Assessment of extreme productivity of microalgae cultivated in the open air around neighborhoods of Isfahan City

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Abstract

The widespread use of microalgae in various fields of human activity including fishery generated a need of highly productive technologies of industrial production of microalgae biomass. In present paper, extreme productivity values of microalgae culturing system were assessed around neighborhoods of the Isfahan City in theory. It will amount to 37.90 g of dry weight (g. d. w.) per 1 m^2 of the illuminated reactor surface under condition that efficiency factor of photobiosynthesis equals to 5%. When photobiosynthetic efficiency is 15%, maximum values of productivity will be 113.71 g. d. w. per 1 m^2. Productivity of microalgae culturing system for its various orientations relative to the Sun at different photobiosynthetic efficiency was calculated on basis of simple model understandings regarding average caloric content of 1 g.d.w. of microalgae and the daily distribution of solar radiation which arrives at the surface of the Earth. If it is drown a curve of the third order (spline) through the points corresponding to days of the vernal (21 March) and autumnal (21 September) equinoxes and a summer solstice (22 June), the extreme (ideal) value of the yield will be 18.5 kg of dry biomass per square meter of illuminated surface (at photobiosynthetic efficiency of 0.15).

Keywords: Microalgae, Sun seeking bioreactor, Open pond, Photobiosynthesis, Solar radiation

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Introduction

The widespread use of microalgae in various fields of human activity including fishery generated a need of creation of highly productive technologies of industrial production of microalgae biomass and the biosynthesis of biologically valuable substances (Borowitska, 1999; Spolaore et al., 2006). Among many factors influencing microalgae growth, the special role is related to light backing of cells because light is the basic energy source in photosynthesis. Quite many different designs of photobioreactors for intense cultivation of microalgae in which are used as natural radiation sources and man-made radiation sources were developed (Lee and Palsson, 1994; Miron et al., 2000; Barbosa, 2003; Pulz, 2007; Ugwu et al., 2008). Man-made radiation sources in comparison with natural radiation sources offer several advantages. The possible control of lighting conditions which provide for organization of controlled intensive culture of microalgae is the most important among these advantages. As a consequence, it is possible to control the biochemical composition (quality) of the biomass and to receive high speed of the biosynthesis of valuable substances that are included in its composition. However, all technologies of photobiosynthesis made on basis of man-made radiation sources are power-consuming enough that enhances significantly the prime cost of the final product.

For Iran, intensive microalgae cultivation with the purpose of commercial use in production quantities remains above field of vision both the scientists and the businessmen in spite of the fact that country has all climatic prerequisites. Moreover, representatives of different microalgae divisions inhabit water bodies of Iran (Zarei-Darki, 2004). Many of them can be considered as biotechnological objects for the man-made cultivation, are as follows: *Dunaliella salina* Teod. (it was found out in the Gavkhini Wetland, Urmia Lake, Maharlu Lake), *Chlorella vulgaris* Beijer. (biological ponds), *Scenedesmus obliquus* (Turp.) Kütz. (Voshmgir and Jiroft Reservoirs, Dizine Pond), *S. quadricauda* (Turp.) Breb. (Aras, Karun, Minab and Zayendehrud Reservoirs), *Nostoc pruniforme* Ag. (Yasuj and Semirom Waterfalls), *Anabaena variabilis* Kütz. (Aras, Karkhe, Toroq Reservoirs).

The aim of present paper is to show simple methods of assessment of extreme productivity value for microalgae culturing system at different efficiency factor of photobiosynthesis by the example data about solar radiation of Isfahan City.

Materials and methods

In the article we use terms like photobiosynthesis, productivity, performance (yield), sun seeking and horizontal reactors therefore it makes sense to give their definitions for better understanding of the work.

Photobiosynthesis is the coordinated synthesis of all components of an organism that is biological synthesis of living structure. Synthesis of an organism occurs mainly at the expense of photosynthesis (light-energy). By this definition, it is necessary to understand name of the organisms and not chemical substances in order to underline the main feature of definition of photobiosynthesis (photobiosynthesis is biosynthesis of a living organism on the whole) (Belyanin, 1984).

