Photosynthetic Reclamation of Organic Wastes

HAROLD B. GOTAAS, WILLIAM J. OSWALD,
HARVEY F. LUDWIG

Dr. Gotaas is professor of sanitary engineering and director of the Sanitary Engineering Research Laboratory of the University of California at Berkeley. He received his training at the University of South Dakota, Iowa State College, and Harvard University. During World War II, he served in a military capacity in Latin America with the Institute of Inter-American Affairs as chief engineer, director of health and sanitation, executive vice president, and finally president of the institute. Mr. Oswald is assistant research engineer and engineer in charge of the Algal Project of the Sanitary Engineering Research Laboratory, University of California, Richmond. After 5 years in the Army Medical Corps, he took degrees in civil and sanitary engineering at the University of California and has been continuously engaged in algal research since 1950. Mr. Ludwig is sanitary engineer director in the U. S. Public Health Service and is currently assigned as engineer consultant in the Office of Health Emergency Planning, Office of the Surgeon General. He previously taught at the University of California, where he was engaged in the research project on treatment of sewage through algal-bacterial symbiosis in 1950–51.

THE advent of water carriage as a method for transporting sewage permitted the easy removal of such organic wastes from man's immediate environment. As cities and industries have expanded, however, it has become increasingly difficult to carry out the ultimate disposal of this organic matter as necessary to protect the public health, maintain the quality of natural waters, and prevent nuisances.

Engineers have continually improved the efficiency of known methods of waste disposal and have given considerable attention to the development of more economical processes. Primary sedimentation followed by biological treatment involving aeration on a trickling filter or in an activated sludge tank, and by anaerobic digestion of the unoxidized organic solids, have in most instances provided effluents satisfactory for discharge into water courses. For economic reasons, common treatment methods have not been designed to recover any appreciable quantity of the approximately 5 million tons annually of organic and other nutrients contained in American domestic sewage. Sewage treatment, therefore, represents a loss of the energy and fertility values in sewage, besides involving the expenditure of considerable sums of money for treatment plant operation.

Conventional secondary sewage treatment on trickling filters or by the activated sludge process depends upon mechanical means to supply the oxygen necessary for bacteriological removal and stabilization of the organic material. For more than 25 years engineers have attempted to reduce the cost of providing this oxygen by using sewage oxidation ponds. These have customarily been designed to detain the sewage long enough to allow sufficient oxygen for stabilization of the organic matter to enter by slow diffusion from the atmosphere.

Algae are frequently observed near the outlet of oxidation ponds where the sewage is usually well oxidized, but there has been little information on their growth in such an environment, and until recently there was considerable difference of opinion on whether algae would grow in relatively strong sewage or polluted waters in sufficient numbers to provide significant amounts of oxygen.

The possibility that algae might supply oxygen to sewage less expensively or more efficiently than mechanical devices or diffusion can supply it from the atmosphere led the Sanitary Engineering Research Laboratory of the University of California to initiate studies designed to determine whether algae could be effectively grown in sewage and other organic wastes and to explore the basic factors influencing algal growths on such mediums. Some of these studies, previously reported by us (*1–4*), have shown that when proper environmental conditions are maintained, certain green algae will grow in large numbers simultaneously with bacteria in

fresh organic wastes or sewage. When such growth is taking place, biological oxidation and photosynthetic reduction proceed rapidly, each process aiding the other.

This report (5) deals primarily with pilot-plant experiments, designed to show whether, under practical outdoor conditions, algae can be grown in sewage simultaneously with bacteria, not only for purifying sewage, but also for harvesting the algae to reclaim a part of the enormous quantity of materials now being wasted. Laboratory-scale studies are included only to introduce some of the results obtained from the less rigidly controlled pilot-plant experiments.

Photosynthetic Oxygenation. The simultaneous growth of bacteria and algae in organic wastes such as sewage is illustrated in Fig. 1. The liquid wastes containing considerable amounts of organic matter, phosphorus, magnesium, and micronutrients are detained in a growth tank an optimum length of time for the organic material to be broken down by bacteria and the nutrients thus released assimilated into algal cell material. The bacteria normally present in sewage in large numbers (up to 1×10^8/ml or more) decompose some of the organic matter, releasing carbon dioxide, ammonia, and other algal growth essentials, before the sewage reaches the tank. This influent sewage is then seeded with algae by recirculating some of the tank effluent. In the presence of light, these algae flourish, producing the oxygen needed by aerobic bacteria, which, in continuing to stabilize the organic matter, make more carbon dioxide and ammonia available to the algae.

The relative amounts of materials utilized in different aspects of the process are suggested by the width of arrows in Fig. 1. Thus, it is seen that most of the organic matter undergoes bacterial decomposition, an unknown amount of the influent material is utilized directly in algal synthesis, and some inorganic compounds and humus pass unutilized into the effluent. The algal cell material produced may exceed the original organic content of the sewage. Some oxygen escapes to the atmosphere and some carbon dioxide enters the liquid from the atmosphere, particularly when the algae have produced a high *p*H in the liquid. Relatively large amounts of stable organic matter (that is, highly oxidized) and inorganic compounds are present in the effluent liquid.

