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Biochemical and Photosynthetic Aspects of Energy Production

Edited by

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Preface

All Americans have to be concerned, individually and collectively, with the energy future of the United States. Economically, continually escalating oil prices have had, and will continue to have, very painful effects. We must, therefore, explore all possibilities for conservation and alternatives to heretofore accepted conventional energy resources.

Photosynthesis is the only method of solar energy conversion presently practiced on a large scale. This biological process supplies all our food energy as well as fiber and wood. Further, the reserves of fossil fuels, on which we depend for most other energy requirements, are the products of photosynthetic conversion of solar energy accumulated over geologic time. Unfortunately, we are now faced with the realization that these resources are finite.

This volume is an initial attempt to describe and evaluate biological processes that may serve in the future to provide alternative energy resources, e.g., biomass for fuels and chemicals production. Clearly, the enormity of the energy problem and the complexity of biological systems preclude complete coverage in a single volume. Many biological processes offer the potential for great benefit to mankind; realization of this benefit requires acquisition of new information. It is hoped that this volume will be a stimulus to acquire this new knowledge with minimum delay.

Anthony San Pietro

1

Biological and Agricultural Systems: An Overview

David O. Hall

I. Introduction*

Solar energy conversion through biology, that is, photosynthesis, supplies us with practically all our food, fuel, and fiber. These products are derived from present-day photosynthesis, or indirectly from fossil fuels, which themselves are products of past photosynthesis and of course are not renewable. A better understanding of the mechanisms and possible uses of photosynthesis should enable us to realize its maximum potential in the future. One of the problems in persuading

*See refs. 1–17.

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people to take this research more seriously is that its relative simplicity, compared to other types of energy research and development, belies its credibility.

Photosynthesis is the conversion of solar energy into fixed energy: $CO_2 + H_2O \rightarrow$ organic material $+ O_2$. The products of photosynthesis represent *stored energy*. Photosynthetic conversion efficiencies of 0.5 to 3% thus represent the efficiency of the total process: sunlight → fixed chemical energy. By contrast, for example, photovoltaic conversion efficiencies of 12–15% represent the process: sunlight → electric power, without including any energy storage.

Only 50 or so years ago, CO_2 fixed in photosynthesis would have been used as food, fuel, and fiber. However, with abundant oil the products of present-day photosynthesis are mainly used as food. We should reexamine and, if possible, reemploy the previous systems; but, with today's increased population and standard of living, we cannot revert to old technologies but must develop new means of utilizing present-day photosynthetic systems more efficiently.

We will deal briefly with a number of ways in which solar/biological systems could be realized to varying degrees over the short and long term. Some, such as the utilization of biological and agricultural wastes, energy farming, and the use of leaf protein, could be put into practice immediately, whereas others may never become practicable. Plant systems are diverse and adaptable; hence photobiological systems can be tailored to suit an individual country, taking into consideration energy availability, local food and fiber production, ecological aspects, and climate and land use. In all cases the total energy input (other than sunlight) into any biological system should be compared with the energy output and also with the energy consumed in the construction of any other energy-producing system.

In more temperate climates, there is still a large potential for the utilization of ever-abundant solar energy—even recognizing land use constraints resulting from high population densities and intensive agriculture. For example, Europe should not feel that it does not have sufficient solar energy—the difference in total annual solar radiation between the United Kingdom (105 W/m^2; continuous) and Australia (200 W/m^2) or the United States (185 W/m^2) is only a factor of 2. The difference between the United Kingdom and the Red Sea area (the area with the greatest amount of solar energy in the world—300 W/m^2) is only a factor of 3. Whatever solar energy systems are developed, these could provide viable alternatives to other types of energy production in the next century.

II. Impending Liquid Fuel Problem*

Numerous reports are emerging that predict shortages and/or large price increases in oil within the next 5 to 15 years. Biological fixation of CO_2 into

*See refs. 18–20.

chemical products is the only known way of renewably providing organic compounds. Until chemists can emulate the plant's ability to capture and store carbon from the atmosphere, we may have to rely on plant systems to do this. It seems prudent to look at photosynthesis seriously, in order to have a practical option available if it becomes necessary as a long term alternative (or coproducer) to coal and nuclear energy.

