calculated for 100% recovery*
$CO_2/O_2(AQ) = 0.82$
CO_2/cells = 0.82 l/g
O_2/cells = 1.00 l/g

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* Carbon recovered in harvested cells divided by carbon taken up as carbon dioxide.

Limiting Factors. There are numerous factors known to directly or indirectly limit photosynthesis. We will limit our discussion to four of the most frequently encountered and, hence, important factors. Light, carbon dioxide, and temperature directly affect photosynthesis, whereas mineral nutrients are generally considered to have an indirect effect. It should be remembered, however, when assessing the importance of growth factors that when any required factor is limiting it controls the overall rate of growth.

Light. Spectral quality is defined by the absorption spectrum for the chlorophylls and other photosynthetically active pigments. Plants typically absorb energy of wave lengths from less than 300 to over 700 mμ with peaks in the blue (435 mμ) and red (680 mμ) regions of the spectrum (Figure 2). However, since prolonged exposure to ultraviolet radiation is inhibitory to growth and cell division, the allowable spectral limits for sustained photosynthesis fall in the range from 400 to 700 mμ When an exposed plant leaf is irradiated with white light, chlorophyll absorbs the red and blue portions of the spectrum but very little of the green portion, hence the leaf appears green. That maximum photosynthesis occurs with wave lengths nearest the absorption peaks in Figure 2 is illustrated by the action spectrum in Figure 3. Another important feature of the action spectrum is that some photosynthesis can occur with wave lengths throughout the visible spectrum.

When plants are placed in the dark they take in oxygen and give off carbon dioxide as a result of respiration. The rate is the basal or endogenous rate and is that required for maintenance of cellular overhead. Under very low light intensity plants may still take in oxygen and give off carbon dioxide, but as the intensity increases a point will be reached where the light intensity is just sufficient to support a photosynthetic rate that equals the respiration rate. This is called the compensation point and no net gas exchange should be observed. Provided other factors are in sufficient supply, photosynthetic rate increases

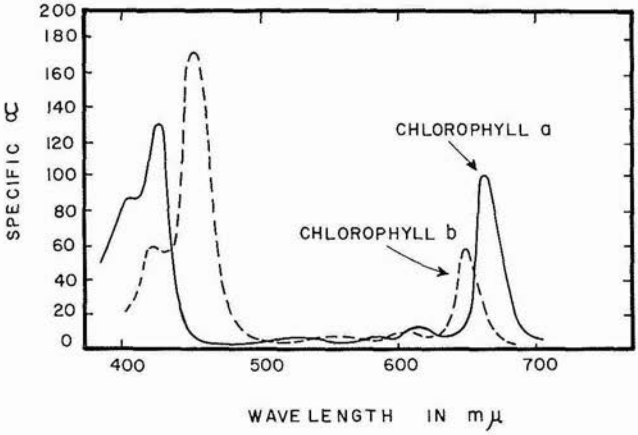

FIG. 2 - ABSORPTION SPECTRA OF EXTRACTED PLANT CHLOROPHYLLS (REDRAWN FROM BONNER, 1952)

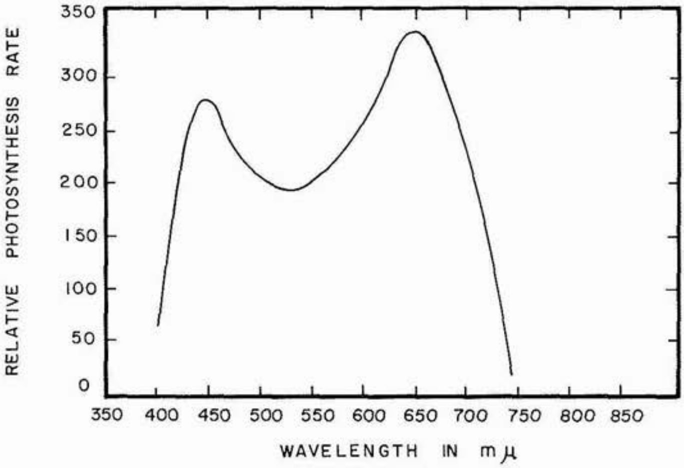

FIG. 3 - ACTION SPECTRUM OF WHEAT LEAF PHOTOSYNTHESIS (REDRAWN FROM BONNER, 1952)