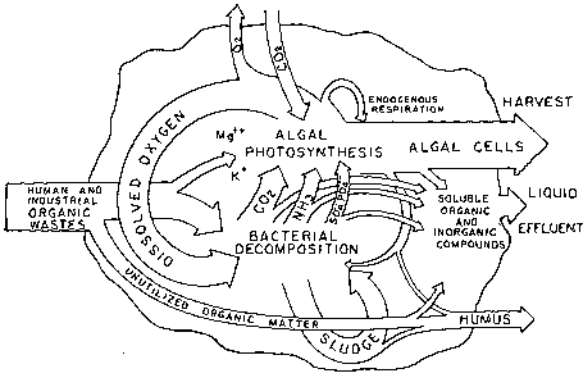

Fig. 1. Schematic diagram of the interaction of bacteria and algae in organic wastes.

For illustration, the basic reactions included in bacterial oxidation and photosynthetic reduction may be shown in the form:

$$\text{Organic matter and other nutrients in sewage} + \text{oxygen} \xrightarrow{\text{bacteria}} CO_2 + NH_3 + H_2O$$

$$\text{Green plants} + \text{light}$$

or represented by the reversible reaction:

$$CO_2 + H_2O \underset{\text{bacteria}}{\overset{\text{algae} + \text{light}}{\rightleftharpoons}} CH_2O + O_2.$$

These reactions take place simultaneously and represent the basic concept of the process. The reaction

$$CH_2O + O_2 \xrightarrow{\text{bacteria}} CO_2 + H_2O$$

represents in part the action of bacteria upon the dead organic matter (CH_2O) in the sewage. Assuming an adequate and diverse bacterial flora, the amount of substrate oxidation depends on the concentration of substrate and the availability of oxygen. Since oxygen from the atmosphere is very limited because of its low solubility, oxygen must be produced by the algae at a high enough rate and in sufficient amounts to permit rapid oxidation by bacteria of the organic material in the sewage substrate.

In the simplified photosynthetic equation

$$CO_2 + H_2O \xrightarrow{\text{algae} + \text{light}} (CH_2O) + O_2,$$

the opposite of bacterial oxidation, the CH_2O represents living algal cells. The algae liberate oxygen to act as the hydrogen acceptor for continued bacterial oxidation. The action of light upon the chloroplastic tissue of the algal cells drives this reaction. The rate is determined by the growth of algal cells, which will depend principally upon the availability of CO_2 and the amount of light. Carbon dioxide is frequently the limiting factor in sewage, and algae

may then obtain carbon by reducing the alkalinity, thus producing a substrate of high *p*H.

The requirements of the process for cultivating algae in waste organic liquids differ considerably from those for growing algae in an inorganic substrate to which carbon dioxide is fed (*6, 7*). Some of the major differences are as follows. (i) The food concentration and volume of substrate can be controlled when inorganic chemicals are used but will be variable for sewage. (ii) The liquid effluent from inorganic substrates can be reused in the process. In the case of sewage, however, large volumes must be handled and the liquid effluent must be continuously and satisfactorily discharged into a natural water course without creating a nuisance or public health problem. (iii) Sterile cultures are preferred in the inorganic process, whereas bacteria present in large numbers in the sewage substrate are necessary for growing algae on sewage. (iv) A greater degree of algal species control can be exercised when an inorganic chemical substrate is used than when a sewage substrate is used. (v) The bacteria actively decompose organic matter either in light or darkness; hence, the algae must supply enough oxygen to maintain aerobic conditions during the period of darkness. (vi) The operating time for harvesting algae can be controlled in the inorganic chemicals processes, but removal of algae must be practically continuous when sewage is used as a substrate. (vii) There may be plant growth nutrients in sewage that would be difficult and costly to supply to the inorganic substrate.

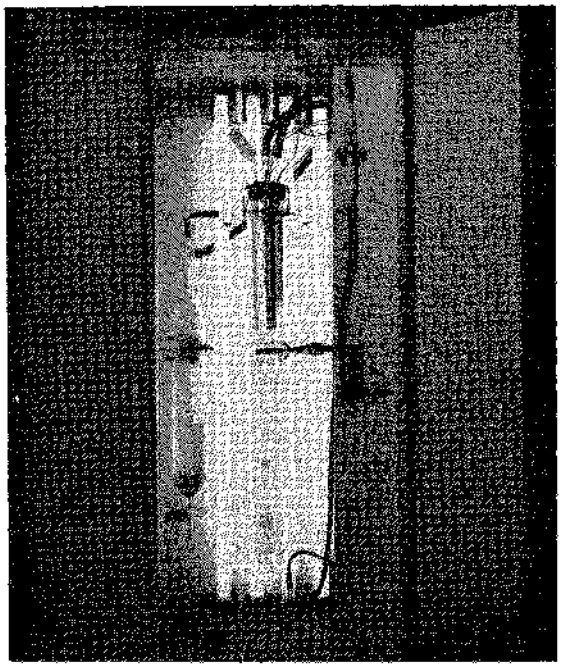

Fig. 2. Automatic continuous-growth unit used in laboratory experiments.

