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A Practical Simulation Model for *Spirulina* Production

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Özet : *Spirulina Üretiminde Kullanılan Pratik Simulasyon Modeli.* *Spirulina* (*Arthrospira platensis*) kültürünün serada veya açıkhavada yürütülmesinin simulasyonu için bir model geliştirildi. Fotosentez hızı, direkt olarak 5 faktörden etkilenir. Fotosentez=k x f(ışık) x f(sıcaklık) x f(ph) x f(karıştırma) x f(tuzluluk). Solunum oranının sıcaklığın bir fonksiyonu olduğu kabul edilir. Güneşin pozisyonuna göre ve yerel meteorolojik bilgiye dayanarak aydınlatma hesaplanır. Gerekirse yapay ışıklandırma sağlanır. Kültürün sıcaklığı , termal basınçtan ve tanktaki karbondioksit basıncından oluşan pH'dan faydalanılarak hesaplanır . 600 gün boyunca her saatte hesaplamalar yapılır. Günlük üretimin grafiklerle gösterilmesi ve fiyat analizini içeren sonuçlar hazılanır. Üretimi optimize edebilmek için bir çok teknik parametreden örneğin sıcaklığın kontrol edilmesinden (yanmaz, çift katlı plastikten yapılmış çatı, hava sirkülasyonu, gölgeleme, geceleyin yüzeyin kapatılması, yapay ısıtma) faydalanılabilir. Isıtmak için veya karbondioksit kaynağı olarak çok çeşitli yakıtların kullanımı mümkündür.

Bu modelin Spirulina üretiminin proses yönetiminde kullanılabileceği tahmin edilmektedir. Operasyon koşullarının optimize edilmesi, teknik ve ekonomik analizlerinin yapılması eğitim ve öğretimin yararına olmaktadır.

Abstract: A model was written to simulate the operation of a spirulina (*Arthrospira platensis)* culture under a greenhouse or in the open air. The rate of photosynthesis is assumed to be directly proportional to five functions : photosynthesis = k x f(light) x f(temperature) x f(pH) x f(stirring) x f(salinity). The rate of respiration is assumed to be a function of the temperature. The solar illumination is calculated from the sun's position and from local meteorological data ; an artificial lighting may be provided. The culture temperature is calculated from a thermal balance and the pH from a CO_2 balance around the tank. The calculations are carried out for each hour for a period of up to 600 days on end. The results include a graph of the daily production and a cost price analysis. In order to optimize the production about 80 technical parameters can be varied at will, including the temperature control means (inflatable double plastic roof, air circulation, shading, night cover, artificial heating). Various fuels are available either for heating or as a source of CO_2.

The model appears to correctly predict the operation of a spirulina culture. It is useful to predict trends, optimize operating conditions, make technical and economic analyses, and as a tutorial aid.

Key Words : *Arthrospira platensis*, culture, simulation, model.

Introduction

The software **SPIRU-E.EXE** containing the mathematical model presented here is available from the Geneva based N.G.O. Antenna Technology. It can be downloaded from their Web site (http://www.antenna.ch/manuel/CALCUL.htm). The program itself contains all necessary information for use.

The model is based on data from the literature plus data obtained by the author in the course of ten years of experiments with spirulina (*Arthrospira platensis)* culture. It makes use of basic equations from the solar energy and chemical engineering fields. It appplies to any spirulina culture in an open air tank or under a greenhouse, in any climate. It also applies to the case of cultures flowing on inclined planes.

In addition to technical aspects, the model also calculates a simplified cost price for the product.

Materials and Method

Starting from a given set of initial conditions, the growth of spirulina is calculated hourly for the desired duration of the culture (up to 18 months), as a batch culture or rather as a semi-batch culture because of harvesting. The basis is one square meter of illuminated tank area. Temperature and pH of the culture are obtained by heat and CO_2 balances around the tank and are the basis for the calculation of growth. The main hypothesis on which the model is based is that the rate of photosynthesis is assumed to be directly proportional to five functions :

photosynthesis = k x f(light) x f(temperature) x f(pH) x f(salinity) x f(stirring)

with the proportinality factor k chosen to fit experimental results. This hypothesis may not be scientifically justified, but it makes the calculation much simpler ans seems to give acceptable results. This equation assumes that photosynthesis is not limited by nutrients other than bicarbonates, and that it is independant of spirulina concentration (which is largely true as the biomass concentration is maintained above 0.15 g/liter). The functions of light, temperature, pH and salinity are based on Zarrouk 1966, adapted to better fit experimental results when necessary. Figs. 1 to 5 show these functions as used in the model. The function of the stirring rate is largely hypothetical (note : stirring and agitation will be synonymous in this paper).

The net growth is calculated as the difference between photosynthesis and respiration.