directly with irradiance and reaches a maximum as irradiance nears saturation (Figure 4). An important feature of the light curve is the relatively low values of irradiance at which photosynthesis becomes saturated. Many plants become light saturated in the range from 250 to 600 footcandles, while other species have saturation values in excess of 1500 footcandles. The low values for saturation impose severe limitations on photosynthetic efficiency.

Photosynthetic efficiency is measured by determining the percentage of the amount of visible light, falling on a plant surface per unit time, that is captured in the form of plant material. In most agricultural situations not more than 0.5 to 2 per cent of the total available light energy is actually stored by the plant in chemical form. I personally think it incredible that the most productive synthesis process known has a practical efficiency generally less than 2 per cent while efficiencies of 18 to 20 per cent have been measured in carefully controlled laboratory experiments. Theory and exhaustive experimental evidence indicate

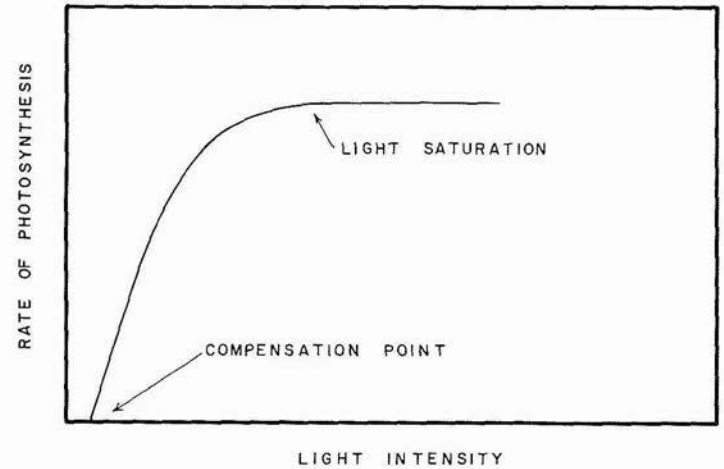

FIG. 4 - RELATIVE RATE OF PHOTOSYNTHESIS AS A FUNCTION OF LIGHT INTENSITY. LIGHT SATURATION OCCURS AT ABOUT 500 ft-c. COMPENSATION POINT UNKNOWN BUT PROBABLY LESS THAN 50 ft-c.

that efficiencies greater than 25 to 30 per cent are unattainable. Increasing the efficiency of photosynthesis would appear to be one of the most challenging and humanitarian areas of biological research. I will return to considerations of efficiencies in a later section. However, those interested are urged to read James Bonner's scholarly presentation on the subject.

Temperature. Changes in temperature affect not only photosynthesis but other physiological processes such as respiration, transpiration, and absorption. In general, when no other factors affecting photosynthesis are limiting, a 10°C increase in temperature in the range from slightly below 0° to 35°C will double the photosynthetic rate (Q_{10}=2). Most plants have optimum temperatures for growth between 20° and 30°C; some alpine, polar, and cold water forms have somewhat lower optima and a few algal forms attain maximum growth rates at light saturation at temperatures above 65°C.

In nature, plant temperature is a function of air temperature as well as intensity of incident irradiation. Leaf temperatures are normally several degrees centigrade higher than atmospheric temperature due to inefficient utilization of absorbed light energy but seldom get high enough to severely inhibit photosynthesis. Transpiration of water from leaf surfaces is rate controlled based on the difference between the vapor pressure of water in or at the leaf and the vapor pressure of the water in the atmosphere. Since the leaf cell walls represent an almost unlimited evaporative surface in relation to gas volume, the vapor pressure at the cell wall will be approximately that of pure water at any given temperature. The vapor pressure of water in the surrounding atmosphere may approach but is seldom at the saturation level. The gradient between the two will control the rate of transpiration which serves to regulate leaf temperature within a suitable range. The water economy of plants can be severely affected in hot climates.