Laboratory experiments. Laboratory studies pertaining to growth characteristics of pure cultures of *Euglena gracilis, Chlorella pyrenoidosa, Scenedesmus obliquus, Chlamydomonas algloeformis* in a substrate of sewage that had been sterilized and inoculated with sewage bacteria were conducted in 1-lit continuous-growth units with fluorescent lighting similar to the units shown in Fig. 2 (*8*). The same organisms were grown in sewage, milk wastes, animal manures, and cannery wastes in nonsterile 50-ml batch cultures. *Euglena gracilis* has been the species studied most extensively, because it has a slower regeneration rate and, hence, smaller amounts of sterilized constant strength sewage, which is difficult to prepare and maintain, are required. Five factors—substrate strength (organic materials and other nutrients); detention period; light (intensity, periodicity, and intermittency); gas exchange in closed units; and temperature—have been investigated for *E. gracilis.* Individual tests have been made with other organisms in order to check or correlate their growth with *E. gracilis.*

Pilot-plant experiments. To translate the laboratory data obtained with fluorescent lighting and sterilized wastes inoculated with sewage bacteria to plant operation with natural lighting and normal variable quality sewage, a continuous-flow pilot-plant growth tank was used. This tank is 80 ft long, 3 ft (average) wide, and 3.5 ft deep. The 3.5-ft depth was selected because it has been the usual practice to build oxidation ponds at least 3 ft deep. This tank is shown in Fig. 3, along with a wider and shallower tank that has more recently been put into service. Both tanks are equipped with automatic devices to control rate of sewage inflow, liquid depth, and rate of recirculation of effluent to seed the incoming sewage. The effluent may be pumped to a centrifuge for harvesting the algal cells on an experimental scale. Normal outdoor lighting is used. Under this condition the only factors that are controllable are the detention period, depth of sewage in the tanks, which affects the light available to the algae, and the rate of recirculation of effluent for seeding.

The detention period, or time the liquid is held in the continuous-flow growth tanks, may be defined as $D = \frac{V}{v}$, where D is the detention period expressed in days, V is the volume of the culture, and

Fig. 3. Continuous-flow growth tanks used in pilot-plant experiments.

v is the daily feed or withdrawal volume. Four different detention periods were studied for each of three different depths—2, 6, and 12 in.—as is shown in the operational schedule, Table 1.

The tanks are oriented in a north and south direction; hence, the time that the water surface at shallow depths receives direct sunlight each day is approximately the same in all seasons, although the light intensity increases and decreases from the solstices. The experiments with a 2-in. depth in the pond were begun on 10 June 1953 and extended until 27 July. Hence, they were made in the period of maximum annual light intensity. This study was followed consecutively by other studies of equal duration at the 6-in. and 12-in. depths, which continued until 19 October 1953. Thus, in judging the results, it is necessary to bear in mind that the experiments at the two greatest depths were made in a period of decreasing light intensity.

The total daily visible light was determined by a pyroheliometer which continuously records the total solar energy as British thermal units per square foot. One-half of the area under the recorded curve provides the approximate total visible light energy per day. Light intensity was also measured daily with a Weston light meter calibrated in standard foot-candles. Since, when the sun was shining, the 3.5-ft high sides of the tank shaded the substrate surface in the early morning and late afternoon, it was necessary to determine by tests how much light energy was received by the cultures. It was found that approximately 0.6 of the total daily visible light determined from the pyroheliometer was available to the substrate surface.

Ambient temperatures were recorded continuously, and temperatures of the liquid were observed twice daily.

Chemical determinations. The chemical character of the influent sewage, of the algae, and of the effluent after the removal of the algal cells, was determined. "Biochemical Oxygen Demand" (BOD) (*9*) was used as an index of the organic-matter content of the sewage because it is a widely used mass bioassay method for determining the strength of sewage or its organic nutritional character for bacterial growth (*10*). Values were reported for 5-day incubation at 25° C. The volatile solids determination was used to ascertain the total amount of organic matter.

Spectrographic and standard methods were used for the determination of organic and inorganic ni-

Table 1. Operational schedule for pilot-plant experiments.

Date started	Series	Run	Pond depth (in.)	Pond volume (gal)	Nominal detention period (days)	Daily influent or effluent volume (gal)	Recirculation rate (gal/hr)
6/10	I	1	2	251	2.5	101	10
6/23	I	2	2	251	0.75	335	24.5
7/3	I	3	2	251	1.25	200	16.6
7/14	I	4	2	251	5.0	50	4.2
7/28	II	1	6	756	5	151	12.6
8/7	II	2	6	756	3	252	21
8/20	II	3	6	756	2	378	32.3
8/28	II	4	6	756	1	756	63
9/9	III	1	12	1566	7	224	18.6
9/19	III	2	12	1566	5	313	26.0
9/30	III	3	12	1566	3	522	43.6
10/12*	III	4	12	1566	1.5	1044	88.0

* Completed 19 Oct. 1953.

trogen, phosphorus, sulfur, calcium, magnesium, potassium, sodium, iron, manganese, boron, zinc, alkalinity, and *p*H. Carbon and hydrogen in the sewage and algal cells were measured by a standard carbon and hydrogen train apparatus. The chlorophyll content of the algae was determined by the method of Mackinney (*11*).

Nutrient quality of sewage. Very little data are available concerning the exact organic composition of sewage. Considerable data on the elementary analysis of sewage have been accumulated in these studies, but they provide little information on the actual organic compounds present. Sewage contains a wide variety of organic materials, together with considerable quantities of calcium, magnesium, sodium, potassium, phosphorus, and traces of most of the elements found in foods. Table 2 shows an elementary analysis of sewage compared with standard inorganic culture medium. It is seen that chemical quality of the two substrates differ considerably.