Productivity (P) is the total number of biomass formed by growing and multiplicating cells of microalgae per day per unit area of the illuminated surface (areal productivity) or per unit volume of the cell suspension (volumetric productivity) (Vonshak, 2002).

$$P = B * \mu, \quad [P] = [g \cdot l^{-1} \cdot day^{-1}] \text{ or } [P] = [g \cdot m^{-2} \cdot day^{-1}]$$

Where: B is current population density, $g \cdot l^{-1}$, μ is the specific growth rate of the microalgae, day^{-1}.

Performance of the culturing system (yield of all culturing system) is total number of the biomass received by the growing and multiplicating cells of microalgae per day per all area of the illuminated surface or per all volume of the culturing system.

In present work, terms of productivity and performance (yield) are equivalent because calculations are made per one m^2 of an illuminated surface. Daily productivity (in grams of absolutely dry biomass, $g \cdot m^{-2} \cdot day^{-1}$ per one square meter of an illuminated reactor surface is determined as:

$$P = \frac{E_x}{R}, \qquad [P] = [g \cdot m^{-2} \cdot day^{-1}]$$

Where: E_x is solar energy which assimilated in the form of biomass, R is calorie content of one gram of dry weight, g.d.w.

It is more suitable, if we will show the main mathematical process which use in this paper for calculation daily productivity and solar energy as table (Table 1).

Table 1: The main mathematical process which use for calculation daily productivity and solar energy

Name of variable	Formulas	Notations and commentaries
Daily productivity	$P = \frac{\eta \cdot E_A}{R} = \frac{\eta \cdot \alpha \cdot E_{PAR}}{R}$, (1)	E_A is luminous energy which absorbed by microalgae suspension; η is photosynthetic efficiency that expressed as proportion ($\eta = 0 \div 1$); α is light absorption coefficient of microalgae suspension ($\alpha = 0 \div 1$); E_{PAR} is total amount of the photosynthetically active radiation (PAR) which arrives to the illuminated surface of reactor per day; R is calorie content of one gram of dry weight, g.d.w.
Law of distribution of solar energy	$E(t) = \frac{E_m}{2} \sin\left(\frac{\pi}{12} \cdot t - \frac{\pi}{2}\right)$, (2)	t is time in hours, E_m is maximal daily total solar radiation falling on a horizontal ground surface. It is sinusoid with minimum at 6 and 18 o'clock position and with maximum at 12 o'clock position during the 24 h.
The total energy of PAR	$E_{PAR} = \int_6^{18} E(t) \cdot dt$ (3)	It falls per day per square meter of the illuminated surface.

In present paper, we also assume that α = 1 in other words all falling solar energy is absorbed and then parameter of E_A is equivalent to parameter of E_{PAR} ($E_A = E_{PAR}$); parameter of η takes the values 0.05, 0.10 and 0.15, corresponding to 5, 10 and 15% photobiosynthetic efficiency. It also is presumed that percent of PAR makes 50 % in falling solar radiation (Tooming and Gulyaev, 1967; Khromov and Petrosyants, 2001).

Average caloric content of 1 g.d.w. of microalgae like *Chlorella vulgaris* Beijer., *Spirulina platensis* Geitl., *Synechococcus elongatus* Nag. and *Platymonas viridis* Rouch. makes about 5 kcal (21 KJ) (Belyanin et al., 1980).

It is supposed that the definition «sun seeking bioreactor» is culturing system in which illuminated surface is always perpendicular to the solar radiation flux. The definition «horizontal reactor» means culturing system in which illuminated surface is always placed in parallel to ground surface. The data of daily flux of the total (direct and diffused) solar radiation to a horizontal surface in the months inclusive days of equinoxes and solstices (in $кJ \cdot m^{-2} \cdot day^{-1}$) have been civilly provided by Isfahan Meteorological Organization.

Results

Assessment of solar radiation flux on the ground surface:

First of all, radiant energy of the Sun that plants transform in process of photosynthesis (PAR) influences on productivity values of microalgae cultivated in the open air.