Carbon Dioxide. The concentration of carbon dioxide in air (0.3 per cent) is sufficient to saturate photosynthesis of most land plants during periods of moderate to low irradiance. However, during the middle four to five hours of the day plants directly exposed to the sun are light saturated and may become rate limited by carbon dioxide. Improved photosynthetic rates and yields have been obtained both experimentally and commercially by increasing the atmospheric concentration of carbon dioxide in greenhouses. In the culture of aquatic plants the problem becomes more one of efficiency of liquid-gas transfer rather than the actual concentration of carbon dioxide in the gas phase. This is evident in that 5 per cent carbon dioxide in air is commonly used to sparge algal cultures while only a small fraction of the influent carbon dioxide is incorporated into plant material. Carbon dioxide limitation in nature is undoubtedly a significant factor in determining the overall light efficiency of plants. To date, there are no practical methods of increasing carbon dioxide concentrations in or over fields of commercial crops.

Nutrients. There is an extensive literature on the mineral nutrition of plants. Our knowledge of mineral nutrition has probably gained greater economic application than any other area of plant science, including application of genetics to improvement of crop varieties. Green plants require, in addition to carbon dioxide and water, a source of fixed nitrogen (urea, ammonia, or nitrate) and mineral salts. Most plant media contain potassium, magnesium, sulfate, and phosphate ions in macro quantities, plus 1-30 ppm of some eight to ten other elements. Actual plant requirements will depend somewhat on the plant species and to a greater degree on growth rate. All elements termed essential are known to be required for one or more plant forms, but may not be essential for all plants. Elements such as nitrogen, iron, and magnesium, known to affect the formation of chlorophyll, may have a direct effect on photosynthesis. Others act indirectly by affecting subsequent synthesis and ultimately growth. Growth will be controlled by the supply of the most deficient element, but interpretation may be confounded by deficiencies of other growth factors.

Interactions. As a result of the early work of Blackman and others we now recognize that three primary interacting external growth factors—light intensity, temperature, and carbon dioxide concentration—largely determine the photosynthetic rate and subsequent anabolism. If we include carbon dioxide reduction as a second step in photosynthesis the influence of temperature on rate depends on whether light or carbon dioxide is limited. However, since the first step is a photochemical reaction it is relatively insensitive to temperature changes, while the second (CO_2 requiring) is a chemical reaction and greatly sensitive to temperature. The photochemical step then is light but not temperature or carbon dioxide dependent, while the reduction step is carbon dioxide and temperature dependent but insensitive to light.

Controlled Photosynthesis

Agricultural applications of photosynthesis and plant growth for production of food, fiber, fuel, and various chemicals is common knowledge. If I have repeatedly referred to crop applications during this discussion it is because the world's readily tillable land is mostly under cultivation, yet the world's population is increasing exponentially. We have yet to reach the maximum limit of conventional food production, but it is obvious that the limit is nearer than the time that the world population will be stabilized.

The concern of this conference is water and waste management. These items cannot be separated logically from management of food supply since they are interdependent and in turn depend on people and population stress. It seems reasonable then that all three—food, water, and waste—should be of intimate concern to, and fall logically under the broad context of, environmental engineering. The products of research on one should significantly benefit technology associated with the others. All three, including wastes, can be viewed as resources requiring multidisciplinary development for optimum control and supply.

Factors governing water supply and waste control have been subjected to detailed engineering study. In contrast, most of the world's food production is accomplished with terrestrial plants using traditional though highly improved agricultural techniques, yielding efficiencies generally less than 1 per cent in the capture of sunlight energy. This fact, combined with the knowledge that the probable maximum of about 4 to 5 per cent efficiency has been reached with some crops, has led to development of a field of research often called "industrial," or perhaps more accurately, "controlled photosynthesis." Controlled photosynthesis, as defined by Oswald, refers to "those processes in which photosynthetic organisms are produced continuously under partially or completely controlled environmental conditions." The approach has centered around algal farming or the mass production of algae, governed in general by the philosophy that through optimization, productivity (efficiency) can be increased.