III. Energy Available from Photosynthesis*

Utilization of the annual total radiation by the earth's plant life is only about 0.1% (see Fig. 1). Only about 0.5% of the fixed carbon is consumed as nutrient energy by the earth's 4×10^9 people. This production of fixed carbon is, however, ten times the present world consumption of energy. Thus the scope for increasing the total utilization and for using photosynthesis in other ways is enormous—to decrease post-harvest deterioration, and so on.

IV. Efficiency of Photosynthesis†

Plants use radiation between 400 and 700 nm, the so-called photosynthetically active radiation (PAR). This PAR comprises about 50% of the total sunlight, which on the earth's surface has an intensity of about 800–1000 W/m^2 (5–6 J cm^{-2} min^{-1}; equivalent to 10^{-2} cal cm^{-2} sec^{-1} or 42×10^4 ergs cm^{-2} sec^{-1} for PAR).

The overall practical maximum efficiency of photosynthetic energy conversion is approximately 5–6% (Table I), and is derived from our knowledge of the process of CO_2 fixation and the physiological and physical losses involved. Fixed CO_2 in the form of carbohydrate has an energy content of 0.47 MJ/mole of CO_2, and the energy of a mole quantum of red light at 680 nm (the least energetic light able to perform photosynthesis efficiently) is 0.176 MJ. Thus the minimum of mole quanta of red light required to fix one mole of CO_2 is $0.47/0.176 = 2.7$. However, since at least eight quanta of light are required to transfer the four electrons from water to fix one CO_2 (Fig. 2), the theoretical CO_2 fixation efficiency of light is $2.7/8 = 33\%$. This is for red light, and obviously will be correspondingly less for white light. Under optimum field conditions, values of between 3 and 5% conversion are achieved by plants. However, these values are

*See refs. 5, 9, and 10.

†See refs. 5, 9, 10, 14, and 21–29.

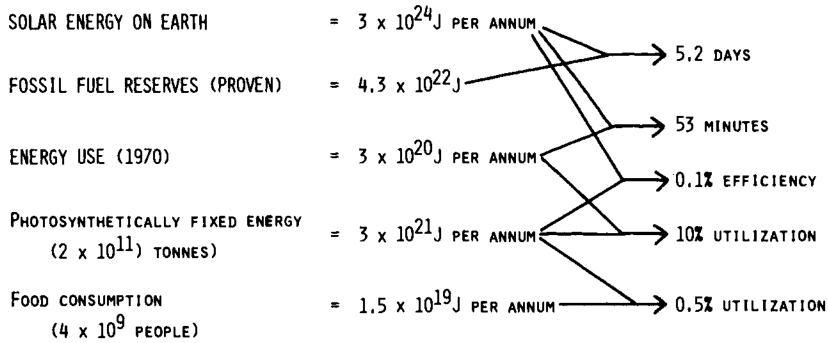

Fig. 1. World energy balances and photosynthesis.

often for short-term growth periods, and when averaged over the whole year, fall to between 1% and 3% (see Tables II and III).

In practice, photosynthetic conversion efficiencies in temperate areas are typically between 0.5% and 1.3% of the total radiation when averaged over the whole year, while values for subtropical crops are between 0.5 and 2.5%. Figure 3 shows the yields which can be expected under various sunlight intensities at different photosynthetic efficiencies.

TABLE I

Photosynthetic Efficiency and Energy Losses[a]

	Available light energy (%)
At sea level	100
50% loss as a result of 400–700 nm light being the photosynthetically usable wavelengths	50
20% loss, due to reflection, absorption, and transmission by leaves	40
77% loss, representing quantum efficiency requirements for CO_2 fixation in 680 nm light (assuming 10 quanta/CO_2)[b] and that the energy content of 575 nm red light is the radiation peak of visible light	9.2
40% loss due to respiration	5.5 Overall PS efficiency

[a] Source: refs. 1 and 9.
[b] If the minimum quantum requirement is 8 quanta/CO_2, then this loss factor becomes 72% (instead of 77%) giving a final photosynthetic efficiency of 6.7% (instead of 5.5%).

