Potential of Algal Production*

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Abstract

Algae, as all green plants, photosynthesize, take up nutrients, utilize light energy and produce new biomass. Production rates of 54 g m^{-2} d^{-1} representing a light utilization efficiency of almost 4% in terms of total radiation, have been measured in open semi-defined systems. More than 50% of the produced biomass is protein. The minimal nutrient removal can be 2 g N m^{-2} d^{-1}, 0,09 g P m^{-2} d^{-1}, and 24 g C m^{-2} d^{-1}. These characteristics make algae particularly attractive for food production (especially protein-rich foods), waste treatment, and bioenergy conversion. Dense open outdoor cultures of algae are subject to infections and parasitism, especially by protozoa and rotifers. This affects the quality of the biomass as well as yields. A mathematical model has been developed, calibrated and verified in a study to optimize production rates. The model can be used to predict optimal biomass concentrations for use in outdoor algal ponds.

Introduction

The objectives of mass algal cultivation have centered mainly around food production, waste treatment, and bioenergy conversion. The initial effort was primarily concerned with food production (Burlew, 1953). However, the dream of producing cheap protein-rich biomass, never became a reality. The cost of producing 1 metric ton of *Chlorella* biomass was estimated in the fifties to be more than 500 US-Dollars (Burlew, 1953). Soeder (1978) determined that 1 ton of dry algal matter would cost between 857 and 1 142 US-Dollars, depending on the rate of production. Algae, nevertheless, remain attractive in terms of food production. This is because they contain more than 50% protein per dry mass, multiply rapidly, and can be grown in technically uncomplicated systems.

The possibility of producing energy from algal biomass created a renewed interest in mass algal culture operations in the late seventies. The impetus came from the energy crisis and research was directed towards maximizing areal yields, improving fermentation efficiencies and minimizing mechanical and energy inputs. However, Meyers (1977) showed that the problem of bioenergy conversion lies in the fact that although vast amounts of solar energy reaches the earth's surface, it is of low influx density. This together with low photosynthetic efficiencies necessitated large exposed surface areas to capture sufficient quantities of energy. It is because of this that Goldman and Ryther (1977) viewed the value of algal systems in terms of "energy conservation", rather than "energy production".

The most promising and best results with mass algal culture, have been in the field of sanitary engineering, where algae are used to treat wastewater in oxidation ponds. Initially the emphasis was on wastewater treatment and not on algal production. Oswald (1970) introduced the "high rate algal pond" (HAP) and Shelef *et al.* (1978) gave the HAP a multipurpose. In their inexpensive system wastewater is treated aerobically, algal-bacterial biomass (ABM) is produced, and treated water of good quality leaves the system. The general consensus is that the greatest benefit, at present, of mass algal culture lies in such multi-purpose waste treatment systems.

The three mentioned objectives are not necessarily divorced from each other, as the success of each depends to a lesser or greater degree on the efficiency of solar energy conversion. Under sub-optimal conditions of energy fixation, growth rates, production, nutrient stripping, and energy fixation will be low. Research directed towards maximizing algal growth, optimizing growth conditions and especially towards improving the efficiency of light energy fixation, is of utmost importance. As Soeder (1978) has shown, the costs of producing 1 ton of dry algal matter can be decreased by 33% with a 59% increase in productivity.

In this paper only aspects dealing with maximal outdoor production rates, infection problems and growth prediction will be reported on.

Material and Methods

All measurements were taken in open cultures operated at an outdoor experimental site at the University of the O.F.S., Bloemfontein. The ponds had surface areas of either 1,78 m^2 or 18 m^2 and the small one's were operated as described by Grobbelaar (1981a). The larger ponds had a maximum depth of 0,2 m and consisted of a meandering channel in which the culture was stirred with paddle wheels (see also Grobbelaar 1981b). The nutrient medium consisted of tapwater enriched with technical grade chemicals to the following concentrations per litre: 1,01 g KNO_3; 0,62 g $NaH_2PO_4 \cdot 12H_2O$; 0,25 g $MgSO_4 \cdot 7H_2O$; 0,02 g $CaCl_2 \cdot 2H_2O$; and 0,007 g $FeSO_4 \cdot 7H_2O$. Carbon dioxide was supplied on demand from a pH controller to maintain a pH of 7,5 ± 0,5. Radiation as total irradiance and photosynthetically active radiation, as well as culture temperatures were recorded continuously.