It is known that the intensity of falling radiation arriving from the Sun makes 1367 $W \cdot m^{-2}$ (solar constant) on average at the upper border of the atmosphere. In other words, 118 MJ of energy falls on every square meter of surface which is perpendicular to the radiation flux during 24 hours. Since percent of PAR in this energy is about 50% (Khromov and Petrosyants, 2001), daily productivity per square meter of illuminated surface outside the earth's atmosphere in ideal case make by the formula 1:

$$P = \frac{0.11 \cdot 1 \cdot 0.5 \cdot 118}{0.021} = 309 \quad \text{g.d.w.}$$

when the photobiosynthetic efficiency is 11%.

For example, the influx of solar radiation amounts to 10-11 $kW \cdot h \cdot m^{-2} \cdot day^{-1}$ that is 39 $MJ \cdot m^{-2} \cdot day^{-1}$ in some areas of Spain and Nevada in July. Then extreme productivity value of one square meter of illuminated surface at the photobiosynthetic efficiency of 11% equals:

$$P = \frac{\eta \cdot \alpha \cdot E_{PAR}}{R} = \frac{0.11 \cdot 1 \cdot 0.5 \cdot 39}{0.021} = 102 \quad \text{g.d.w.}$$

Limit number productivity of microalgae around neighborhoods of Isfahan City:

Also, it is possible to consider Iran's territory as very favorable for the microalgae culturing in production quantities in the open air. It's geographic latitude that lies between 24° and 40° N and climate features show that territory of Iran gets one of the greatest influxes of solar radiation on the ground surface (Khromov and Petrosyants, 2001, www.esfahanmet.ir).

If maximum total daily values of falling solar radiation on a horizontal ground surface are known, it is possible to calculate extreme productivity values of microalgae for this area (Table 2).

Table 2: The data about influx of maximal daily total solar radiation E_m on a horizontal surface ($\kappa J \cdot m^{-2} \cdot day^{-1}$) in the months including days of equinoxes and solstices (data taken from the Isfahan Metrological Organization)

Day	E_m, $\kappa J \cdot m^{-2} \cdot day^{-1}$	E_{PAR}, κJ
29/III	24320	12160
20/VI	31839	15919.5
06/IX	25472	12736
05/XII	9391	4695.5

Value of falling solar energy E_A PAR is calculated with the equation:

$$E_A = E_{PAR} = 0.5 \cdot E_m; \quad [W] = [\kappa J]$$

Now, it is possible to calculate productivity by the formula 1 and to enter findings for ideal conditions on a ground surface in the Table 3.

The presented calculations of extreme productivity values of microalgae in this table show that the maximal productivity will make 37.90 g. d. w. per square meter of the illuminated reactor surface under condition that efficiency factor of photobiosynthesis equals to 5% in the summer. When photobiosynthetic efficiency is 15%, maximum values of productivity will be 113.71 g. d. w. per square meter.

The calculated extreme productivity values are productivity of "sun seeking bioreactor». The reactor of this type turns following the Sun so that the falling solar influx remains perpendicular to an illuminated reactor surface all time. That is to say, in the elementary case, the reactor surface of "sun seeking bioreactor» will be illuminated E_{SSR} according to the sinusoidal law in the course of day (2) (Fig. 1):

$$E_{SSR}(t) = \frac{E_m}{2}\sin\left(\frac{\pi}{12}\cdot t - \frac{\pi}{2}\right)$$

Table 3: Daily productivity *P (η)*, g·m^{-2}·day^{-1} of the illuminated surface depending on reactor type for different photobiosynthetic efficiency

Type of the reactor	**Productivity,** g·m^{-2}·day^{-1}				For summer half year
	29/III	**20/VI**	**06/IX**	**05/XII**	
Under conditions that photobiosynthetic efficiency takes values 0.05					
Horizontal	22.86	30.00	23.96	8.86	
Sun seeking	28.95	37.90	30.32	11.18	**6190**
Under conditions that photobiosynthetic efficiency takes values 0.1					
Horizontal	45.71	60.00	47.93	17.71	
Sun seeking	57.90	75.81	60.65	22.36	**12385**
Under conditions that photobiosynthetic efficiency takes values 0.15					
Horizontal	68.57	90.00	71.89	26.57	
Sun seeking	86.86	113.71	90.97	33.54	**18577**