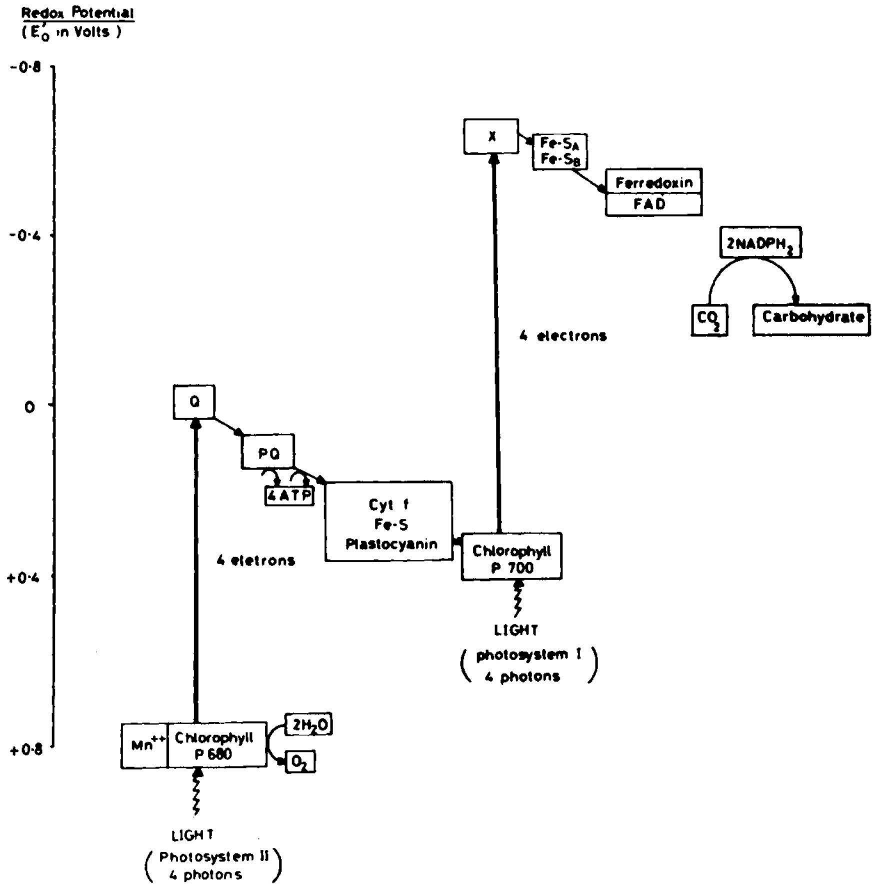

Fig. 2. The photosynthetic electron transport scheme. One photon of light activates each electron at each photosystem. A minimum of eight photons activate four electrons through the two photosystems to liberate one O_2 and fix one CO_2. (See ref. 14.)

V. Areas Required for Solar Power*

The proven primary energy resources of the earth are equivalent to about 4.3 $\times$ 10^{22} J. This means that the solar energy annually reaching the earth's surface in about 5 days is equivalent to our total proven energy resources, or is equivalent in about 50 min to the world's 1970 energy consumption.

*See refs. 9 and 37.

TABLE II

Some High Short-Term Dry Weight Yields of Crops and Their Short-Term Photosynthetic Efficiencies[a]

Crop	Country	Yield[b] (gm^{-2} day^{-1})	Photosynthetic efficiency (% of total radiation)
Temperate			
Tall fescue	United Kingdom	43	3.5
Rye-grass	United Kingdom	28	2.5
Cocksfoot	United Kingdom	40	3.3
Sugar beet	United Kingdom	31	4.3
Kale	United Kingdom	21	2.2
Barley	United Kingdom	23	1.8
Maize	United Kingdom	24	3.4
Wheat	Netherlands	18	1.7
Peas	Netherlands	20	1.9
Red clover	New Zealand	23	1.9
Maize	New Zealand	29	2.7
Maize	United States (Kentucky)	40	3.4
Subtropical			
Alfalfa	United States (California)	23	1.4
Potato	United States (California)	37	2.3
Pine	Australia	41	2.7
Cotton	United States (Georgia)	27	2.1
Rice	Southern Australia	23	1.4
Sugar cane	United States (Texas)	31	2.8
Sudan grass	United States (California)	51	3.0
Maize	United States (California)	52	2.9
Algae	United States (California)	24	1.5
Tropical			
Cassava	Malaysia	18	2.0
Rice	Tanzania	17	1.7
Rice	Philippines	27	2.9
Palm oil	Malaysia (whole year)	11	1.4
Napier grass	El Salvador	39	4.2
Bullrush millet	Australia (Northern Territory)	54	4.3
Sugar cane	Hawaii	37	3.8
Maize	Thailand	31	2.7

[a] Source: refs. 1 and 9.

[b] Yields in gm^{-2} day^{-1} can be converted to tonnes ha^{-1} $year^{-1}$ by multiplying by 3.65.