Algal biomass was determined after filtering a known volume of culture under vacuum through pre-ignited and weighed Whatman GF/C filters. The filters with algae were dried at 105°C for approximately 10 h before their weight were determined. From the difference the biomass as dry mass was determined (all biomass productions in the paper calculated on a dry mass basis). Organic carbon analyses were done with a Beckman Total Carbon Analyser (Model 915A) and a distinction was made between dissolved organic carbon (DOC, fraction in filtrate), particular organic carbon (POC, total organic carbon minus DOC), and total organic carbon (TOC, whole sample).

Measurements in the 18 m^2 pond were taken at irregular

*Revised paper, originally presented at *Symposium on aquaculture in wastewater*, 24–26 November 1980, CSIR Conference Centre, Pretoria

intervals. The pond was operated as a batch culture and tap-water was added only to maintain a culture depth of 0,15 m. Production was calculated according to Grobbelaar (1981a) and the model of Grobbelaar (1981b) was used in the prediction analysis.

The initial measured biomass was used as a state variable, whereafter hourly measured temperature and light intensity values were used as input variables.

Preparation of the samples for investigation under the ISI-100 SEM scanning electronmicroscope was done as described by Grobbelaar (1981c).

Results and Discussion

According to the generalised growth equation:

$$CO_2 + NO_3^- + PO_4 + H_2O \xrightarrow[\text{Algal cells (chlorophyll)}]{\text{light energy}} (CH_2ONP) + O_2$$

Algal biomass

New biomass is formed at a photosynthetic efficiency which has been shown by Ryther (1959) to vary between 6 and 17%, depending on the light intensity. Bassham (1977) derived an average overall daily maximum efficiency of 6,7% in terms of photosynthetically active radiation (PAR). He also pointed out that this was a theoretical efficiency and set the best achievable efficiency for land plants at between 3,3 and 5,0%. In a more recent paper Pirt *et al.* (1980) claimed an efficiency of 46,8% for PAR or 18% based on total radiation. Although highly controversial, it indicates the possible attainment of much higher productivity potentials. It should, however, be born in mind that the experiments of Pirt *et al.* (1980) were done at low light intensities, where efficiencies are much higher (see Ryther, 1959).

The photosynthetic efficiency is, furthermore, dependent on whether a plant has a C_3 or C_4 metabolic pathway. The latter is more efficient because photo-respiration is avoided. Although algae are C_3-plants, extremely high production rates have been measured in outdoor algal cultures. The conditions of light intensity, culture temperature, dilution rate, and productivity of a *Chlorella* sp. grown as described in Grobbelaar (1981a) are given in Table 1.

The recorded rate of 54 g m^{-2} d^{-1} is of the highest recorded for autotrophic production alone. The efficiency of light utilization was more than 8% for PAR (photosynthetic active radiation) which is somewhat higher than the calculated maximum of 6,7%. Algae, which are C_3-plants, can thus be as efficient as C_4-plants and exhibit high production rates. This has been observed in higher C_3-plants under conditions of high CO_2 levels (Bassham, 1977).

A production rate of 54 g m^{-2} d^{-1} scaled-up gives 0,54 t ha^{-1} d^{-1}, which is enormous in terms of food production. At a protein content of 50%, this amounts to a protein production of 0,27 t ha^{-1} d^{-1}. For nutrient stripping in wastewater treatment systems this would amount to a minimal removal of about 2 g N m^{-2} d^{-1}, 0,09 g P m^{-2} d^{-1}, and 24 g C m^{-2} d^{-1} (calculated from yield co-efficients (Y) of Y_N = 25, Y_p = 600, and Y_C = 2,2). The energy content of 54 g can be calculated from the relationship of Gons and Mur (1975). This gives a fixation of 1212 kJ m^{-2} d^{-1}, which is equivalent to about 14,5 W m^{-2}. An average person requires 5 kW of energy per day. Sufficient energy is, therefore, fixed per ha^{-2} d^{-1}, to satisfy the requirements of 28 people.

Infection by organisms

Outdoor algal cultures are subject to infections by a variety of organisms (Grobbelaar, 1981c). These infections influence achievable yields in that produced biomass is consumed and the quality of the produced product changes. Protozoa and rotifers present the greatest threat. Shown in Figure 1 is an example of a *Strobilidium* sp. found in an outdoor algal culture. Four means of combating infections have been proposed by Grobbelaar (1981c). Heussler *et al.* (1978) developed a mathematical model to simulate the growth of infected algal cultures and predict suitable control measures. The problems of infections, have generally been ignored in the literature on mass outdoor algal cultivation. It is a problem especially in semi-defined systems when conditions of stress (e.g. nutrient limitations, and artificially raised temperatures) are introduced. The most promising results have been obtained when the cultures are acidified to pH 2 for a short period of time and also by the daily removal of particulate matter larger than 100 μ with a small porosity screen.