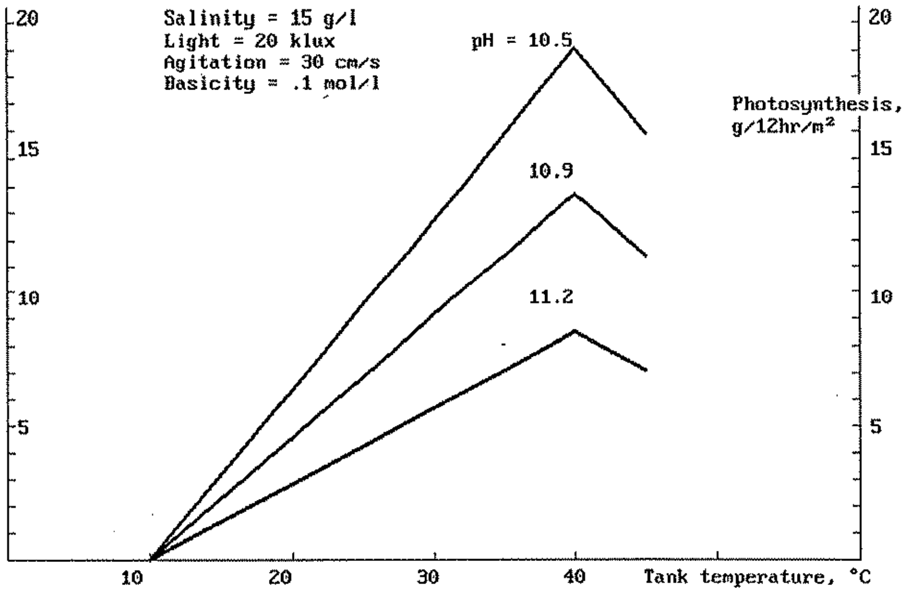

Figure1. Photosynthesis vs. Temperature

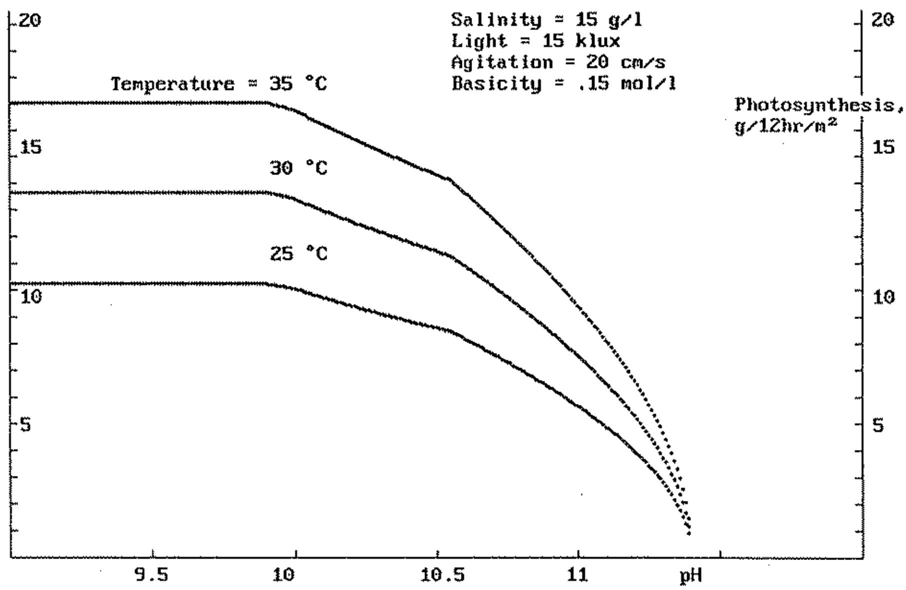

Figure 2. Photosynthesis vs. pH

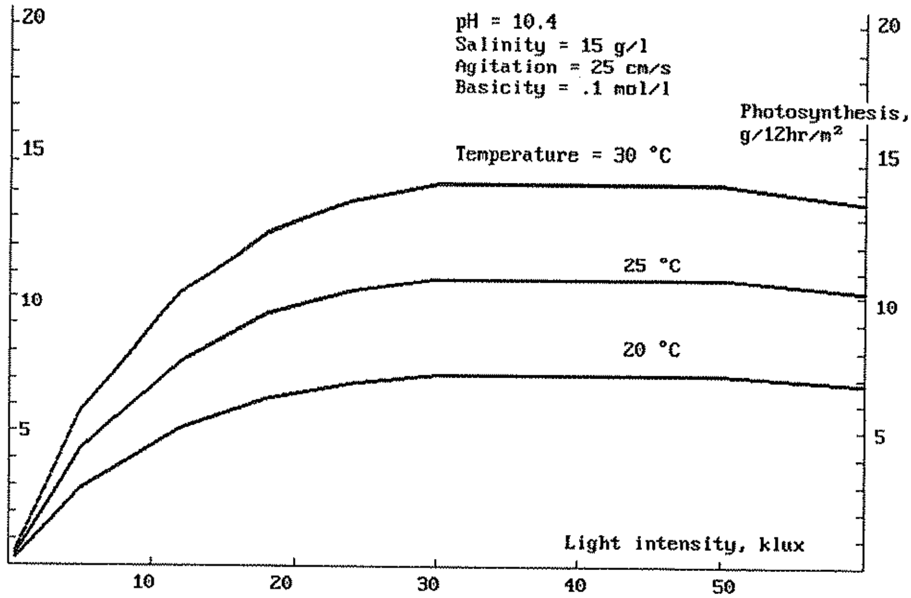

Figure 3. Photosynthesis vs. light intensity

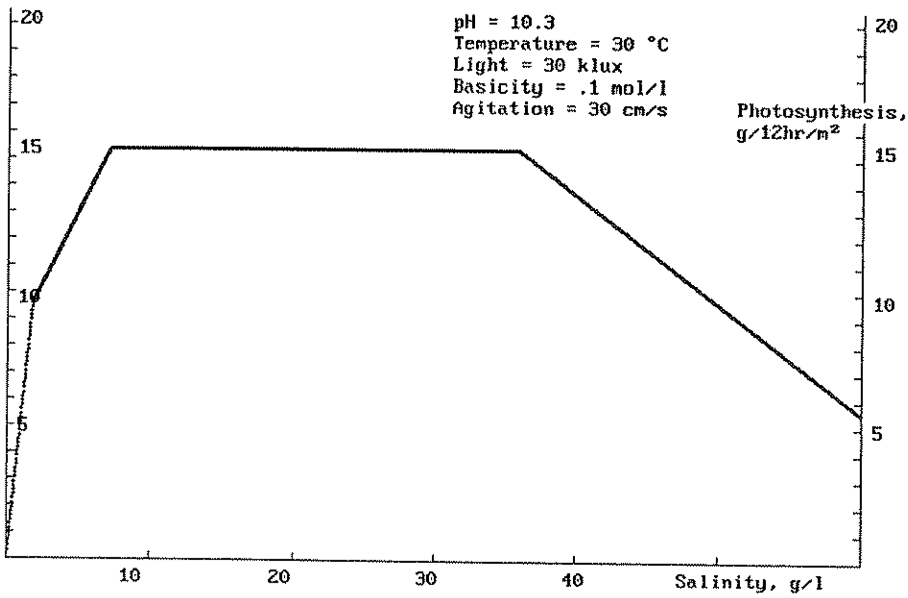

Figure 4. Photosynthesis vs. salinity

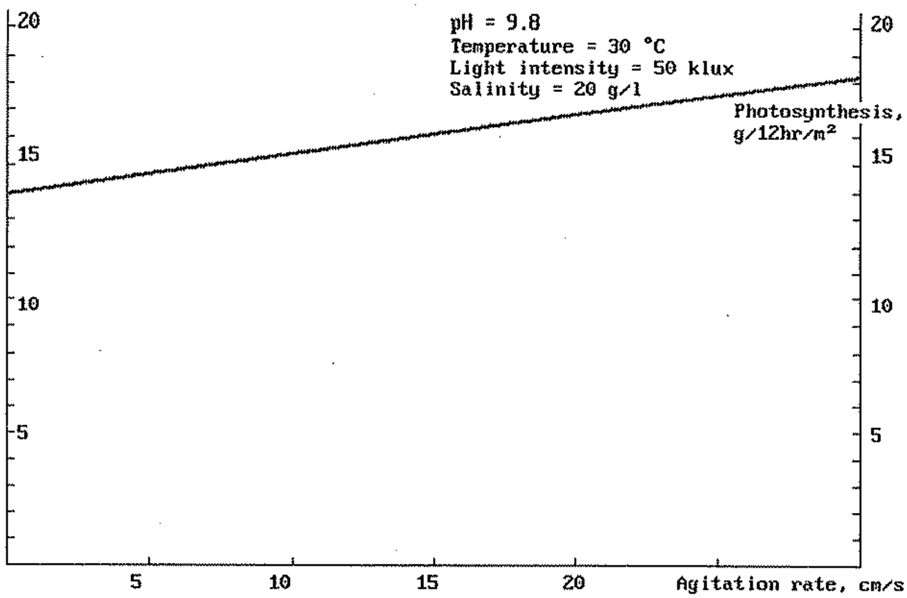

Figure 5. Photosynthesis vs. stirring rate

The assumed influence of temperature on the rate of respiration is illustrated in Fig. 6, based on Tomaselli *et al.*, 1987 and Cornet 1992, for homogeneous cultures maintained in contact with air.

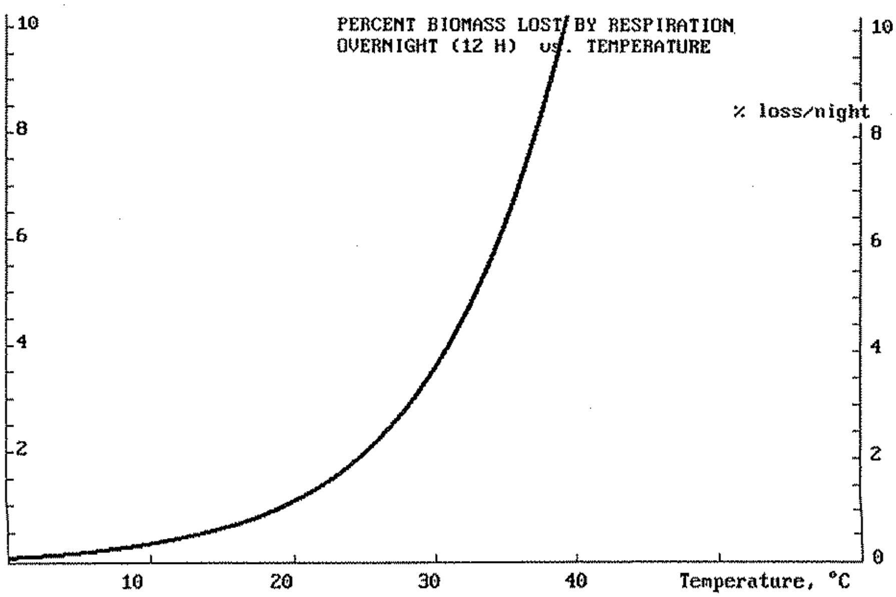

Figure 6. Respiration rate vs. temperature

Ambiant air temperature and solar radiation are calculated hourly from meteorological data, latitude and altitude of the site, with formulas used commonly in the solar energy field. The average percent cloudiness is assumed to be concentrated each month in three series of days evenly distributed within the month, which are the rainy days of the month. Dew point and wind velocity are assumed to be constant within each month.

Greenhouses used may be equipped with various devices to control their internal climates : inflatable double plastic roof, adjustable ventilation, adjustable shading, fixed shading, infra-red reflectors (night screen) and night insulation. Various additional options for greenhouses in cold climates are available including heating by fuel combustion, night insulation and artificial lighting.

Adjustable and/or fixed shading and night screen may also be mounted on open air tanks.

Options for artificial carbon feeding include liquid CO_2, bicarbonate or sugar injection and (for greenhouses) fuel combustion. Various clean fuels are available for combustion, including biogas and methanol, with optional cogeneration of electricity.

Harvesting is done six days a week at a given time of the day, reducing the spirulina concentration down to a given fixed value, but is limited by the harvesting capacity. There is no harvest as long as the pH is below a limit (generally 9.6) in order to minimize the pathogenic germs. At the end of the culture period a final harvest reduces the concentration down to the initial value of 0.15 g/l. The average productivity is based on the total duration of the culture period from inoculation to restarting a new culture, including the idle days.