[c] Other yields: Loomis and Gerakis (28) discuss figures for (1) sunflower, growth rates of 79 to 104 gm^{-2} day^{-1} have been reported, with a 3-week mean rate of 63.8 gm^{-2} day^{-1} giving a photosynthetic efficiency of 7.5%; (2) carrot, growth rates of 146 gm^{-2} day and a dry matter yield of 54.5 tonnes/ha after 160 days were reported.

TABLE III

Average-to-Good Annual Yields of Dry Matter Production[a]

Land type/crop	Tonnes ha^{-1} $year^{-1}$	Yield $(gm^{-2}$ $day^{-1})$	Photosynthetic efficiency (percent of total radiation)
Tropical			
Napier grass	88	24	1.6
Sugar cane	66	18	1.2
Reed swamp	59	16	1.1
Annual crops	30	—	—
Perennial crops	75–80	—	—
Rain forest	35–50	—	
Temperate (Europe)			
Perennial crops	29	8	1.0
Annual crops	22	6	0.8
Grassland	22	6	0.8
Evergreen forest	22	6	0.8
Deciduous forest	15	4	0.6
Savanna	11	3	—
Desert	1	0.3	0.02

[a] Source: refs. 1, 5 and 9

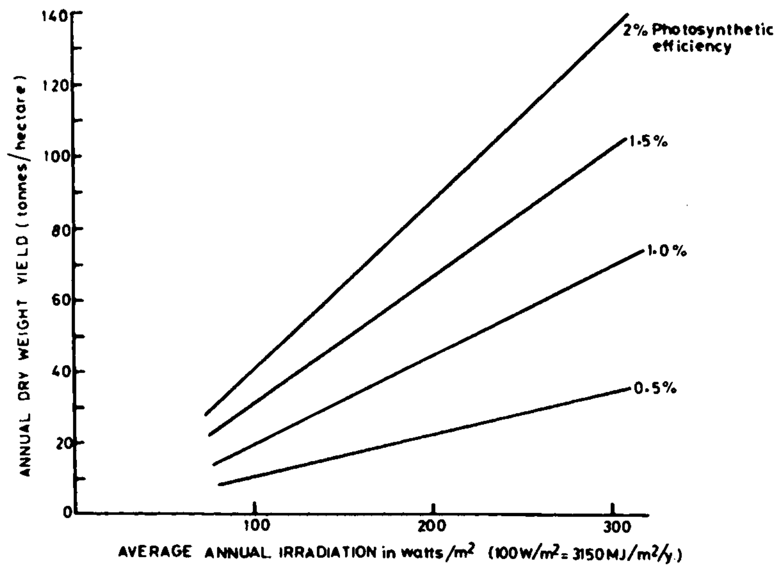

Fig. 3. Expected annual plant yields as a function of annual solar irradiation at various photosynthetic efficiencies. (See refs. 1, 26, 27, 28, 29.)

TABLE IV

Land Areas Required to Provide Total Energy Requirements (1970) from Solar Energy at a 10% Conversion Efficiency

Country	Area required (%)
Australia	0.03
South Africa	0.25
Norway	0.50
Sweden	0.75
Eire	1.00
Spain	1.00
United States	1.50
Israel	2.50
France	3.50
Italy	4.00
Denmark	4.50
United Kingdom	8.00
West Germany	8.00
Netherlands	15.00

[a] Approximate percentage of total.

There are problems in collecting solar energy, the most obvious of which is its diffuse nature and the fact that it is intermittent; therefore, *any* solar energy system has to have a storable component. If a 10% solar energy conversion were achieved (solar cells vary between 12 and 15% efficiency already), the land areas required in various countries to provide total energy requirements can be calculated (Table IV). It is not implied that any country will ever achieve a complete solar energy economy, however, but Table IV shows the magnitude of the land areas involved. Net energy output of any system is essential; so-called "solar energy breeder" systems might accomplish the tantalizing target of producing more energy than is used in their construction and fueling.