TABLE 1
PRODUCTION RATE IN OPEN SEMI-DEFINED OUTDOOR MASS ALGAL CULTURES
(After Grobbelaar, 1981a)

Date	Radiation		Temperature °C			
	Einst. m^{-2} d^{-1}	J cm^{-2} d^{-1}	Air		Culture	
			min	max	min	max
24 30 11 78	60,55	3084	10,0	34,5	8,3	28,0

Residence time (d^{-1})	Average suspended solids mg l^{-1}	Average ash weight mg l^{-1}	Production g(d.w.) m^{-2} d^{-1}	Production g C m^{-2} d^{-1}	Efficiency %
1,11	534,8	108,8	54,08	21,54	3,93*

*In terms of total radiation

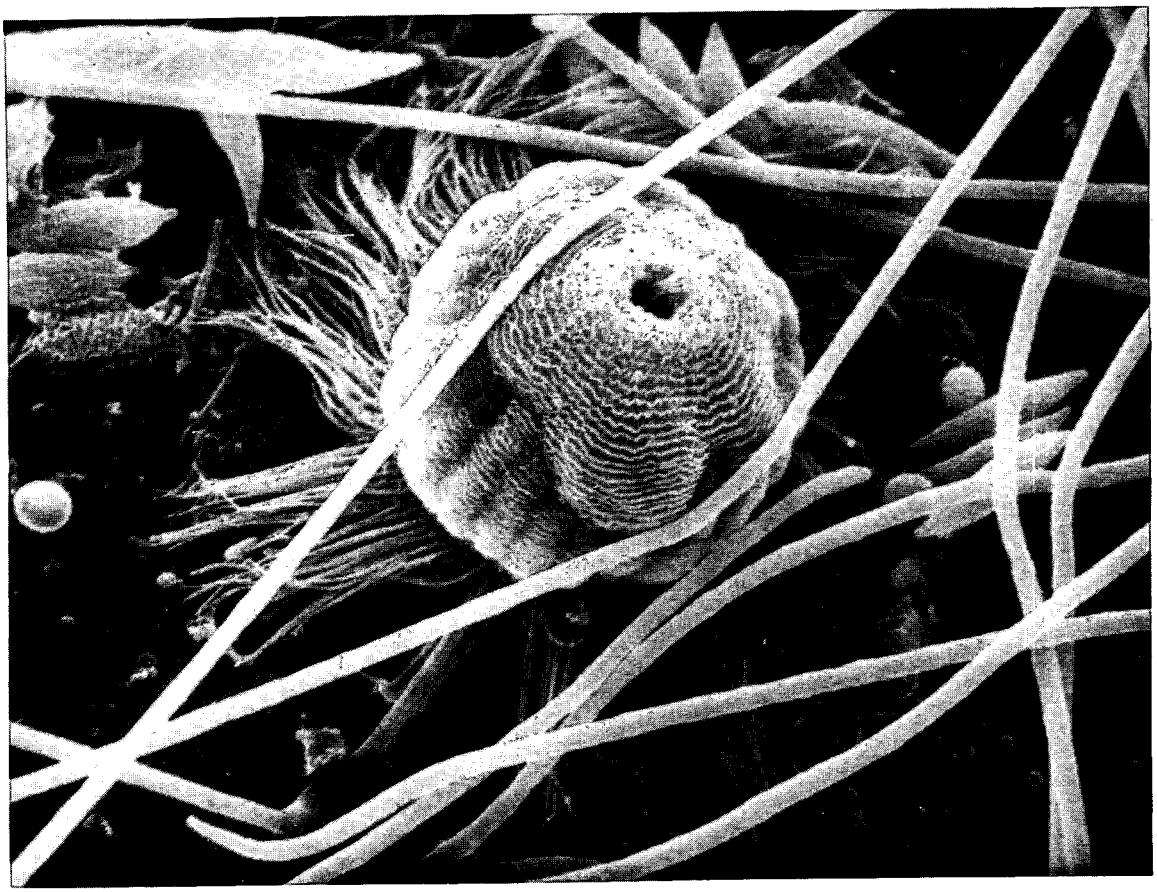

Figure 1
Strobilidium sp. and fungal mycelia infections of a mass outdoor algal culture