Controlled photosynthesis for the production of food, organic products, bioregeneration for space life support, and waste reclamation has been extensively investigated, publicized, popularized, and criticized. The general subject, especially the space life support aspect, has captured the imagination of thousands of secondary school science students. Research on algal mass culture has been variously described by both the informed and uninformed as a panacea for the world's food, waste, and space problems and, at times, as a waste of time and tax money. Millions of dollars have been spent for research on algal culture during the last 15 years. Much has been learned of scientific interest if not of direct benefit in solving the problems for which the research was originally intended. What then is the status of algal mass culture? Is algal farming for food on an industrial scale feasible? Can algal cultures be used effectively for respiratory and nutritional support of man in space? Does algal culture offer an effective, economical method of water renovation? Let us look briefly at some of the background (assumptions and philosophy) suggesting possible development, broadly summarize the evidence that has accumulated through research, and attempt to arrive at the "state of the art."

Culture of Algae for Food. The rationale for the large scale culture of unicellular algae for food was first advanced in 1947-1948 by Spoehr and Milner of the Carnegie Institution of Washington. Since the theoretical maximum photosynthetic yield is largely controlled by the inherent inefficiency of the green plant in converting sunlight energy into plant material, it was reasoned that significant increase in productivity could be obtained by absorbing more of the incident energy striking the earth's surface. Crop plants are limited in distribution, require favorable climatic and edaphic conditions, and can be grown only during part of the year (about four months in temperate areas). Energy received during the early part of the growing season when plants are small is only partially absorbed; none is used for food production following harvest. Crop plants are limited in productivity by carbon dioxide deficiency (during periods of intense illumination), availability of water and mineral nutrients, soil type and reaction, pests, disease, and by the fact that few yield greater than 50 per cent of their dry mass as usable food. The ideal plant then should be one that absorbs all of the available sunlight, grows the year-round in a physical and chemical environment that is subject to precise control, and yields a large percentage of its constitution as a recognizable food, hopefully protein.

The unicellular green algae would appear to be ideally suited to controlled photosynthesis application. Growth factors are generally known, as well as methods for their control. Cultures can be grown easily in the laboratory in simple inorganic media at a variety of temperatures provided carbon dioxide and light are supplied. Species of the genus *Chlorella* have been used extensively for research on photosynthesis, resulting in a considerable literature on their physiology. Individual plants consist of single cells that can yield up to three to nine doublings in cell mass per day. The composition of the cells can be varied depending on nutrition and culture techniques. *Chlorella* normally yields about 50 per cent protein on a dry weight basis. Other constituents would indicate a high potential as human food. Algae are known to be our primary energy converters, synthesizing approximately 90 per cent of the world's organic carbon. In addition, several researchers have obtained light conversion efficiencies up to 20 per cent with algal cultures under carefully controlled conditions.

Numerous mass culture devices have been constructed. Most have been considered research devices rather then "pilot plant" models. The A. D. Little Company in the United States and the Japanese Microalgae Research Institute near Tokyo have operated pilot plant models. The Japanese unit is still in operation. The A. D. Little Company unit was operated for several months during 1951. They estimated a potential yield of 17.5 tons algal dry mass per acre year, but admitted that half this value more nearly reflects extrapolation of their actual yield. Costs were tentatively estimated at \$0.17-\$0.25/lb. Assuming an improbable yield of 80 tons per acre year, Thacker and Babcock analyzed the costs of a plant capable of producing 100 tons per day and estimated that algae would cost \$0.50/lb. to produce. They also felt their estimate was low by 50 per cent. Only the Japanese facility has been operated for periods sufficient to establish actual costs. They originally estimated that *Chlorella* could be produced for \$0.26/lb; however, their actual running costs are roughly \$2.00/lb. The striking thing about the Japanese operation is that revenues from sales approximately equal production costs. It has been shown that small quantities of dried *Chlorella* greatly accelerate the rate of *Lactobacillus acidophilus* fermentation of milk. About three million bottles of lactic acid fermented milk are sold daily in Japan.