VI. Complete Crop Utilization*

The harvesting of the whole crop and its conversion into food, fuel, and fertilizer will undoubtedly become economical if energy costs continue to rise. The good agricultural efficiency achieved over the last 30 or more years has primarily been through the greater use of fossil fuel, e.g., the use of fertilizers

*See refs. 30–42.

such as nitrate and of mechanical operation systems. The following values show the comparative figures for the food energy output per unit of energy input: low intensity agriculture, 20; intensive field crops, 2; livestock production, 0.2; greenhouse production, 0.02. It has been calculated that for every calorie of food that we eat it has taken 5 calories of energy to get it onto our plates—this is with a western standard of living. Most of these calories are inputs after the products have left the farm gate and include transportation, packaging, retailing, and cooking.

Calculations in the United States on energy output-input ratios in the production of maize grain have shown that this ratio has fallen from 3.7 in 1945 to 2.8 in 1970; that is, a doubling of yield has been achieved by a trebling of energy input, mostly as a result of increased fertilization. In the United Kingdom, where maize production is mostly for forage and the whole plant is considered, the output-input energy ratios are between 5 and 9. If the extensive use of nitrogen fertilizers (which often contribute 50% of the energy input) could be decreased without lowering yields, e.g., by N_2 fixation or use of manure, considerable savings in energy could result.

The aim is to maximize energy output-input ratios. At the farm level, we must be sure that we are not just converting oil into food without any net gain in energy, since it is the process of solar radiation via photosynthesis that increases energy output. Many of the agricultural systems that have been considered unprofitable in the past may now become more profitable, due to the combined increased cost of food and fuel.

Leaves are potentially a large source of protein. Traditionally they are composted, discarded as waste, or fed to animals for conversion to meat, which is a very inefficient process. Techniques have been developed for the extraction of leaf protein, which yield at the same time other useful products, namely fiber and soluble components such as carbohydrates, nitrogen, and inorganic nutrient compounds. The composition of leaves is about 60–70% protein, 20–30% lipid, and 5–10% starch. Yields of 2 tonnes of dry leaf protein/ha have been obtained without irrigation and 3 tonnes can be expected. In the southwestern United States, it has been proposed that if the yields of alfalfa (grown in an enclosed environment) reached that of sugar cane, at 100 tonnes dry weight ha^{-1} $year^{-1}$, about 25 tonnes of protein could be extracted per hectare from alfalfa. Once extracted, the protein is probably more valuable as a food than an energy source—the by-products from the extraction process could be used for energy or raw material.

The choice of suitable crops for the extraction of leaf protein, fiber, and other products should be carefully examined. Beside those crops usually used (fodder crops, potatoes, sugar beets, and peas) consideration should also be given to perennial crops such as grasses and clovers, trees and bushes, and crops regenerating themselves—making it economical to obtain a number of cuts in a given time. Additionally, both annual and perennial weeds, especially those species that start to grow early in the year, despite low root temperatures, and that provide maximum year-round cover, may provide very good sources of leaf protein. Integrated approaches for using all possible leaf material, produced either as a by-product in conventional agriculture, or from plants grown specifically from such extraction, would seem to be of benefit in many countries of the world.

VII. Energy Farming*

This implies the growing of plant materials for their fuel value, and is the only known operation that offers a renewable source of liquid fuel and organic chemicals. Energy farms or plantations may be considered as a long-term alternative to fossil and nuclear energy and fossil-derived chemicals, providing us with the energy options we may require in the next century. They have been subject to feasibility studies in the United States, Australia, Europe, and Brazil and the following advantages have been identified: (1) They are capable of storing energy for use at will. (2) They are renewable. (3) They are dependent on technology that is already available, with minimal capital input. (4) They can be developed with our present manpower and material resources. (5) They are reasonably priced. (6) They are ecologically inoffensive and free of hazards, other than fire risk. The easily identified problems are (1) land use competition; (2) land areas required; (3) supply uncertainty in the initial phases; and (4) fertilizer and water requirements. The long-term advantages are, however, very considerable, which is why so much research is being conducted on these systems.

Traditionally we think of energy plantations as forests, but increasingly we should consider alternatives, such as shrubs, weeds, agricultural crops, grasses, and algae (fresh-water and marine). For example, in Australia, five species have been selected—*Eucalyptus, Cassava, Hibiscus,* Napier Grass (*Pennisetum*), and sugar cane—as being potentially the most desirable high-yielding crops that can be harvested over the whole year. Recent calculations show that alcohol produced from cassava (starch-rich) is an economically viable system, but that if processing to destroy cell walls of woody materials is required, the costs become too high. The cost of alcohol from *Cassava* is calculated to be 250 Australian dollars/tonne from a 100,000 tonnes/year batch process plant, which compares favorably with the current market price of alcohol (275 Australian dollars/tonne) as an industrial solvent. Alcohol production from *Eucalyptus* by acid or enzyme hydrolysis is calculated to be 400–600 Australian dollars/tonne because of the chemical pre-

*See refs. 10–12, 15, 23, and 43–64.

treatment or fine milling required. Methane and pyrolytic oil production from cereal straw and *Eucalyptus* is calculated to be two to four times the equivalent fuel costs in 1975 in Australia. If the prices of fossil fuels increase, the economics of photobiological processes will become more favorable, since fossil fuels and electricity account for only 10–25% of the cost of photobiological fuels.