The pH of the culture is controlled by daily feeding of CO_2 or CO_2-evolving compounds (bicarbonate, sugar) or CO_2-containing combustion gases. The CO_2 contributed by the urea and by the ventilation air is taken into account in the carbon balance. The absorption coefficient of CO_2 from the air into the culture medium was experimentally determined as 18 gmoles/hr/m²/atm; this figure is the default value in the program, but it may be changed. The vapor pressure of CO_2 over the medium is calculated using the formula given in Kohl and Riesenfeld 1960. The resulting rate of CO_2 absorption from the air is illustrated in Fig. 7. The experimentally determined graph in Fig. 8 is used to relate the amount of CO_2 contained in the medium to the pH of the medium. The CO_2 consumption assumed in the examples given below is 1.8 gram per gram of spirulina grown, but the model allows it to be adjusted to take into account variations in the exopolysaccharide and other by-products

according to the strain and the culture conditions.

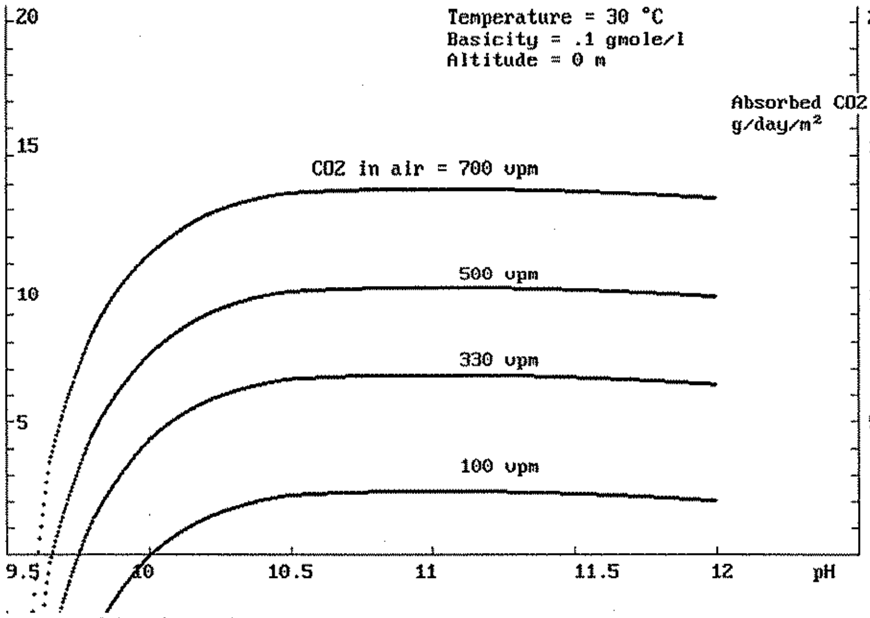

Figure 7. CO2 absorption vs. pH

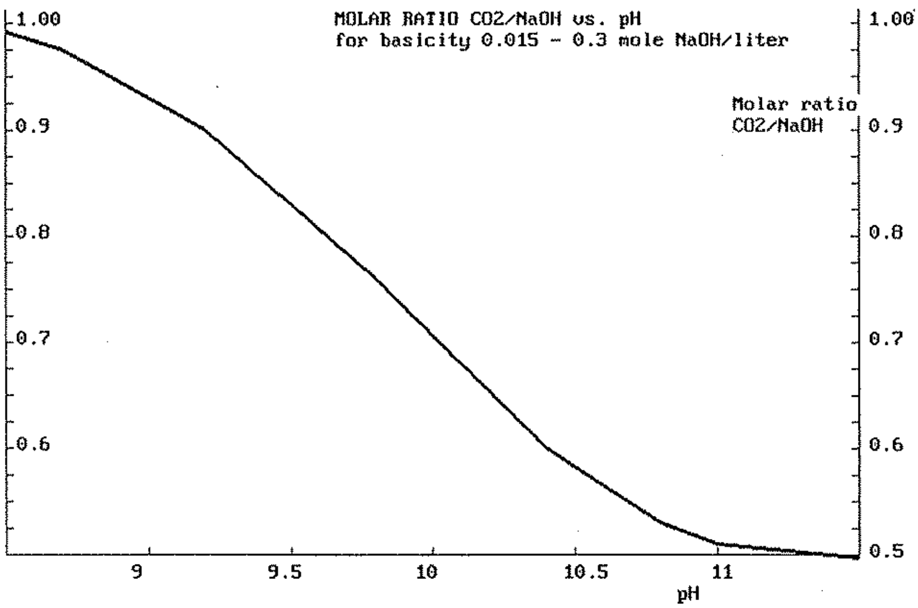

Figure 8. CO_2/base vs. pH

The tank level is allowed to fluctuate between a minimum and a maximum value, and is controlled either by draining part of the medium or by adding water (plus the salts needed to maintain the quality of the medium) depending on the needs. The salinity and alcalinity of the make-up water are taken into account, but its hardness is neglected. The salinity and the basicity of the medium are controlled below given maximum values by replacing part of the medium by water (plus the required salts).

The cost price calculated by the model is based on the following formulas for chemicals usages :

	Medium, g/liter*	Production, g/kg**
Monoammonium phosphate	0.08	50
Dipotassium sulfate	1.00	40
Epsom salt	0.16	30
Urea	0.02	300

(*plus the required sodium bicarbonate, carbonate and chloride corresponding to the initial basicity, pH and salinity)
(**plus the required amounts of CO_2 or CO_2 containing compounds).

The cost price also includes an adjustable fixed costs contribution.
The model does not take into account the cost of treatment nor the recycling of the spent culture medium.

Results

The site of Izmir, Turkey was chosen to give a series of examples of results obtained using the model. To facilitate comparison of the various cases, the same set of data were used in all cases, except the parameters being varied. A greenhouse of the simplest type is used in all cases, with no inflatable double roof, no shading, no night insulation nor night screen, but with adjustable ventilation. The standard duration chosen for the culture is one year. Table 1 and 2 show the printout of the standard data used.