Figure 4 shows the yield of *E. gracilis* with batch and continuous cultures in sewage of different 5-day, 25°C BOD values. The batch culture shows that with a 7-day detention period the yield of algae

Table 2. Comparative composition of a settled sewage and a synthetic medium for algal growth.

Element	Composition of medium in ppm of indicated element	
	Standard pilot plant*	Settled Richmond sewage†
C	‡	176§
N	346‖	50#
P	248	11
S	335	19
K	1330	14
Mg	248	22
Na	5.5	62
Ca	15.0	17
Fe	0.15	<1.0
B	.5	<0.5
Mn	.5	.2
Zn	.05	Trace
Cu	.02	<0.05
Mo	.01	Trace
BOD		212

* From "Pilot Plant Studies in the Production of *Chlorella*" (7).

† Mean values from 10 or more analyses. The coefficient of variation is less than 20 percent when samples are collected at approximately the same time each day.

‡ Carbon supplied from 5 percent CO_2 in air.

§ Including organic carbon and carbon contained in alkalinity.

‖ Nitrate nitrogen.

Including 13 ppm organic N, 37 ppm ammonia N, and traces of nitrate N.

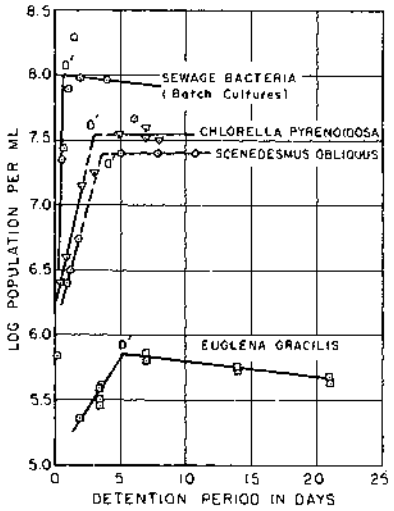

Fig. 4. Effect of detention period on equilibrium populations of sewage bacteria and various species of algae.

increased directly with BOD up to a value of about 300 ppm. Thereafter a slight decrease occurred. The continuous culture shows a higher yield than the batch culture without any evidence of reaching a maximum. These and other data for algal growth on milk wastes, animal manure, and abattoir wastes indicate that the yield of algae is about proportional to the strength of the waste if other nutrients are not limiting. Carbon has usually been found to be the limiting element. It is possible that at times phosphorus might become limiting, particularly at long detention periods when considerable phosphorus may become bound up in bacterial and algal cells. When the vigorously growing algae have raised the *p*H to 10, some of the phosphorus may be precipitated, hence limiting that available to the algae.

Comparative yields for *C. pyrenoidosa* and *S. obliquus* in the same substrates for similar conditions have invariably been larger than for *E. gracilis*.

Table 3 shows the comparative composition of fresh-water and sewage-grown algae. The mean values for the quantities of different elements in sewage-grown algae are similar to those of fresh-water algae, except that the percentage of carbon in the sewage-grown algae is below the range for fresh-water algae. This may be due to the fact that carbon is usually a limiting element in sewage.

If the usual method of multiplying the nitrogen content by 6.25 to estimate the protein is applied, it is seen that algae grown in sewage average 55 percent protein.

Detention period. The effect of varying the de-

tention period (D) on the cell population of different species of algae under laboratory conditions is shown in Fig. 4. The critical detention period (D') at which the maximum equilibrium population occurs differs with the species, being shortest for the smallest organisms studied. In previous reports (*2, 4*), it was shown that for the condition D greater than D' the algal cells are old, grow slowly, and hence produce little more or even less oxygen than they use in respiration. When D is less than D' algal growth is in the logarithmic phase, and oxygen is produced in excess of the needs of all organisms in the system.

The detention period (D') for maximum population does not coincide with the detention period (D'') for maximum yield of photosynthate. Figure 5, based on previous laboratory studies of *E. gracilis* and *C. pyrenoidosa,* shows that D'' is less than D' for maximum yield of dry cell material. For periods shorter than D'' the yield decreases rapidly because the cells do not multiply as fast as they are removed from the system. A minimum detention period at which an equilibrium reproduction rate can be maintained is thus imposed by the regeneration time of the species, and a practical lower limit is set on the economy of growing algae in growth tanks on a continuous basis.

Since bacteria multiply more rapidly than algae, their regeneration time does not limit the detention period. The BOD that they exert during the detention period, however, must be satisfied by oxygen

Table 3. Comparative composition of fresh-water and sewage-grown algae.

Element	Percentage of total dry weight in	
	Fresh-water algae	Sewage-grown algae
Carbon	49.51–70.17*	44.9†
Oxygen	17.40–33.20*	25.7†
Hydrogen	6.57–10.20*	7.69†
Nitrogen	1.39–10.98*	8.92†
Sulfur	0.91‡	1.11§
Phosphorus	0.94– 1.51‖	1.00§
Calcium	0.00– 1.55‖	1.2#
Magnesium	0.26– 1.51‖	0.35#
Manganese		.001#

* Spoehr and Milner as reported by Kraus (*12*).

† Mean values based on 10 or more analyses of algae in pilot plant; coefficient of variation less than 10 percent.