In the United States, fast-growing deciduous trees that resprout from stumps (coppice) when cut, e.g., hybrid poplars are being investigated. It is claimed[53] that at a 0.6% solar energy conversion efficiency with a rainfall of 38 cm or more per year on nonarable land, about 1.2×10^4 ha would be needed to fuel a medium-sized 400-MW electricity generating plant. Recent calculations by this group has shown that about 100 million acres of land is available for energy plantations in the mainland United States. This land is considered marginal in that it is not used for agriculture, forestry, or pasture, but has more than 20 in. of rainfall; interestingly, it is mostly privately owned. A plantation of 28,500 acres, comprising about one-half of the geographical area, with a yield of 9 tons acre^{-1} year^{-1} is calculated to produce dry material at $14/ton, resulting in fuel costs of $1.22 per 10^6 Btu (useful heating value); this is competitive now with fuel costs in many parts of the United States. It is calculated that use of this 100 million acres of land could provide 10^{16} Btu, which is 14% of the total US energy requirements or 61% of its 1974 electricity use.

Another major study has just been completed in the United States[45] on the economic feasibility of silviculture biomass farms to produce energy. The conclusions are promising: "major energy products which could be economically derived from wood biomass at some time in the future include electricity, ammonia, methanol, ethanol, and possibly medium-Btu fuel gas"; "the major opportunity for biomass in electric generation is in small plant retrofit or co-firing with coal"; "production of ammonia from wood biomass is estimated to be marginally competitive today"; "methanol production from wood could become competitive within the next decade." One interesting fact to emerge from this detailed study on ten areas (six nonagricultural, two agricultural, one swampland, and one forest) is that only 10% of the land in a given area need be used for energy farming, thus removing the necessity of acquiring 20,000–40,000-acre blocks of lands to fuel a power station. The limiting factor seems to be the distance required to transport the timber from the farm to the conversion facility.

In Brazil a $400 million program is underway to produce ethanol from sugar cane and cassava so as to replace 20% of its gasoline requirements in the early 1980's[56–58]. Less than 2% of the land area of Brazil could produce enough fuel to replace *all* imported petroleum. Cars run efficiently and have little pollution when running on alcohol. The plan is to plant 1 to 2 million ha of cassava to produce 4×10^9 liters of alcohol. At present alcohol costs the consumer $1 per gallon, as compared to $1.50 for petroleum. The government will stimulate the production by loans and guaranteed purchases.

The production of alcohol from molasses, corn, wheat, and sugar beets has been studied and undertaken in Japan and the United States.[59] Costs vary from $0.99 to $2.20 per U.S. gallon, as compared to the 1975 production cost of $0.95 per U.S. gallon from ethylene (costing $0.15 per pound). The cost of synthetically produced alcohol is slightly less than that produced from crops but "the gap is narrowing rapidly." In New Zealand it has been calculated[59a] that ethanol production from sugar beets could economically replace 10% of the gasoline requirements using 54,000 ha of dryland farming (0.6% of the total area under cultivation).

Canadian studies on the large-scale production of methanol from biomass show that by the year 2025 between 4 and 42% (depending on total energy use) of transport fuels could be provided by such methanol.[47] "Methanol represents a rather unique fuel combining the portability of liquid petroleum products and the clean even-burning characteristics of natural gas." It is shown that commercial production of methanol fuel would be feasible under certain conditions, e.g., methanol value of $0.70/gallon and electricity power costs of 10 mills* or $0.55/gallon and power at 14 mills; if the methanol price were only $0.40/gallon at the refinery, it would not be attractive. In the Pacific a U.S. Navy project is investigating the under-water farming of giant kelp beds, which would be converted to methane and other products. In the Republic of Ireland it has been estimated that they could provide their total energy requirements on 11% of their land area, using crops operating at only 1% photosynthetic efficiency. These energy crops could be grown on peat bogs (and other marginal land), which could be harvested on a continuous basis, resulting in a recurring energy source, rather than a once-and-for-all harvest as at present. Work is underway to identify the most suitable trees and shrubs to start experimental plantations.