Table 1. Example of data

```
SIMULATION OF PRODUCTION OF SPIRULINA BY PROGRAMM SPIRU-E
IZMIR          Date : 10-11-2001

                         HYPOTHESES
Notice : if variables were modified during the simulation,
            these modifications are reproduced here

1. bicar added = 150     2. CO2 added= 0            3. sugar added = 0
4. depth = 10            5. thermal equiv. = 5      6. days = 360
7. no carbon days = 5    8. inter days = 5          9. pH control = 10.2
10. initial c = 1        11. harvest cap. = 20      12. wind coeff. = 1
13. shad. coeff. = .3    14. night cover = 0        15. max temp. = 41
16. initial b = .1       17. max. b = .2            18. fixed salts = 5
19. max. sal. = 20       20. water tds = 0          21. ventilation = 2
22. vent. coeff = 1      23. fuel type = 2          24. biogas % CO2 = 0
25. fuel flow rate = 0   26. electr. gener. = 0     27. heat used = 100
28. gases used = 100     29. insulation = 0         30. insul. coeff = 1
31. double roof = 0      32. lamps = 0              33. lamps control = 0
34. lamps heat = 0       35. % drainage = 10        36. initial day = 15
37. initial mo. = 1      38. CO2 outside = 340      39. yield = 90
40. spir. conc. = .3     41. harv. time = 8         42. stirring rate = 20
43. adjust. coeff = 1    44. kg CO2/kg spi = 1.8    45. interest rate = 0
46. azimuth = 0          47. slope = 0              48. altitude = 120
49. latitude = 39.2      50. fixed shad. = 0        51. Reference = IZMIR
74. b (eau) = 0          75. pH (eau) = 0           76. klux max @ 10øC = 30
Prices, $/kg (except otherwise mentioned)
60. carbonate = .8       61. bicarbonate = .8       62. salt (NaCl) = .17
63. urea = .17           64. liquid CO2 = 1         65. sugar = .7
66. sulfate (Mg) = 3     67. sulfate (K) = 3        68. phosphate = 3
69. water = .1           70. kWh = .13              71. fixed costs = 15
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Table 1 Example of input data