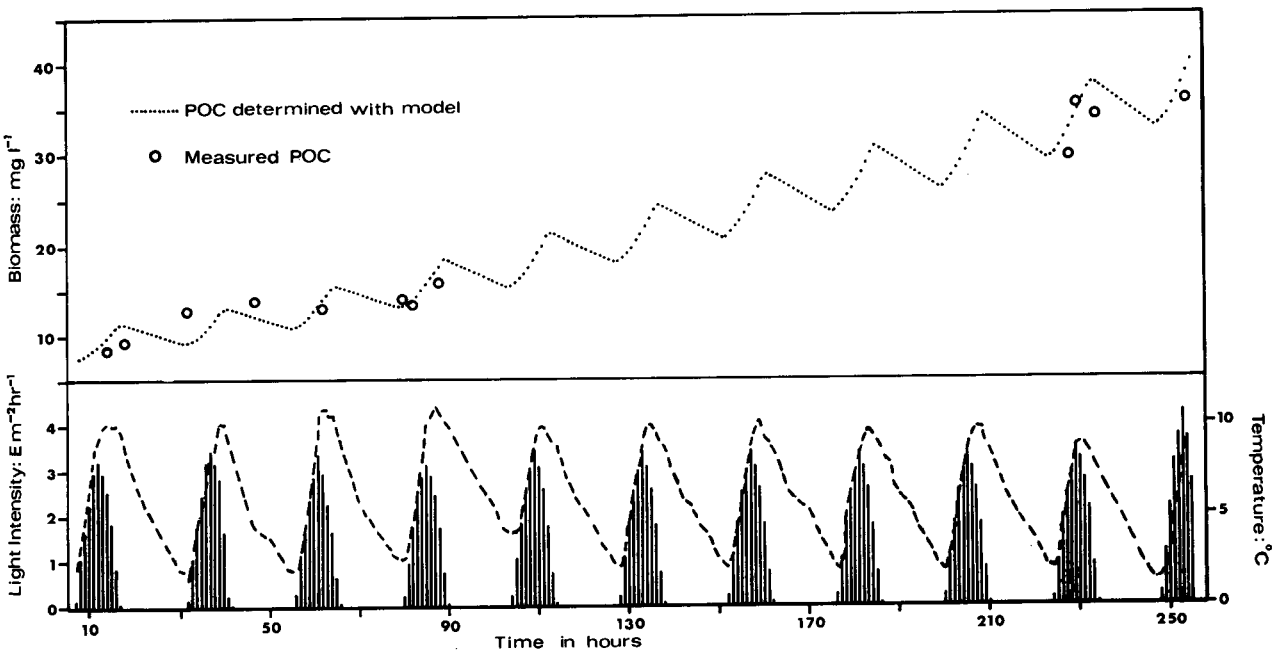

Figure 2
Temperature, light intensity, measured and calculated POC values in an 18 m² outdoor algal culture (23 June to 3 July 1980)

Development of models

The development of predictive mathematical models has been recognized as an important facet in this research. A deterministic model was calibrated by Grobbelaar (1981b) using data obtained during a 56 h experiment in December 1979 (summer) from an 18 m^2 outdoor pond operated as a batch culture in which an *Ankistrodesmus* sp. dominated. The validity of this model to predict algal growth in mass outdoor algal cultures was verified after an eleven day experiment in June 1980. The results are shown in Figure 2, together with the calculated POC values. Production was calculated as described by Grobbelaar (1981b) for 10 mm intervals where the decrease in light intensity with increased depth and biomass was taken into account. Nutrients were not taken into account in the model and it was assumed that respiration and organic excretion maintained a constant rate.

The results in Figure 2 show the low culture temperatures which prevailed during the month of June 1980. Temperatures as low as 1,5 °C were measured. The maximum recorded culture temperature was only 10,5 °C. The culture temperature reached a minimum at about 08h00 and a maximum at about 17h00 each day. The maximum light intensity just exceeded 4 Einst. m^{-2} h^{-1}, which was about half that recorded during December 1979 (summer). The daily lag of maximum temperature with regards to maximum light intensity can clearly be seen. Little difference can be seen in the daily patterns of both temperature and light intensity during the period under investigation.