‡ Kraus (*12*).

§ Mean values based on 10 or more analyses of algae in pilot plant; coefficient of variation approximately 60 percent.

‖ Scott as reported by Kraus (*12*).

Mean of five analyses from laboratory cultures of *E. gracilis*.

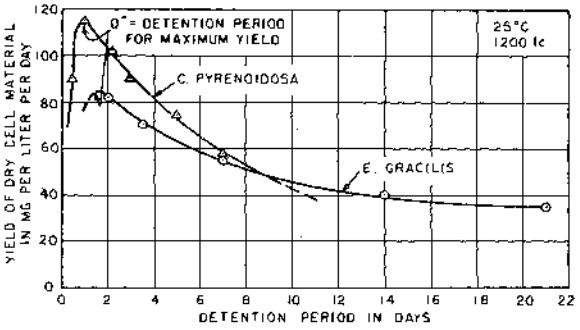

Fig. 5. Laboratory yields of algal cell material grown in sewage at various detention periods.

made available by the algae. If a high degree of sewage treatment is to be accomplished, excess oxygen is required and the detention period should approach D', even though a greater yield of algae might be obtained at D''.

In the outdoor pilot-plant studies the relation of detention period to cell population of different species was not determined because artificial control of species is impossible. A growth tank inoculated with 20 gal of *E. gracilis* culture was rapidly overgrown by *Chlamydomonas,* which in turn soon gave way to *Chlorella* and *Scenedesmus*. These latter two organisms were numerically dominant in the experiments summarized in Table 4. These data show the *Chlorella* population increasing with detention period and decreasing with tank depth, while the *Scenedesmus* population increased with both detention and depth. *Chlamydomonas* and *Euglena* were endemic in the culture but were unable to compete with the more rapidly growing species. At longer detention periods such as 7 days at the 12-in. depth (Table 4) *Euglena* increased until the mass of its cell material was as great as that of other species in spite of its numerically small population.

Figure 6 shows the relationship between detention period and average daily yield of algae at different tank depths. The dispersion of the curves may be exaggerated somewhat because sludge settled to the bottom of the tank at the 6- and 12-in. depths, leaving the algae in an impoverished liquid medium, whereas at the 2-in. depth there was little opportunity for food stratification or anaerobic bacterial decomposition of the settled sludge, since it remained in the light and, hence, was subject to photosynthetic oxygenation.

The variation in chlorophyll content of the cell material with detention period for various tank depths is shown in Fig. 7. At the 2- and 6-in. depths the chlorophyll content increased to a maximum,

Table 4. Algal counts, total and by genera at various depths and detention periods.

Depth (in.)	Detention period (days)	Total count (cells/ml × 10^{-6})	Algal population by species (cells/ml × 10^{-6})			
			Chlorella sp.	*Scenedesmus* sp.	*Chlamydomonas* sp.	*Euglena* sp.
2	0.75	4.06	3.54	0.40	0.12	
	1.25	3.00	1.68	1.11	.21	
	2.50	15.10	14.60	.46	.10	0.01
	5.00	4.99	3.80	.96	.14	.04
6	0.92	1.56	0.52	1.04		
	2.10	2.62	1.34	1.28		
	3.10	4.80	0.90	3.90		
	5.15	8.62	3.80	4.62	.20	
12	1.50	1.72	0.98	0.49	.20	.01
	3.00	1.82	1.08	.72	.02	
	4.90	3.64	1.60	1.92	.06	.06
	7.18	3.58	1.32	1.66	.30	.30

then dropped off, probably owing to a combination of photo-destruction of chlorophyll and decrease in nutrients as detention period increased beyond a critical point. This is consistent with the results of laboratory experiments (*3*) using pure cultures of *C. pyrenoidosa* at constant light intensity. The continued increase, instead of a decrease, of chlorophyll at the 12-in. depth as the detention period increased was probably due in part to light limitations. Inasmuch as the 12-in. study was the last of the series it was made in September and October, when the amount of light is diminished. It is difficult to correlate the yield shown in Fig. 6 for the 12-in. depth and 1.5-day detention with the small amount of chlorophyll contained by the cells grown under these same conditions, as is shown in Fig. 7. There is evidence, however, that at detention periods less than 2 days bacterial cell material may contribute an appreciable part of the apparent yield of algal cell material.

Observations to determine the effect of detention period on BOD removal were made both in the laboratory and in the growth tanks. In the laboratory BOD removal was not significantly affected by detention period except at very high BOD loadings corresponding to extremely short detention periods. Under these conditions photosynthetic oxygenation is limited. Pilot-plant results shown in Fig. 8 indicate, however, that at the greater depths there may be an optimum detention period for maximum BOD removal. Maximum removal at the 2-in. depth occurred at the shortest detention period studied, but for greater depths larger detention periods were required, probably because light became limiting.

Light, depth, and energy conversion. Laboratory studies have been previously reported (*4*) on the effect of varying light intensity in growing *E. gracilis* at 25°C under a 7-day detention period in a sewage that had been sterilized and inoculated with sewage bacteria. The findings included the observation that maximum algal population and maximum dry weight yield of cells occurred at light intensities between 400 and 1200 ft-ca. Chlorophyll per cell was greatest for light intensities less than 400 ft-ca and decreased rapidly to low amounts at intensities above 800 ft-ca. Since cultures were developed under unilateral illumination, and *E. gracilis* has an elongated shape such that when it is pointed toward or away from the light source only a small portion of the cell receives light, these values would seem to be consistent with the values near 400 ft-ca suggested by Myers (*13, 14*) as representing the saturation intensity for single *Chlorella* cells—that is—the intensity above which no further benefit is evident.