Table 2. Example of meteorological data

WHEATHER DATA for IZMIR
(Average monthly values)

Month	Temp max	Temp min	Dew point	% cloud	Wind	Haze	Rain
1	11.1	3.3	3.3	18.7	2	0.26	87
2	12.2	4.4	4.4	20.7	2	0.26	72
3	15	6.1	6.1	15.3	2	0.26	63
4	20.5	9.4	9.4	8.8	2	0.26	38
5	25.5	13.3	13.3	8.5	2	0.26	29
6	30.5	17.7	17.7	3.3	2	0.26	12
7	33.3	20	20	0	2	0.26	0
8	32.7	19.4	19.4	3.2	2	0.26	8
9	28.8	15.5	15.5	6.7	2	0.26	21
10	24.4	12.2	12.2	6.5	2	0.26	20
11	18.8	9.4	9.4	13.2	2	0.26	52
12	14.4	7.2	7.2	22.9	2	0.26	110

Note : Temperatures in deg C
Wind = velocity in meters/second
Haze scale : 0.5 = very polluted, 0.26 = normal, 0.17 = very clear
Rain = rainfall in liters/sq.m./month

The daily results of each simulation come out both as a graph (Fig. 9) and as a table (not shown here), while average results over the period of culture come out as a table (Table 3).

Table 3. Example of results

RESULTS

Nutriments, kg/kg of harvested spirulina :
bicarbonate (initial medium and drainages included): 9.17
bicarbonate (excluding initial medium) : 8.85
carbonate = 0.00
sugar : 0.00
liquid CO2 : 0.00
Water consumption
(including medium, drainages, evaporation), l/kg = 710
Total rainfall on area equal to tank area, l/kg = 192
Drainages, average %/day = 3.35
Fuel consumption, kg/kg = 0.00
Surplus electricity (sold), kWh/kg = -3.8
Electricity consumption by lamps, kWh/kg = 0.0
Electricity consumption by agitation, kWh/kg = 3.8
Final concentration in spirulina, g/l = 0.3
Final salinity of medium, g/l = 17.4
Final basicity of medium, moles/l = 0.20
Maximum pH (before days without carbon feed) = 10.32
Maximum tank temperature, °C = 38.2
Minimum tank temperature, °C = 4.4
Maximum CO2 concentration in internal air, vpm = 398
Minimum CO2 concentration in internal air, vpm = 302
Maximum level in tank, cm = 10.0
PRODUCTIVITY, gram per day per m² = 6.79
PRODUCTION, kg per m² = 2.48
COST PRICE (present value at day 1), $/kg = 16.86

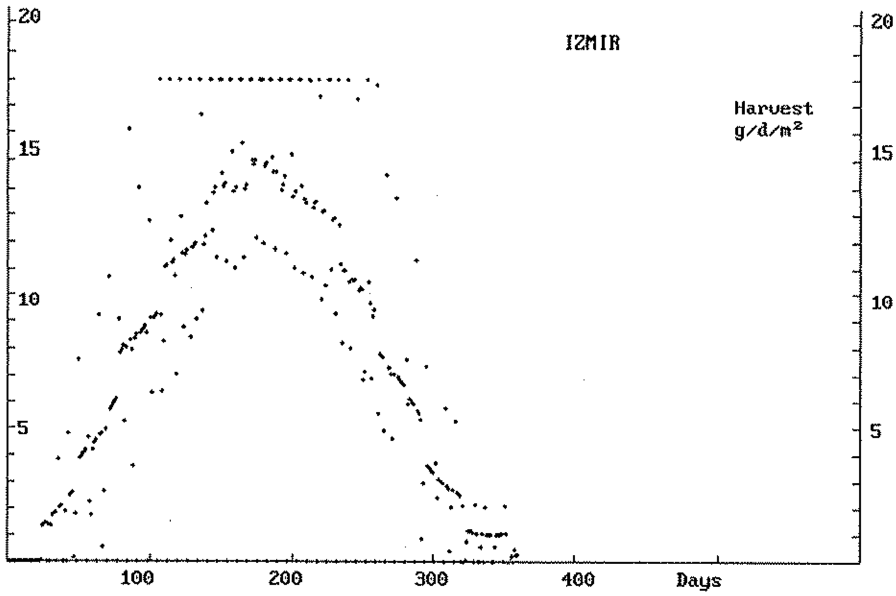

