Biochemical and Photosynthetic Aspects of Energy Production

Edited by

Anthony San Pietro

Biochemical and Photosynthetic Aspects of Energy Production

Edited by

Anthony San Pietro

Department of Biology
Indiana University
Bloomington, Indiana

1980

ACADEMIC PRESS

A Subsidiary of Harcourt Brace Jovanovich, Publishers

New York London Toronto Sydney San Francisco

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data
Main entry under title:

Biochemical and photosynthetic aspects of energy production.

Includes bibliographies and index.
1. Biomass energy. I. San Pietro, Anthony Gordan, Date
TP360.B54 662'.6 80-45
ISBN 0-12-618980-3

PRINTED IN THE UNITED STATES OF AMERICA

80 81 82 83 9 8 7 6 5 4 3 2 1

Contributors

James A. Bassham
Ami Ben-Amotz
John R. Benemann
Peter Böger
D. W. Emerich
H. J. Evans
David O. Hall
George A. Jackson
C. W. Lewis
William J. Oswald
Donald L. Wise

List of Contributors

Numbers in parentheses indicate the pages on which the authors' contributions begin.

James A. Bassham (147), Lawrence Berkeley Laboratory, Berkeley, California 94720

Ami Ben-Amotz (191), Israel Oceanographic and Limnological Research, Tel-Shikmona, Haifa, Israel

John R. Benemann (59), Sanitary Engineering Research Laboratory, College of Engineering, University of California, Richmond, California 94804

Peter Böger (175), Lehrstuhl Physiologie und Biochemie der Pflanzen, Universität Konstanz, D - 7750 Konstanz, West Germany

D. W. Emerich (117), Laboratory for Nitrogen Fixation Research, Oregon State University, Corvallis, Oregon 97331

H. J. Evans (117), Laboratory for Nitrogen Fixation Research, Oregon State University, Corvallis, Oregon 97331

David O. Hall (1), King's College, University of London, London SE 24 9JF, England

George A. Jackson* (31), Environmental Quality Laboratory, and Environmental Engineering Science, California Institute of Technology, Pasadena, California 91125

C. W. Lewis (209), Energy Studies Unit, International Institute for Environment and Development, University of Strathclyde, Glasgow G4 OLZ, Scotland

William J. Oswald (59), Sanitary Engineering Research Laboratory, College of Engineering, University of California, Richmond, California 94804

Donald L. Wise (81), Biochemical Engineering, Dynatech R/D Company, Cambridge, Massachusetts 02139

*PRESENT ADDRESS: Institute of Marine Sources, Scripps Institution of Oceanography, La Jolla, California 92093.

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

Contents

List of Contributors ix
Preface xi

1 Biological and Agricultural Systems: An Overview
David O. Hall

I. Introduction 1
II. Impending Liquid Fuel Problem 2
III. Energy Available from Photosynthesis 3
IV. Efficiency of Photosynthesis 3
V. Areas Required for Solar Power 5
VI. Complete Crop Utilization 8
VII. Energy Farming 10
VIII. Cellulose 12
IX. Waste Disposal and Algae 13
X. Plant Selection and Breeding 15
XI. Regulation of Plant Reactions and Selected End Products 16
XII. Controlled Environments 18
XIII. Nitrogen Fixation 19
XIV. Biocatalytic Hydrogen Production Systems 20
XV. Carbon Reduction 21
XVI. Artificial Chlorophyll Membranes 22
XVII. Bacteriorhodopsin Membranes 22
XVIII. Concluding Remarks 23
References 24

2 Marine Biomass Production through Seaweed Aquaculture
George A. Jackson

I. Introduction 31
II. Seaweed Growth 33
III. Impact of Advective-Convective Processes on Oceanic Culture 52
IV. Conclusions 54
References 56

3 Algal–Bacterial Systems
William J. Oswald and John R. Benemann
I. Introduction 59
II. Elements of Algal–Bacterial Systems 63
III. Conclusions 77
References 79

4 Fuels and Organic Chemicals via Anaerobic Fermentation of Residues and Biomass
Donald L. Wise
I. Introduction 81
II. Perspective of Economic Impact 83
III. Temperature Effect 85
IV. New Processing Concepts 90
V. Fermenter Functioning 99
VI. Biomass Sources 104
VII. Summary 111
References 112