The apparent photosynthetic efficiency in pilot-plant investigations was calculated by dividing the light energy incident to a unit volume of culture, as measured by the pyroheliometer, by the energy bound up in the algal cells grown per unit volume. Shading of the substrate surface by the high side walls of the tank excluded about 40 percent of the total daily light energy. The available portion of the remainder averaged 103, 82, and 58 cal/cm^2 per day for the 2-, 6-, and 12-in. depths, respectively. The energy content of the algal cells was determined by standard calorimetric methods.

Figure 9 shows the average apparent photosynthetic efficiency in relation to detention period for different depths. Each of the plotted points represents from 4 to 7 determinations of the dry weight of algae. It is possible that the high apparent photosynthetic efficiency at the shortest detention periods may be deceptive because of direct assimilation of

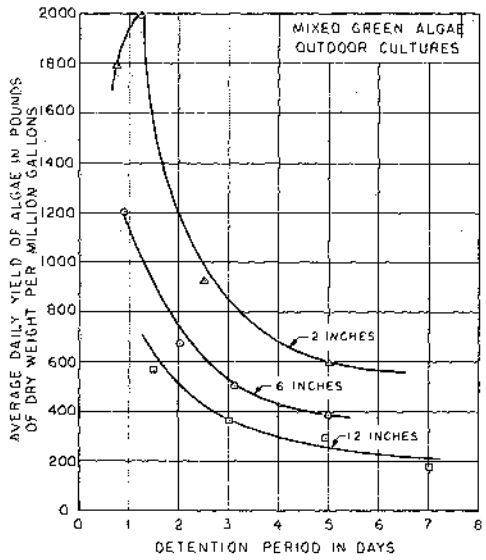

Fig. 6. Average daily pilot-plant yields of algae as affected by detention period and depth.

organic nutrients from the sewage by the algae as well as by the bacteria. A replot of the data of Fig. 9 in relation to depth is shown in Fig. 10, which illustrates that the efficiency of solar-energy utilization increases with depth.

The yields of algae shown in Fig. 6 for 2-, 6-, and 12-in. depths and different detention periods are converted to energy yields and shown in Fig. 11 for detention periods of 2, 3, 4, and 5 days. The energy yield in the form of algae per cubic foot of sewage is greatest for the shortest detention period and the shallowest depth. The algal cell energy yield decreases rapidly with both increasing depth and detention. Comparing Figs. 10 and 11, it is seen that maximum photosynthetic efficiency occurs at greatest depth, and maximum energy yield occurs

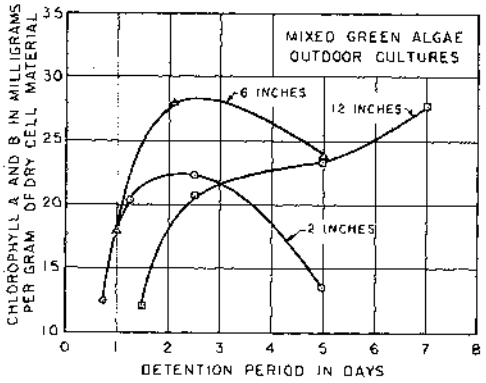

Fig. 7. Effect of depth and detention period on algal chlorophyll content.

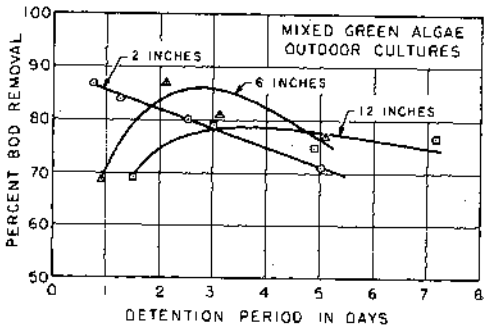

Fig. 8. Effect of depth and detention period on BOD removal.

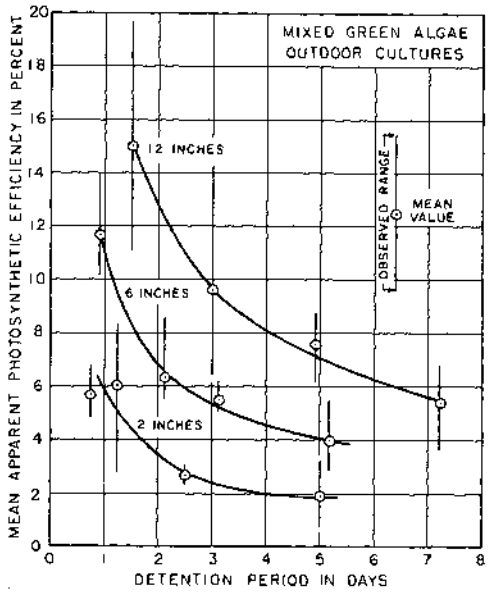

Fig. 9. Mean apparent photosynthetic efficiency at various detention periods for constant depths.