Figure 9. Daily production

The search for the minimum cost price or the maximum production is effected by varying parameters.

Fig. 10 gives the relationship between the bicarbonate consumption (used as the sole pH controlling agent) and the productivity when using the simplest type of greenhouse (standard case for the examples given here) and when using a fully equipped, modern greenhouse. At low pH the simplest greenhouse is 25 % better than without any greenhouse.

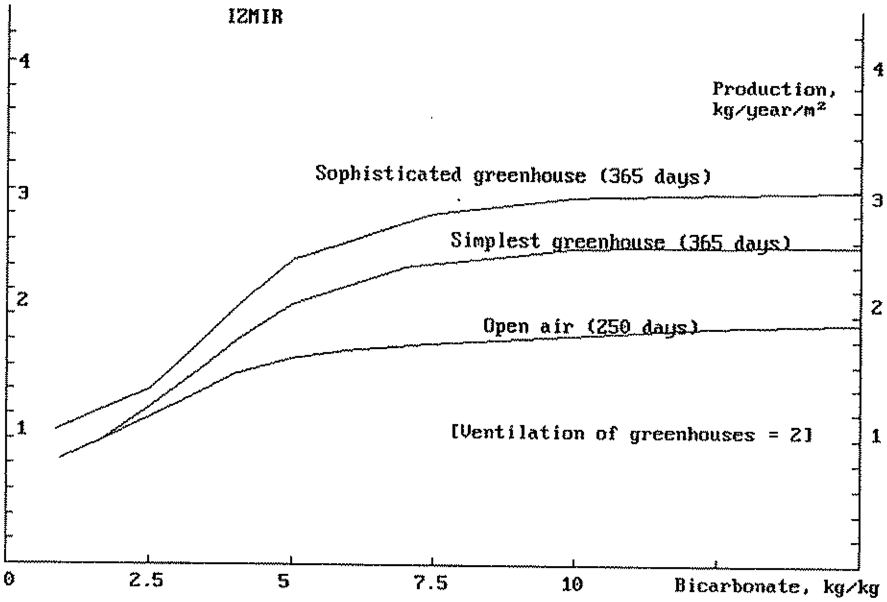

Figure 10. Productivity vs. bicarbonate consumption

Fig. 11 show typical results obtained by varying the pH control value while using bicarbonate as the sole pH controlling agent and Fig. 12 shows the same using liquid CO2. The optimum pH obviously depends on the cost of the carbon source.

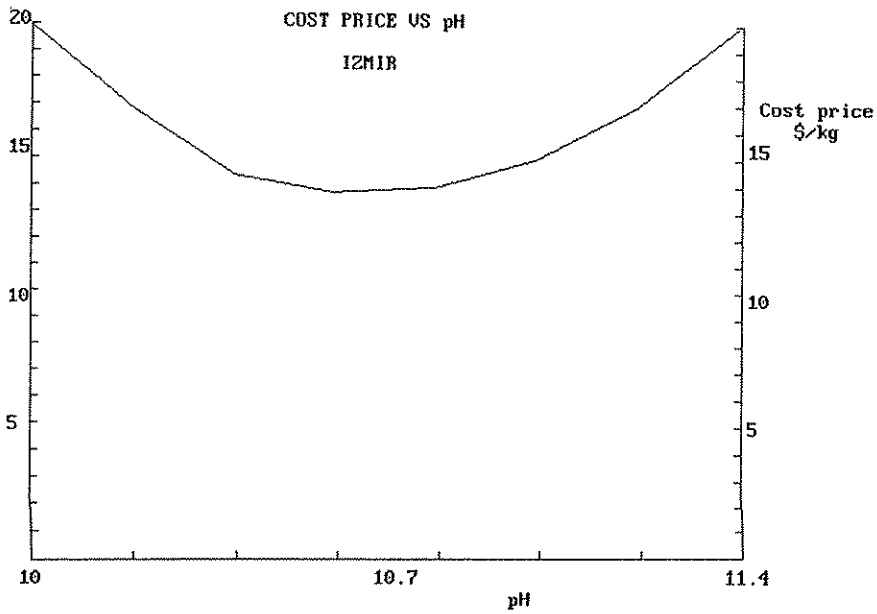

Figure 11. Cost price vs. pH with bicarbonate (@ 0.8 $/kg)

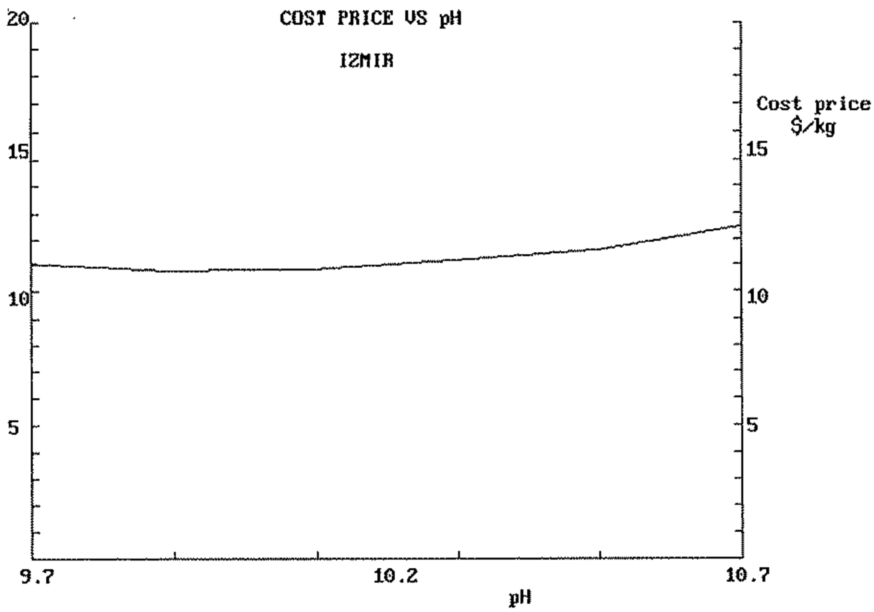

Figure 12. Cost price vs. pH with CO_2 (@ 4 $/kg)

Fig.13 shows the negative influence of high biomass concentrations on the productivity, due to the effect of respiration.

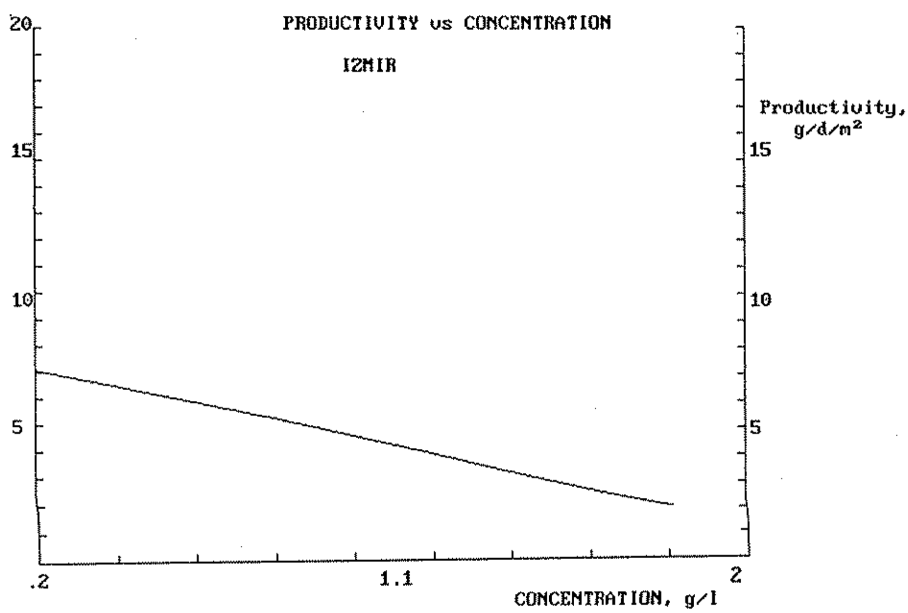

Figure 13. Productivity vs. biomass concentration

Fig. 14 shows the negative influence of a high depth of culture on the productivity, due both to the reduction of the maximum temperature and to higher respiration.

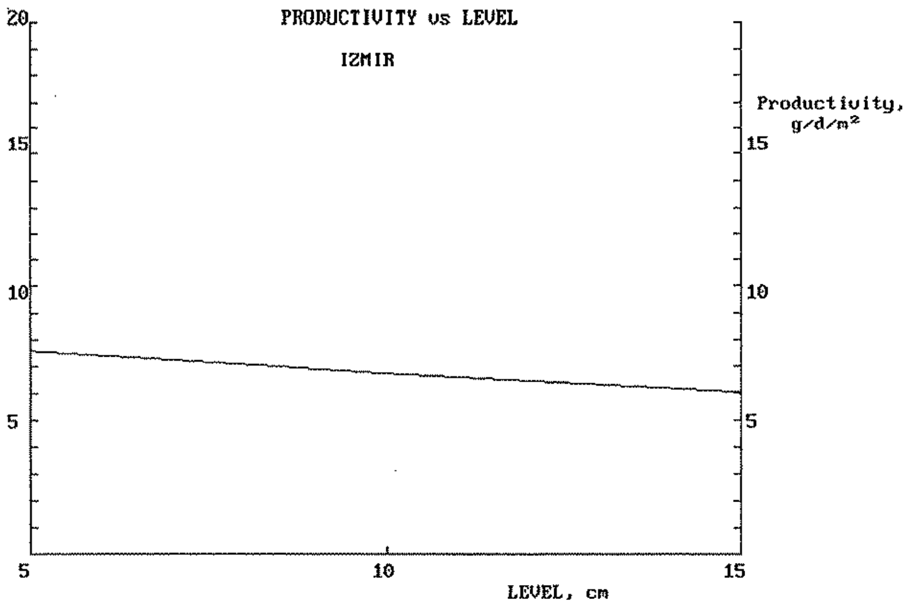

Figure 14. Productivity vs. culture depth or level

Fig. 15 shows the minute influence the air circulation rate has on the productivity. When an artificial carbon source is used, the influence is negative due to lower temperatures. Without an artificial carbon source, it becomes positive due to more CO_2 available from the air, but it remains negligible.

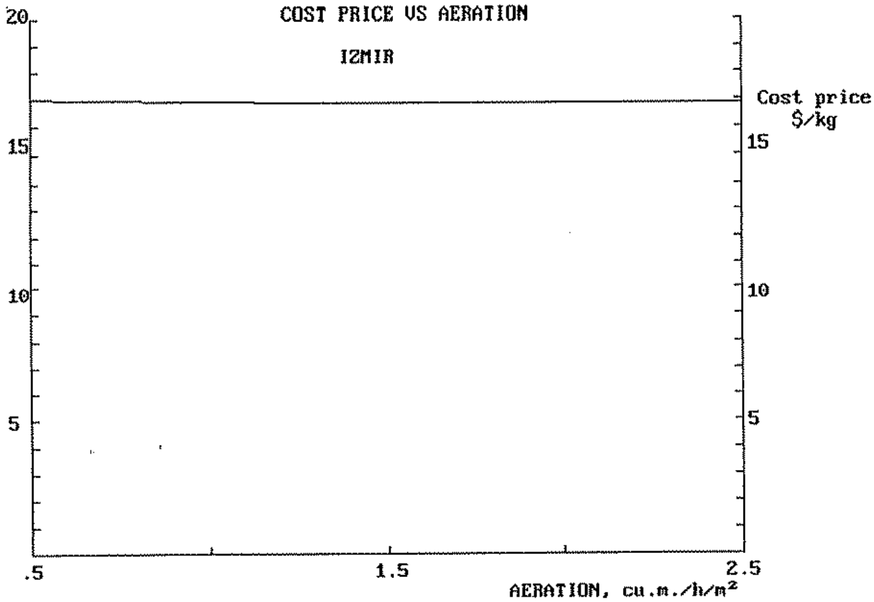

Figure 15. Productivity vs. ventilation rate

Fig. 16 shows the influence of the salinity of the make-up water on the productivity.

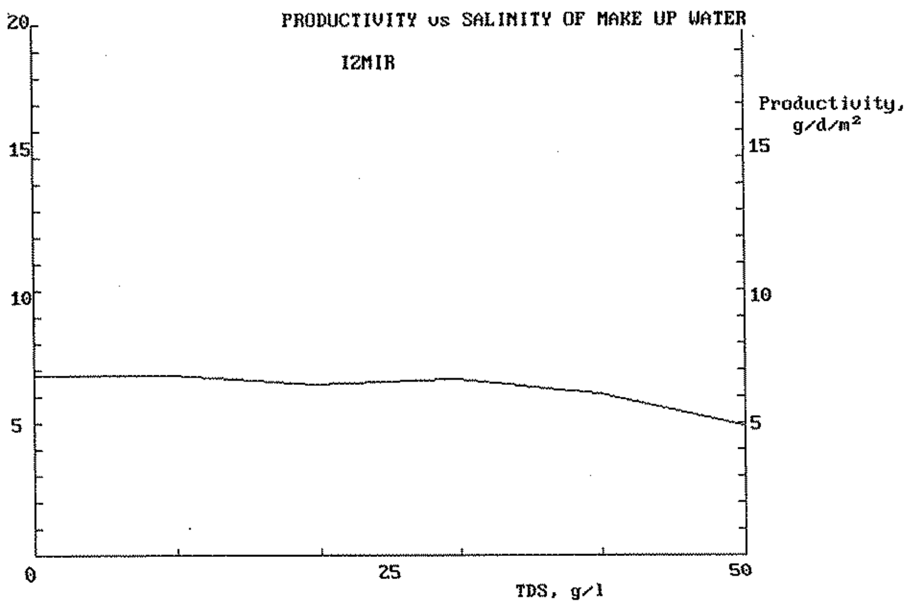