There are numerous reasons why algal yields have not reached the original estimates. The most obvious is that optimization of growth factors in large outdoor plants is difficult and expensive to attain. In general, techniques found effective and relatively easy to accomplish in the laboratory were attempted on pilot plant scale. Operating costs for equipment, media, carbon dioxide, mixing, and harvest were found to be far above early expectations. The early predictions of 10-20 per cent conversion of the *total* visible sunlight energy were in error. Efficiencies of this magnitude cannot be expected even when dense cultures continuously absorb all of the available light energy. Approximately 50 per cent of the radiation received from the sun is visible light available for photosynthesis. Most plants, including algae, become light saturated at about 500 footcandles or about 1/20 the intensity of full sunlight. Of the energy absorbed at light saturation, up to 20 per cent is used for photosynthesis. Assuming a value of 7.3 x 10^9 kilocalories as reasonable for the radiation received from the sun on an acre of land per year, a probable yield may be calculated:

$$\frac{7.3 \text{ x } 10^9\text{Kcal}}{\text{acre year}} \times \frac{.5}{\text{visible light}} \times \frac{.05}{\text{saturation}} \times \frac{.2}{\text{efficiency}} \times \frac{\text{gm algae}}{5.5 \text{ Kcal}} \times \frac{\text{lb}}{454 \text{ gm}} \times \frac{\text{ton}}{2{,}000}$$

$$= 7.5 \text{ tons dry algae/acre year.}$$

Yields of this magnitude have been obtained. Several investigators have reported yields significantly greater. However, yields have generally been closer to the above calculated value than to the early estimates of 50-100 tons per acre year. Controlled culture conditions, including increased carbon dioxide tension and mixing, have allowed, in some cases, greater efficiencies in the conversion of light energy.

To summarize, algae of high quality can be produced in large quantities with yields equal to or greater than our most productive crops. Furthermore, good farm land, which has become scarce, is not required. There is also a growing amount of evidence that algae produced in artificial culture have high potential as human food. Regrettably, costs required for high yields are prohibitive.

Bioregeneration for Space Life Support. The use of algae for space life support has been dated as originating in 1951 when Dr. Heinz Specht suggested that human respiratory requirements might be managed by photosynthesis of plants. The approach has as its pattern the complex multiorganismal life support system that has evolved on earth. Simply stated, green plants, in the presence of light, fix carbon dioxide in the form of more plant material and evolve oxygen. Man can consume plant material as a source of energy but requires oxygen for respiratory metabolism and gives off carbon dioxide as a waste product. Man's solid and liquid wastes, if properly treated, could in turn serve as nutrient for the growth of more plants.

Several investigators, led primarily by Dr. J. Myers of the University of Texas, made preliminary estimates of the logistics of photosynthetic regeneration. In this particular application of controlled photosynthesis, cost was of little or no importance. Volume, area, and power requirements, all of which must ultimately be translated into terms of weight, were of critical concern. Again, the primary limiting factor in dealing with green plants was efficiency of energy conversion. Many of the early estimates did not properly reflect the severe consequences of light saturation. During the last 14 years a sizable literature, mostly in the form of laboratory reports, has appeared describing the virtues of the bioregenerative approach and results obtained with mass culture apparatus. The current status of development is summarized in Figure 5. Illuminated surface area required for the respiratory support of one man is plotted against the power required for artificial illumination. A one-man requirement is taken as 600 liters of oxygen per day which can be produced by the growth of 600 grams of (dry) algae. Data are for photosynthetic exchangers that have been reasonably well described. The curves were calculated from a form of the Bush equation which describes, at least in a qualitative sense, the overall effect of increasing irradiance on dense culture performance. Figure 5 shows the approximate compromise required between area and power for a one-man support capacity. Power and area are inversely related. A large surface is required to minimize power, while area and hence volume may be reduced by increasing light intensity. Using fluorescent lamps with a maximum efficiency of 20 per cent for conversion of electrical to light energy, and assuming a maximum algal efficiency of about 20 per cent for the photosynthetic conversion of light to chemical energy, the maximum theoretical efficiency becomes 4 per cent. The most efficient gas exchangers generally perform at less than half this value.