The calculated POC values show a steady increase with daily maxima and minima. The daily amplitude of production and losses becomes greater with increased biomass, indicating more production and respiration plus excretion. The measured POC values are in agreement with the calculated ones. The

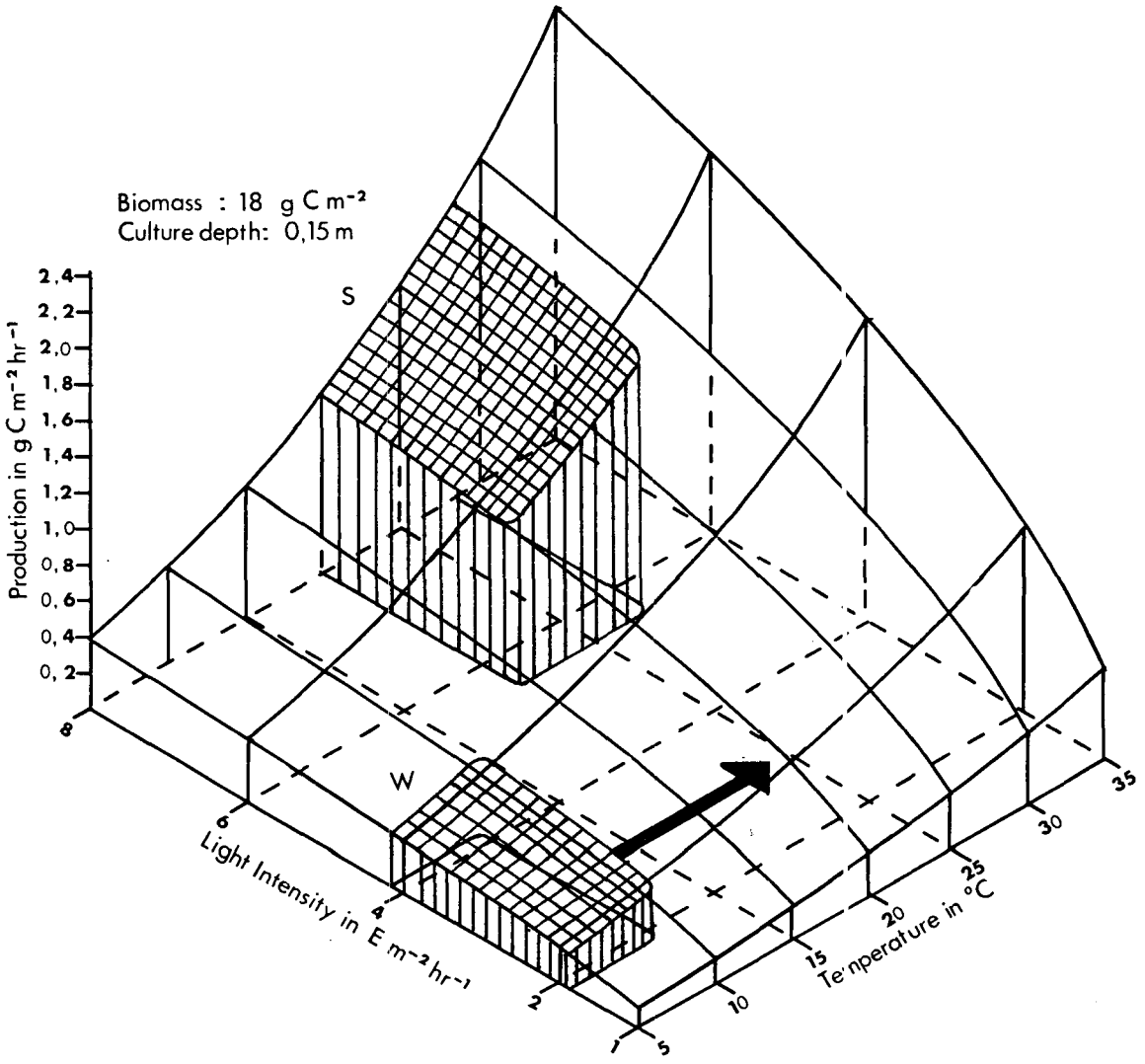

Figure 3
Production in a 0,15 m deep culture with a biomass of 18 g C m^{-2} as a function of light intensity and temperature. The area indicated by S shows the production potential during summer and that by W during winter. The arrow indicates the response of production to raising the temperature during winter