Figure 16. Cost price vs. salinity (total disolved salts) of make-up water

Fig. 17 gives an example where propane fuel is the sole artificial carbon source. The cost price can be quite low provided the air circulation rate is kept minimal.

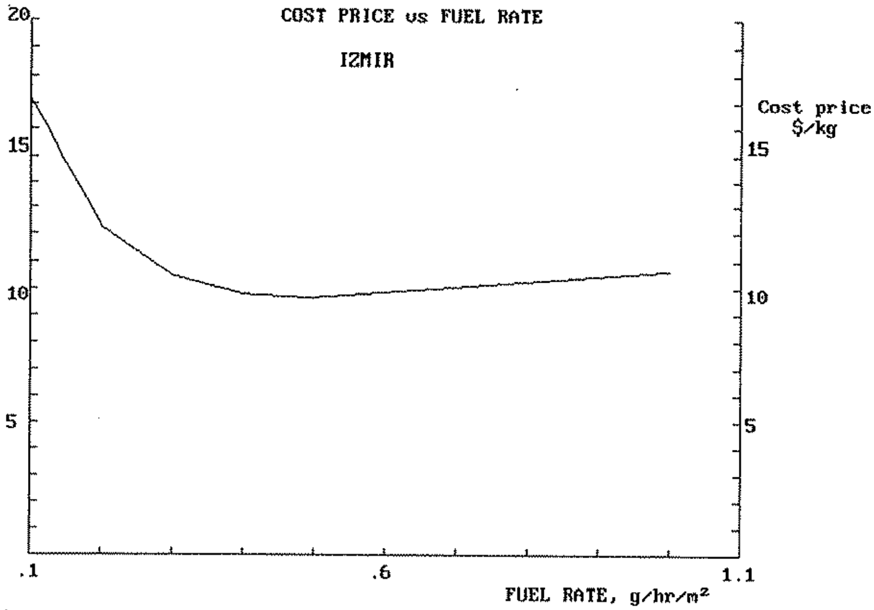

Figure 17. Cost price vs. fuel rate with propane @ 1 $/kg as sole carbon source and ventilation rate = 0.1 m/hr

Another use of the model is to evaluate the economic penalty due to shorter periods between changing the culture medium. For three changes per year instead of one, the penalty comes out to be 4 % on productivity and only 1 % on cost price in the example given here. So, as a new culture is easier to harvest, it is recommendable to renew the medium several times a year.

Discussion

In spite of taking into account around eighty parameters, the model is far from comprehending the totality of the factors, notably biological, that influence the growth and quality of the spirulina produced in artificial conditions.

Although results from the model fit actual data generally well, the model has yet to be fully validated. It would be extremely desirable to compare a number of calculated and observed results, but for such comparisons to be valid, the data used should closely match the experimental conditions. Such a close match actually is beyond the scope of this work, but could constitute interesting thesis subjects for students. It is suggested that comparisons with actual results be communicated to the author for further validation or modification of the model. Laboratory studies are often conducted as batch cultures under constant illumination twelve hours a day. A variant of the model was developed to facilitate validation from such laboratory studies.

As it is, this model can be useful to predict trends, optimize operating conditions, make technical and economic analyses, and as a teachingl aid.

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