5 Biological Nitrogen Fixation with an Emphasis on the Legumes
D. W. Emerich and H. J. Evans
I. Introduction 118
II. Biological Nitrogen-Fixation Systems 118
III. The Symbiotic Association in Legumes 120
IV. Asymbiotic Fixation by Rhizobia 123
V. The Enzymology of Nitrogen Fixation 124
VI. Energy Requirements for Nitrogen Fixation 131
VII. Increasing Biological Nitrogen Fixation 135
References 141

6 Energy Crops (Energy Farming)
James A. Bassham
I. Introduction 147
II. Why Is Efficiency Important? 149
III. Advantages of Energy Farming 150
IV. Efficiencies of Solar Energy Conversion by Plants 151
V. Calculated Maximum Biomass Production and Reported High Yields 155
VI. C-4 Metabolism and Photorespiration and Effects of CO_2 Enrichment 156
VII. Energy Content of Biomass 159
VIII. Types of Energy Farms 159

IX. Crops Requiring Moderate Rainfall or Irrigation 160
X. Energy Crops in Semi-Arid and Arid Regions 163
XI. Ponds and Fresh-Water or Brackish-Water Bodies 167
XII. Marine: Giant Kelp 169
XIII. Biomass Residues from Agriculture and Forestry 170
XIV. Summary 170
XV. Epilogue 171
References 172

7 The O_2/CO_2 Cycle: Development and Atmospheric Consequences
Peter Böger
I. Rise of Atmospheric Oxygen 175
II. Distribution of Biogenic Carbon and Oxygen 180
III. Stability of Atmospheric Oxygen Content 183
IV. Increase of Carbon Dioxide—The ''Greenhouse'' Effect 184
References 188

8 Glycerol Production in the Alga *Dunaliella*
Ami Ben-Amotz
I. Introduction 191
II. Growth of *Dunaliella* under Measurable and Controlled Conditions 194
III. Glycerol Production in *Dunaliella* 199
IV. Bioengineering Approach 203
V. Economic Appraisal 205
VI. Conclusion 206
References 206

9 Energy Considerations of Biofuels Production
C. W. Lewis
I. Energy Analysis 209
II. Solar Energy 213
III. Fuels from Biomass 214
IV. Conclusion 224
References 224

Index 227

1

Biological and Agricultural Systems: An Overview

David O. Hall

I.	Introduction	1
II.	Impending Liquid Fuel Problem	2
III.	Energy Available from Photosynthesis	3
IV.	Efficiency of Photosynthesis	3
V.	Areas Required for Solar Power	5
VI.	Complete Crop Utilization	8
VII.	Energy Farming	10
VIII.	Cellulose	12
IX.	Waste Disposal and Algae	13
X.	Plant Selection and Breeding	15
XI.	Regulation of Plant Reactions and Selected End Products	16
XII.	Controlled Environments	18
XIII.	Nitrogen Fixation	19
XIV.	Biocatalytic Hydrogen Production Systems	20
XV.	Carbon Reduction	21
XVI.	Artificial Chlorophyll Membranes	22
XVII.	Bacteriorhodopsin Membranes	22
XVIII.	Concluding Remarks	23
	References	24

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.

BIOCHEMICAL AND PHOTOSYNTHETIC
ASPECTS OF ENERGY PRODUCTION

ISBN 0-12-618980-3

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 $\rightarrow$ fixed chemical energy. By contrast, for example, photovoltaic conversion efficiencies of 12–15% represent the process: sunlight $\rightarrow$ 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.

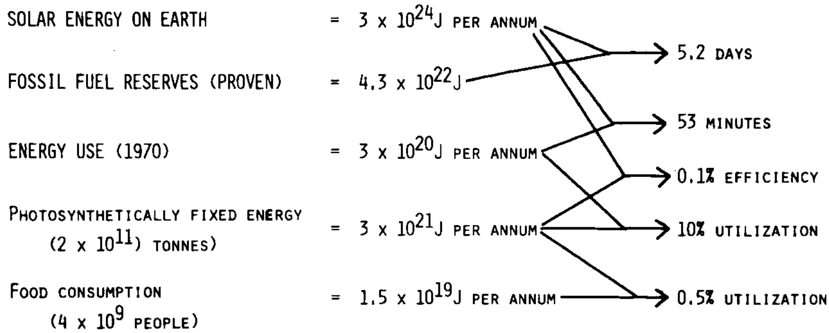

Fig. 1. World energy balances and photosynthesis.

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%).