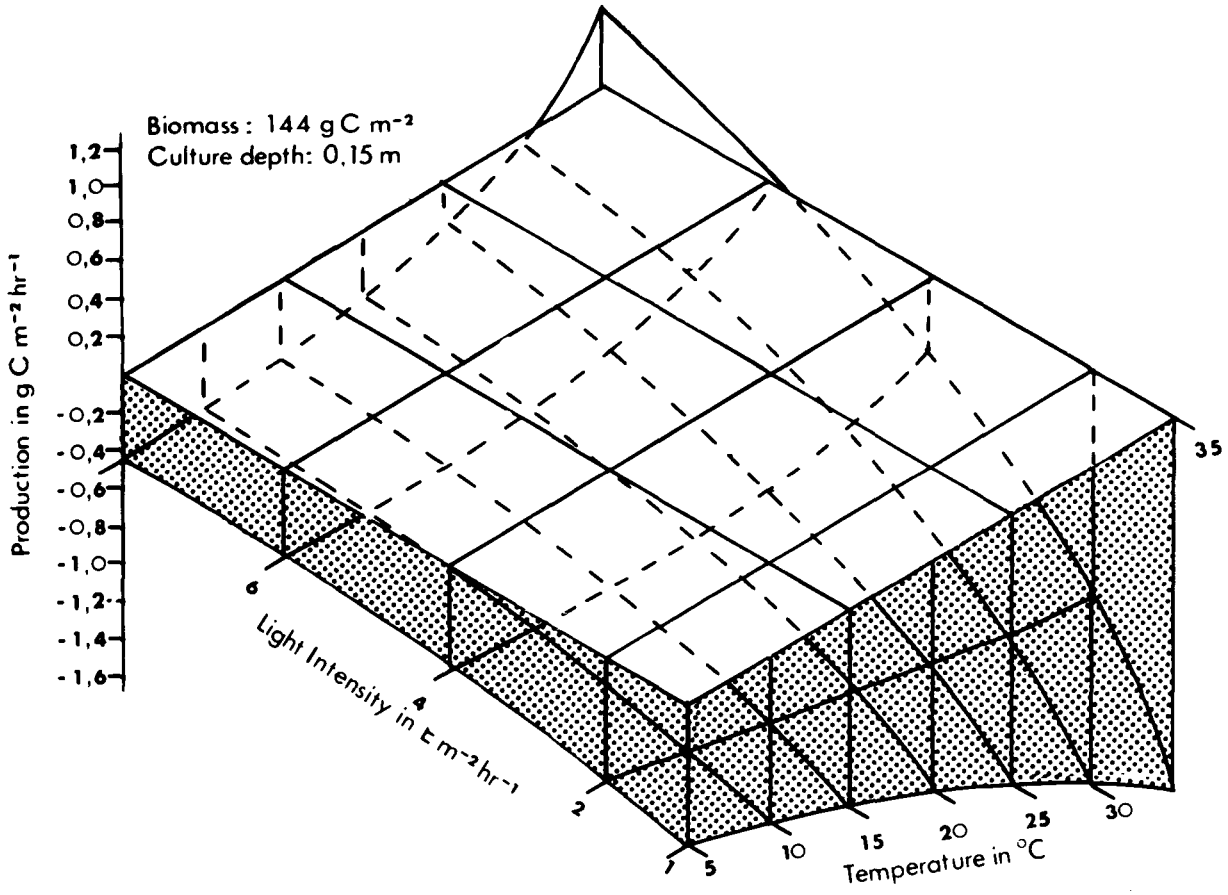

Figure 4
Production as a function of light intensity and temperature in a 0,15 m deep outdoor culture, at an areal density of 144 g C m^{-2}

ability of the model to predict algal growth in open semi-defined systems has, therefore, been verified under summer and winter conditions.

The rate of photosynthesis in algal cultures, like any endergonic chemical reaction, is controlled by the input of energy and temperature. This is when everything else (nutrients and CO_2) is in excess. Temperature not only influences biochemical processes but also the distribution of algal species (Soeder and Stengel, 1974). The effect of temperature on the growth rate of algae has been analysed by many (e.g. Sorokin, 1960 and Goldman and Carpenter, 1974) and Q_{10} values of between 1,0 and 2,3 at different light intensities have been quoted from Piccinin by Harris (1978). Sorokin (1960) and Krüger and Eloff (1978) recorded slope changes when Arrhenius plots of temperature versus growth rate were made. These changes in activation energy were, however, not recorded by Harris (1978 — referring to work of Piccinin) and Van Vuren and Grobbelaar (1982), within a temperature range of 5 — 30°C. The influence of temperature on algal growth therefore, seems to be described by a single Q_{10} value which is specific for the particular algal species, and not by a series of Q_{10} values depending on temperature.