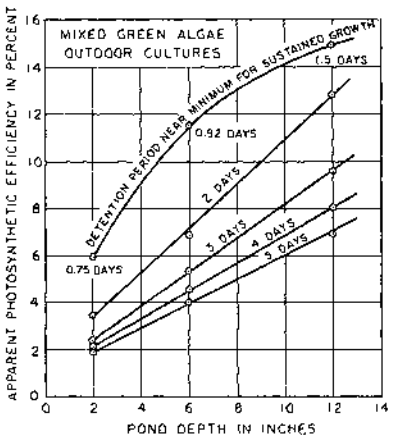

Fig. 10. Apparent photosynthetic efficiency at various depths for constant detention periods.

at minimum depth. Thus, maximum efficiency in utilization of light is obtained at sacrifice of efficiency in utilization of nutrients, and vice versa. For maximum sewage treatment where the object is efficient utilization of nutrients, therefore, light should not be limiting.

Yield of algae. The algal yields in sewage on an acre basis are quite high compared with normal crop yields of plants on agricultural land. Figure 12 shows the yield in tons per acre per year for 2-, 6-, and 12-in. depths and varying detention periods. For the shortest detention periods at the 6- and 12-in. depths, the respective yields are 35.6 and 33.6 tons/acre per year. The maximum yield at the 2-in. depth is 22.5 tons/acre per year, which is considerably below that for the two greater depths. It is believed that if a detention of about 1 day instead of 0.75 day at the 2-in. depth had been used, the maximum yield might have been considerably higher.

The yield of algae per unit area increases directly with the loading of organic matter per unit area until light becomes limiting. At the 6- and 12-in. depths the rate yields were approximately 15 tons/acre per year for a BOD loading of 100 lb/acre per day, and 35 tons/acre per year for the maximum loading investigated of 420 lb/acre per day. The high yields and loadings were near the upper limit for light and detention time in the experiment, but the degree of sewage treatment accomplished was reduced.

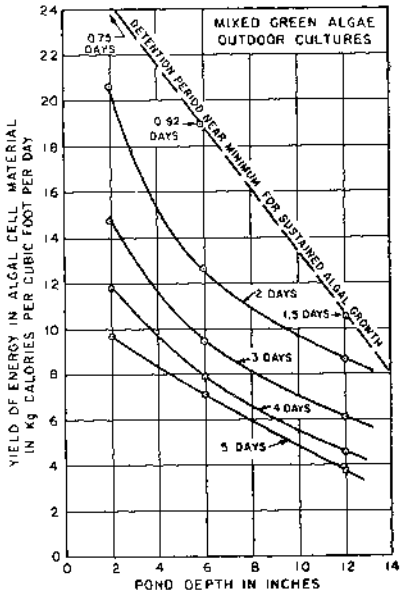

Fig. 11. Yield of energy in algal cell material as a function of depth for various detention periods.

If the yield per acre per year is analyzed in terms of loading in pounds of BOD per acre per day, it will be seen that the yield increases with loading until the light becomes limiting and the algae do not increase sufficiently to provide the oxygen required to keep the culture aerobic.

There is evidence that yields can be improved by keeping the substrate sufficiently turbulent to prevent flocculent particles of organic food material from settling to the bottom of the tank. This would keep the bacteria and nutrients in close contact with the algae and prevent anaerobic decomposition with its release of methane, which is not a source of carbon for algae. Also, greater agitation may improve the light utilization by the algae, as concluded by Kok (*15*) in his studies of light intermittency through turbulence.

Harvesting of algae. In the experimental investigation, centrifuging has been used for harvesting the algae needed for the various studies. Present centrifuge equipment does not appear to be satisfactory from an economic standpoint for separating the algae from the large volumes of liquid used in growing algae in sewage. In laboratory experiments, algae have been readily precipitated with alum as a coagulant, forming an aluminum hydroxide-algal floc. Studies are in progress to determine the feasibility of separating and recovering the aluminum floc. Since the alum dosage required is relatively large, this is desirable both because the mixture would have decreased nutritive value, and because the recovered aluminum could be reused. It is also possible that some flotation process might permit separation of the algae from the water to an extent such that spray drying might be accomplished.

Discussion. The information reported here, together with other laboratory data, shows that algae will grow abundantly in sewage, utilizing nutrients made available by aerobic bacteria which oxidize the organic matter in sewage. Furthermore, this algal growth will supply sufficient oxygen for the bacteria and will produce large yields of cell material high in protein content. It is evident, therefore, that sewage may have important possibilities as a low-cost nutrient for industrialized photosynthesis. Assuming that algal cells can be economically separated from the liquid, the growing of algae in sewage would provide adequate sewage treatment while reclaiming a large part of the organic material contained in such a waste. The process, however, loses much of its value as a method of sewage treatment if the algal cells are not removed. Presumably, effluent containing large numbers of such cells could be emptied into some watercourses

where the rheological environment is such that the cells will continue to live until reaching the ocean, but in general the practice would be impractical. In some rivers, and in lakes or ponds, the load of decomposing organic matter occasioned by the death of algae might place an excessive burden on the oxygen resources of the water. The situation is made particularly acute by the fact that there may be more organic matter in algal cells than was in the original sewage.