VIII. Cellulose†

This is probably the most abundant single organic compound on Earth (about 10^{11} tonnes are produced annually). It could be exploited as a source of energy or food, or as a source of chemicals in the chemical industry. Technology for converting cellulose to glucose is now well advanced. This may be done with acid or alkaline treatment in order to break down the cellulose, but significant advances have been made in the utilization of enzymes or enzyme extracts from fungi (Fig. 4). Costly milling processes need to be avoided. Good sources of cellulose are grasses, cereal straws, shrubs, trees, etc. Another source is household refuse, which may contain 60% of its total weight as paper and vegetable

*1 mill = $0.001.
†See refs. 23 and 65–73.

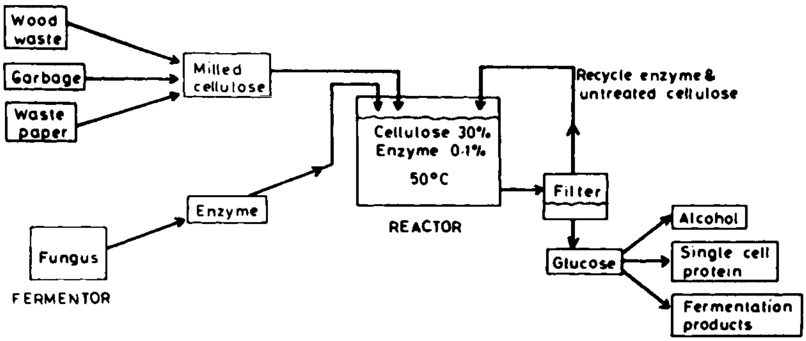

Fig. 4. Fermentation of cellulose to produce glucose. (See ref. 67.)

material. It has been shown that 1 tonne of waste paper will produce one-half of a tonne of glucose, which could yield 250 liters of alcohol. Although the production of industrial alcohol from cellulosic materials, agricultural residues, and industrial wastes is technically feasible, it was considered economically unattractive at 1975 prices, alcohol sold for $1.25/gal in the United States, and the enzymatic process was calculated to produce alcohol at $1.86/gal and $1.31/gal after taking credits for byproducts. Using the glucose as a chemical feestock or a food source is being considered, but little cost data is available.

IX. Waste Disposal and Algae*

Many of the liquid and semisolid wastes from our houses, industries and farms are ideal for the growth of photosynthetic algae. Under favorable conditions, rapid growth with about 3–5% solar conversion efficiency can be obtained. The harvested algae may be fed directly to animals, fermented to produce methane, or burned to produce electricity. Simultaneously, waste can be disposed of and water purified; it is estimated that such algal systems are one-half to three-quarters as expensive as conventional waste disposal systems in California (Fig. 5). The main economic problem is harvesting costs, but the development of new techniques and using different, easily harvested species of algae is proving important. Two-stage algal ponds for complete liquid waste treatment are being tested. Algae that can be harvested by straining grow in the first pond, while nitrogen-fixing blue-green algae (also easily harvested) grow in the second pond, deriving their nutrients from the first treatment ponds. Utilization of CO_2, e.g., wastes from industry, also increases productivity. The harvested biomass can be fermented to methane (equivalent to 5000 Btu/lb algae), while the residues would

*See refs. 23 and 74–80.

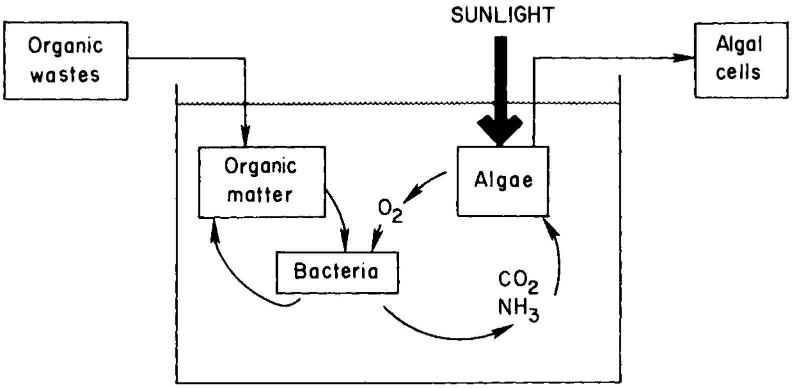

Fig. 5. Production of algal biomass in an algal-bacterial pond. (See ref. 74.)