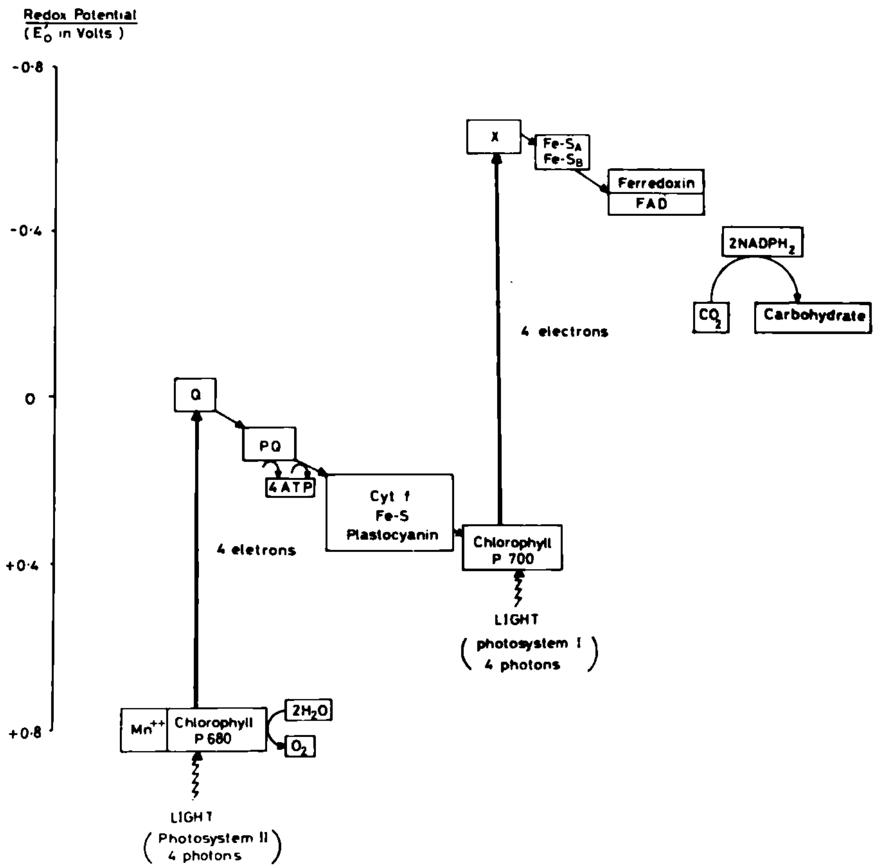

Fig. 2. The photosynthetic electron transport scheme. One photon of light activates each electron at each photosystem. A minimum of eight photons activate four electrons through the two photosystems to liberate one O_2 and fix one CO_2. (See ref. 14.)

V. Areas Required for Solar Power*

The proven primary energy resources of the earth are equivalent to about 4.3×10^{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

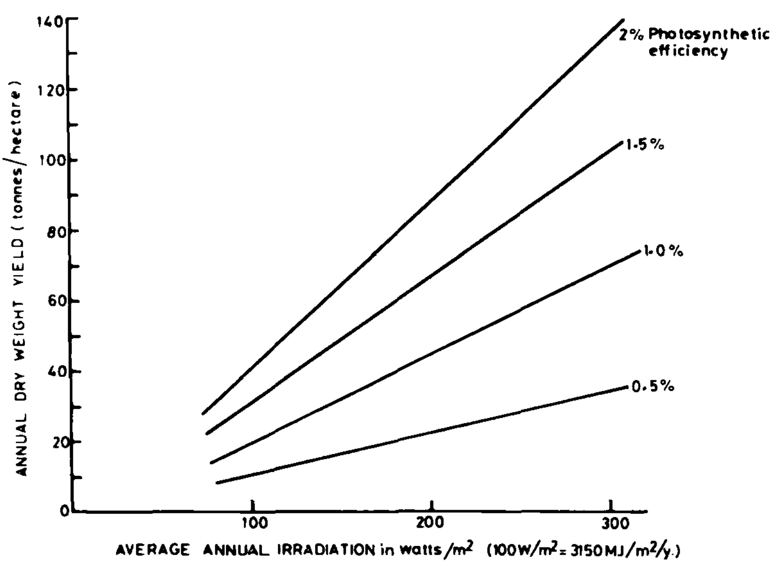

Fig. 3. Expected annual plant yields as a function of annual solar irradiation at various photosynthetic efficiencies. (See refs. 1, 26, 27, 28, 29.)

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.