The exact amount of algal cell material that can be produced on sewage or other wastes depends upon a number of factors, including the average strength of wastes, amount of light available, the temperature of the waste, and the depth and detention period in the growth units. Present information indicates that growth units designed for from 1.5- to 3-day detention periods, depending on the season of the year, can be operated satisfactorily for the purpose of converting organic and other nutrients into algal cell material. Evidently depths should be quite shallow, probably from 6 to 12 in. in winter in moderate climates, and from 12 to 18 in. or possibly deeper in summer. The most economical detention period and depth would be related to land values as well as to conditions for optimum algal production.

To what extent algae could be grown in sewage during the winter in cold climates is not known, although it seems certain that growth would be small where growth units were subject to freezing. It is known that climatic conditions would permit year-round growing of algae on the Pacific Coast and in the southern half of the United States, and it is believed that algae could be grown in sewage during 6 months of the year in most other sections of the country.

The value of algal cell material is an important item in evaluating the process of treating sewage by growing and harvesting algae. At the present time the degree of sewage treatment necessary to produce an effluent of the quality obtainable by growing and harvesting algae costs from 25 to 60 dollars per million gallons of sewage. It is estimated that algal cell material might be worth approximately 2 dol/ton per percentage unit of protein as a protein supplement for animal feed. At 50 percent protein, this amounts to 100 dol/ton. If, as it now seems possible, from ¾ to 1 ton of algae can be produced per million gallons of sewage under good operating conditions, there would be around 150 dollars per million gallons to pay for treating the sewage and marketing the algal product. It is estimated that growth units could be built for much less than other sewage treatment facilities, the major problem then being the development of an economical method for removing the algae from the liquid.

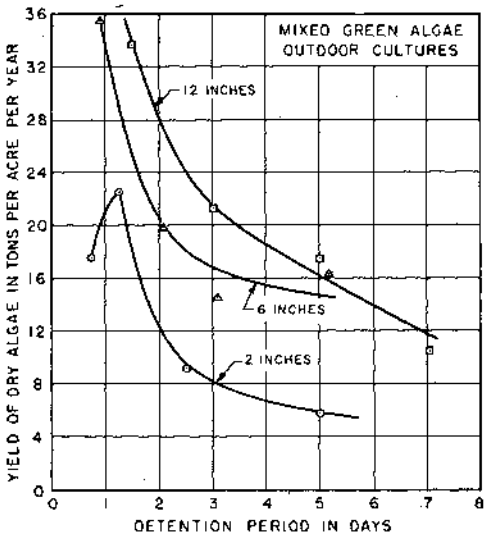

Fig. 12. Yield of algae per acre of land area as a function of detention period for various depths.

Estimates (*16*) indicate that the total annual land photosynthate in the United States has an energy content of about 15×10^{12} kw hr. Of this 2.32×10^{12} kw hr is processed for all purposes, including 1.25×10^{12} kw hr processed for food production. Of that processed for food only 0.13×10^{12} kw hr is actually consumed. About 0.06×10^{12} kw hr is disposed of as domestic sewage, although this quantity is increasing as the growing use of garbage grinders has the effect of transferring greater amounts of food wastes from the refuse can to the sewer. In addition, the amount of organic matter in industrial processing wastes probably approaches that of human wastes. The foregoing values in terms of energy do not represent the total energy content. By utilizing the fertility value of these organic materials as substrate for algal growth, much additional organic matter is created by photosynthesis. Moreover, this organic matter has a greater energy content per unit of weight than had the waste organic materials. Thus, the resultant material has a total fixed energy content much greater than the original waste from which it was produced. One indication of the fertility of the material discharged in American domestic sewage each year is its content of fixed nitrogen and phosphorus. This amounts to some 2.3×10^9 lb of nitrogen worth about a quarter of a billion dollars, and perhaps one-quarter as much phosphorus annually.

In the vicinity of metropolitan areas land suitable for sewage reclamation by algal culture may impose economic limitations on the process. It is possible

that algal growth units could be developed on waste land such as tidal flats or swamp areas. However, since potential yields of algae are from 10 to 20 times those now obtained from cultivated land, it may not be difficult to justify the use of rather expensive land for this process.

Sewage and organic industrial wastes represent a source of valuable raw materials, the quantity of which will increase in parallel with the growth of the earth's population. In a world that is poor in proteins, with untold millions of undernourished people and declining fixed energy sources, it would seem that the reclamation of organic wastes by algal culture has a hopeful future.

References and Notes

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5. This article is based on a paper read in the symposium on *Uses of Large-Scale Algal Cultures* arranged by Barry Commoner and presented in a joint session of AAAS Section G and the New England Section of the American Society of Plant Physiologists, Boston, 29 Dec. 1953. Other papers on this same general subject will appear in subsequent issues. The study reported in this article was aided by a grant from the National Institutes of Health, U. S. Public Health Service, together with funds provided by the University of California. The authors express their gratitude to P. H. McGauhey, Edwin W. Lee, Richard Hee, Carol Lopas, Jerome F. Thomas, Gerhard Klein, and M. B. Allen for their generous assistance.
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Transition

O, insatiate breast of
Mother Earth,
Giver of life in myriad forms,
Receive with infinite care
This part of him
We knew as father—friend
To all thy children.
This part of him transmute
In your magic crucible,
Returning him to us
In sunset, flower, tree
And cloud.
The rest of him
Will rest with us
Forever undistilled.

CHARLES W. COLLINS