contain virtually all the N and P of the algal biomass, thus providing a good agricultural fertilizer—1 acre of algal ponds would provide the fertilizer required by 10 to 50 acres of agriculture. By optimization of yields, and by including energy inputs and conversion losses, a net production of 200 million Btu $acre^{-1}$ $year^{-1}$ of methane seems feasible. At a 30° latitude this would represent a 1½% annual photosynthetic conversion efficiency. The cost of the methane so produced is calculated to be $2.75–4.10/million Btu, depending on land costs and the size of the pond. These costs are high but do not take into account the benefit value of waste treatment (which is becoming increasingly expensive) and any byproducts, such as fertilizers. It is estimated that complete municipal waste treatment—microalgal biomass and bioconversion systems—could provide about 5% of local (U.S.) methane usage, if animal wastes were available this figure may reach 10%.

In California average yields of algae in excess of 100 dry kg ha^{-1} day^{-1} are obtained, with peak production in summer reaching three times this figure. Yields of 50–60 tonnes dry wt ha^{-1} $year^{-1}$ would produce 74,000 kW hr of electricity. Oswald has constructed algal ponds of 10^6 liters, which give a 2 to 3% photosynthetic efficiency on a steady-state basis. Large feeding systems for cattle and chickens have now been provided by algal ponds, where the animal waste is fed directly into the ponds; about 40% of the nitrogen is recovered in the algae, which is subsequently refed to the animals. Oswald calculates that 4 million ha of algal pond systems, producing an average of 12 g dry wt m^{-2} day^{-1} could produce all the U.S. protein requirements (compared to the presently used 121 million ha of agricultural land). The green algae presently grown have 50–60% protein, but blue-green algae that contain 60–70% of extractable protein are also being tried. Algal ponds for oxidation of sewage are operating in at least ten countries in the world, and the interest in these systems as possible net energy and fertilizer producers and as water purifiers is increasing. They will obviously never provide major portions of any country's primary energy requirements, but these algal systems have many advantages, not the least of which are their energy-conserving and pollution-abating characteristics.

X. Plant Selection and Breeding*

In order to obtain the maximum energy output from plants in a given area, photosynthesis must be optimized. Considering those factors which limit production, individually and together, plants could be developed from the great diversity of species available throughout the world and within given climates that would give integrated maximum yields of food, fuel, and fiber during the entire year.

The discovery of the C_4 pathway of photosynthesis, in which certain types of plants—e.g., maize—fix carbon dioxide into a C_4 compound as their initial product (instead of the conventional C_3 sugar, which is normally formed by temperate plants such as wheat) has given us a deeper understanding of the intricacies of photosynthesis. This discovery also led to the hypothesis that increased productivity might be achieved by manipulating plants to emulate some of the C_4 characteristics, such as the efficient utilization of low concentrations of CO_2, the ability to grow under water stress and high salt concentrations, and the ability to use intense light efficiently. It has also been suggested that the process of photorespiration *may* decrease yields by up to 50%. This loss arises from the recycling of the photosynthetically fixed carbon in the plant so as to reevolve CO_2, which is thus lost from the plant. Utilizing our knowledge of C_4 characteristics of plants and of photorespiration *may* allow the breeding and selection of efficient photosynthetic plants. As Chollet and Ogren stated:[88] "The control of this process (photorespiration) and the associated oxygen inhibition of photosynthesis has emerged as representing one of the most promising avenues for dramatically increasing the world supply of food and fiber." The major factor that probably prohibits the immediate implementation of these ideas is our limited knowledge of the interacting physiological limiting factors in plant productivity. Research in the plant sciences—especially biochemistry and physiology—has been very poorly funded over the last 10–15 years; agriculture, food, and the plant sciences were taken for granted. Thus many simple questions being asked today about plant science problems have no answer. This state of affairs will take many years to change, and only with increased funding by industrial and government sources.

A reevaluation and possible utilization of CAM-type photosynthesis (crassulacean acid metabolism) may be worthwhile. These CAM plants fix CO_2 to acids at

*See refs. 6, 9, 21, 62, 64, and 81–95.