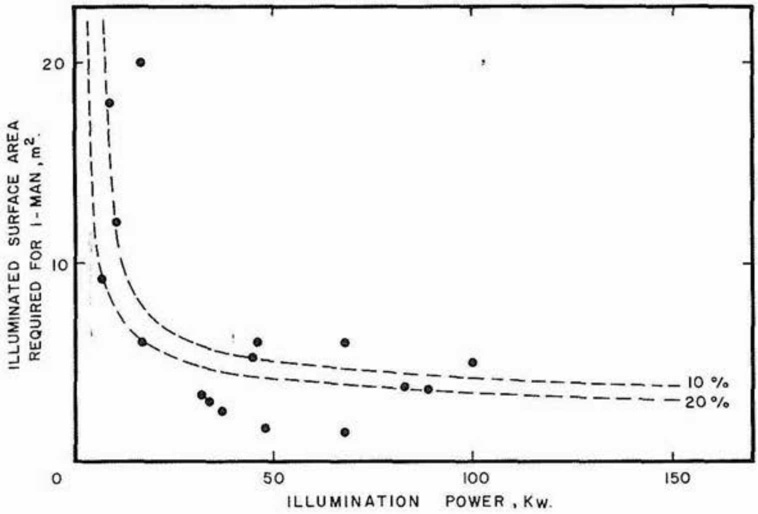

FIG. 5 - ILLUMINATED SURFACE AREA REQUIRED FOR ONE MAN SUPPORT (600 L. O_2 /DAY) AS A FUNCTION OF ILLUMINATION POWER.

DATA ARE FOR EXPERIMENTAL GAS EXCHANGERS. CURVES REPRESENT THEORETICAL PHOTOSYNTHETIC EFFICIENCIES USING LAMPS THAT ARE 10 AND 20 PERCENT EFFICIENT IN CONVERTING ELECTRICAL ENERGY TO VISIBLE LIGHT ENERGY (FROM MILLER AND WARD, 1966)

Photosynthetic gas exchange systems for space life support have been demonstrated to be feasible. Lack of electrical efficiency will severely restrict the use of algae for missions of short duration; however, weight, volume, and power flexibility may be of advantage for some space applications. Continued development is warranted since there is no other proven alternative.

Water and Waste Treatment. It is difficult to place the origin of work on treatment of sewage through use of algae. Gotaas, Oswald, and Golueke at The University of California at Berkeley have been the most productive in development of the concept. As previously mentioned, Oswald named and defined the general area known as controlled photosynthesis.

Historically, waste and water treatment have been improperly or incompletely accomplished or, if accomplished correctly, at considerable cost. The causes are undoubtedly manifold, not the least of which would be public as well as legislative apathy. That this is partially true is evidenced by our current national effort to generate concern over both air and water pollution.

Few enterprises as large as the control of wastes in water operate at a financial loss. It is my understanding that there is a limited market for the end products of processes currently used for partial renovation of contaminated water. The processes now in use have been expertly developed for the removal of settleable materials and organic compounds subject to microbial breakdown. The products then are unusable "two by fours" and sludge consisting of undissolved materials and microbial cells, both of which have little obvious commercial value. The above statements are appropriate only by way of introducing the rationale for a yet to be proven approach to water and waste management; no criticism of the field of environmental engineering is intended.