Harris (1978) discusses the influence of light intensity on photosynthesis in detail. Two distinct slopes are found, i.e. light-limited and light-saturated. Intersection of these two slopes occurs between about 0,18 and 0,43 Einst. m^{-2} h^{-1}. Light saturated rates of photosynthesis can, therefore, be expected for the greater part of the day (see Figure 2) under normal conditions.

An understanding of the combined influence of temperature and light intensity on algal growth is of importance in mass algal operation. The model of Grobbelaar (1981b) was used to determine production rates at various biomass concentrations under varying temperatures and light intensity conditions. These plots (Figures 3 and 4) compare favourably with experimental results obtained by Setlik *et al.* (1970) and once again the production model is validated as a true indicator of algal response to light intensity and temperature.

At a biomass concentration of 18,0 g C m^{-2} and a culture depth of 0,15 m (Figure 3) it can be seen that production increases with increased temperature and light intensity. The increase in production at temperatures below about 15°C with increased light intensity is small. Similarly, minimal increase in production with increased temperature was found at light intensities below 2 Einst. m^{-2} h^{-1}. Production is, however, greatly increased at temperatures above 20°C and light intensities above 4 Einst. m^{-2} h^{-1}. The conditions of light intensity and temperature during summer and winter are shown in Figure 3, which clearly indicates the low production rates, which can be expected during winter as compared to summer rates. Grobbelaar (1981a) has shown that open outdoor cultures are temperature-limited during the winter months in the central

part of South Africa. The influence of raised temperatures on production can clearly be seen in Figure 3. Sufficient light energy is available to increase production by about 250% when the culture temperature is raised by 20°C in winter.

Production in a culture with a biomass of 144 g C m^{-2} and 0,15 m deep at various temperatures and light intensities can be seen in Figure 4. Respiration and organic excretion exceeds production in such a dense culture, except at light intensities above 6 Einst. m^{-2} h^{-1} and temperatures above 30°C. Increased respiration and excretion with increased production can also be seen. As the greatest proportion of the culture exists below the compensation point (production = losses) biomass is actually lost. The situation presented in Figure 4 is, therefore, hypothetical and cannot exist in reality.

The value of a model, therefore, lies not only in its predictive capabilities for real situations, but also in its capacity for testing the influence of abnormal conditions. Similar analyses, such as shown in Figures 3 and 4 were done for various biomass concentrations. The areas under the three-dimensional plots were integrated to give an "average" production for a certain biomass over temperature and light intensity ranges from 5 to 35°C and 1 to 8 Einst. m^{-2} h^{-1}. These "average production" values are plotted against biomass in Figure 5. Also shown in Figure 5, are the activity coefficients (Production/Biomass as a percentage), which are an indication of the efficiency of the biomass to produce new biomass. This latter curve shows greater efficiency with lower biomass as is to be expected.

Production reaches an optimum at an areal density of 16 g C m^{-2} and the compensation density (production equals losses) is at 90,5 g C m^{-2}. The optimum areal density for culture depths of 0,05 to 0,5 m are shown in Figure 6. This shows, e.g., that the optimum biomass in a 0,2 m deep culture for the greatest pro-

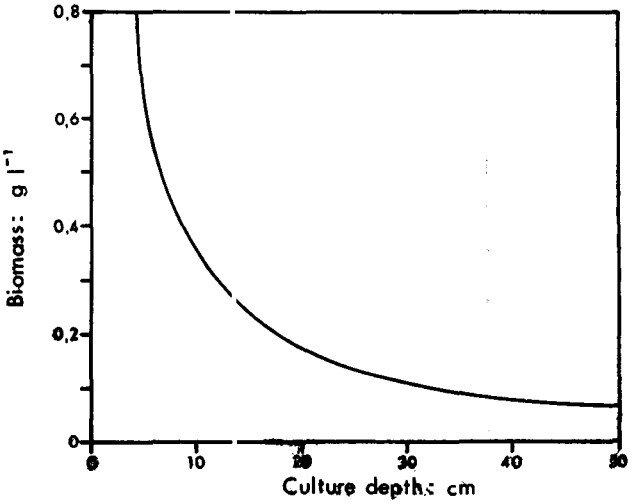

Figure 6
Biomass concentrations as a function of culture depth at which maximum production occurs