Current waste treatment processes can reduce the BOD of waters up to and above 95 per cent but do not satisfactorily remove mineral ions such as nitrates and phosphates. These minerals contribute significantly to eutrophication of streams and lakes, often resulting in troublesome and unsightly algal blooms. Settled sewage is known to be a satisfactory if not ideal medium for algal growth. However, the technique of using algal-bacterial interactions for high-rate sewage treatment appears to have had only marginal success. The technique as currently practiced extends the essential features of the familiar low-rate oxidation pond process. The sewage stabilizing capacity of oxidation ponds is primarily limited by availability of oxygen to support aerobic microbial action. Careful design and operation are required to prevent development of anaerobic conditions which can cause unpleasant odors.

The overall process for high-rate photosynthetic treatment of sewage is given in Figure 6. Organic matter in settled sewage is broken down into carbon dioxide and ammonia by aerobic microbial action. These products, along with other mineral ions, are assimilated by algae in the presence of light to form more algal cells and oxygen. The oxygen pro-

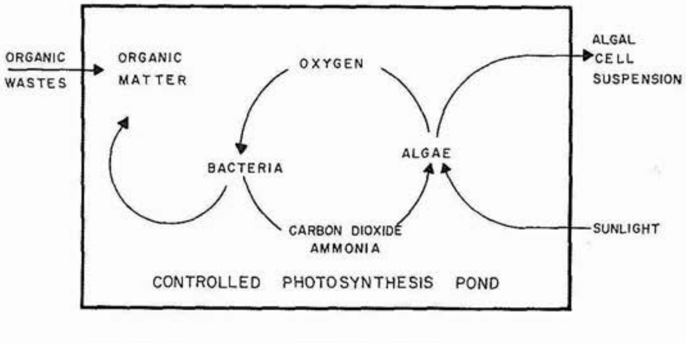

FIG. 6 - OVERALL CYCLE OF CONTROLLED PHOTOSYNTHESIS IN WASTE TREATMENT (FROM OSWALD, 1964)

duced controls the rate of organic matter digestion, which, in turn, regulates the supply of carbon dioxide and ammonia required for additional photosynthesis. The gross product is algal and bacterial cells suspended in water. Following removal of the algae the effluent water should be stable and incapable of producing another crop of algae. If the process works according to theory, waters receiving the effluent should not be contaminated.

How well does the process work? According to a recent report from the Sanitary Engineering Research Laboratory at Berkeley, the following values for per cent reduction of contaminants have been obtained through controlled photosynthesis treatment: BOD, 62-94; phosphate, 21-85; nitrogen, 55-93; calcium, 11-68; and magnesium, 15-56. The wide range in reported values is due to seasonal effects; however, advocates of this process feel that maximum rates can be obtained in areas having abundant sunlight.

Wide scale application of this process appears to be limited by economic considerations rather than questions of reliability. To obtain effective, high-rate treatment a dense population of algae must be produced. The algae should be considered a contaminant and removed from the effluent before it is released or reused. Release of large masses of algae into rivers and lakes would probably create greater problems than the normal treated sewage effluent. To obtain high algal growth rates, specially constructed shallow tanks with provisions for mixing are required. Oswald states that algal yields up to 30 tons per acre year and from 0.75 to 1.5 tons of algae per million gallons of waste can be produced with proper management. The primary limiting factors appear to be initial cost of installations, and algal harvesting and processing costs. Possibilities for greater application of controlled photosynthesis for waste treatment appear excellent provided low cost methods of harvesting algae can be developed. Dried algae has already been shown to be a potentially valuable livestock feed. Relatively high costs of operation may be justified if the process can be demonstrated to consistently yield water of high quality.

NOTE

1. This lecture was prepared while the writer was on temporary duty at Vandenberg Air Force Base in California. Since library facilities were not available, no references to the literature have been made in the text. However, the writer has drawn heavily from notes on published works, frequently without proper credit given, and offers below a general bibliography from which the majority of the material presented can be obtained:

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