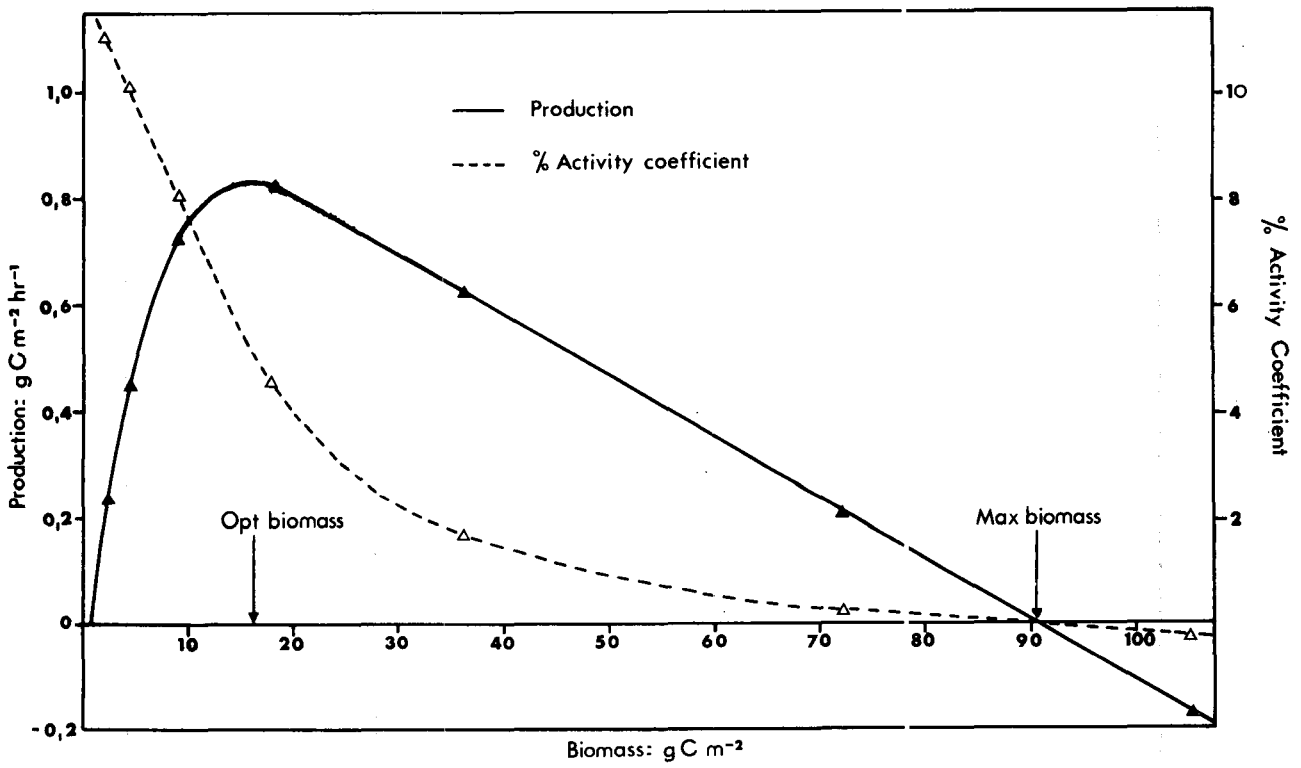

Figure 5
Production and activity coefficients as a function of biomass concentration at light intensities from 1 to 8 Einst. m^{-2} h^{-1} and temperatures from 5 to 35°C

duction, would be 0,175 g ℓ^{-1}. Estimates of the optimum and maximum areal densities are of great practical value, especially in terms of pond operation and construction.

Conclusions

Algae offer unique and outstanding possibilities in alleviating food shortages, treating wastes and conserving energy. Algal cultures are subject to infections and parasitism and research regarding interactions and control is desperately needed. It is possible to model algal growth in mass algal cultures and these models are valuable in determining optimum and maximum areal densities, establishing design criteria, investigating environmental influences on algal growth, etc. The greatest research effort, however, should be directed towards optimizing conditions for maximal growth and investigating biochemical means of improving energy fixation efficiencies.

Acknowledgements

The help of the following is acknowledged: Mr J.A.S. van Straaten, Mrs. M.M.J. van Vuren, Mrs. E.S. Mostert and Miss M.H. van Zyl, are thanked for assistance from time to time and Mr M.T. Seaman for reading the manuscript, Professor D.F. Toerien, director of the Institute for Environmental Sciences is thanked for his interest and encouragement and the University of the OFS and CSIR for its financial support.

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