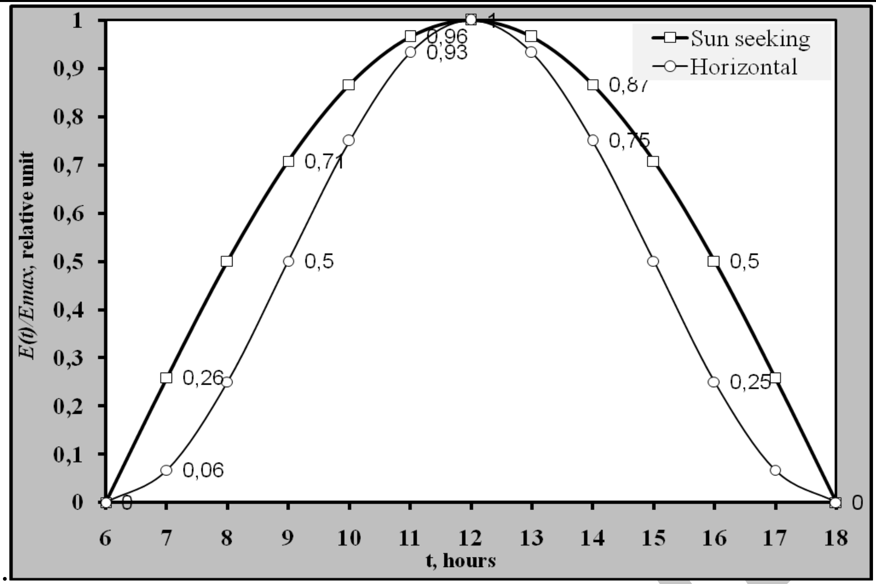

Figure 1: Relative distribution of the solar radiation arriving on a surface of sun seeking and horizontal bioreactors

If values of the maximal daily energy of PAR E_{PAR} on a horizontal surface (кJ) are known, it is possible to calculate E_m by formula (3) in the present months.

It is interesting to compare sun seeking bioreactor with usual open pond so-called "horizontal reactor" which has reduced productivity because of decrease of irradiation in the course of day.

Horizontal reactor is located parallel to the ground surface therefore projection of the solar flux E_{HR} will get to it in the following way:

$$E_{HR}(t) = E(t) \cdot \sin(\theta) = E_m \sin^2(\theta),$$

where $\theta = \frac{\pi}{12} \cdot t - \frac{\pi}{2}$

On the basis of above mentioned assumptions concerning distribution of solar radiation falling on sun seeking and horizontal bioreactors, it is possible to calculate the total energy arriving on a horizontal reactor by the formula (3) per day. Then if total energy of PAR E_{PAR} and caloric content R is known, productivity of culturing system in the open pond would calculate by the formula (1). Calculation results have been given in Table 3.

The received values of productivity amount to 30, 60, and 90 g. d. w. per square meter of the illuminated reactor surface under condition that efficiency factor of photobiosynthesis correspondingly equals to 5, 10 and 15%.

Comparing received charts of sun seeking and horizontal bioreactors, it can say that all improvements of a horizontal reactor design as form and orientation concerning an influx direction of solar radiation can increase productivity no more than 21%.

Assessment of the basic yield over a period of vernal-autumnal equinox:

It is clear that the basic yield can be received during summer months when the highest activity of the sun is observed. Now, we calculate the highest possible value of a yield per unit area (m^2) of an illuminated reactor surface over a period of vernal-autumnal equinox. A curve of the third order (spline) is drawn through the points presented in the Table 1 and conformed to days of the vernal (21 March) and autumnal (21 September) equinoxes and a summer solstice (22 June). Thus, the simplified model of distribution of the daily irradiations is found over specified period. If obtained data are summed, it will be possible to determine value of solar radiation for a half-year. In our case, it makes about 5200 MJ•m-2 •day-1 (Fig. 2). Then productivity (yield) is found by the formula (1) with Table 1 in a similar above mentioned calculations (Table 3). Extreme (ideal) productivity value will make 18.5 kg of a dry biomass per one square meter of an illuminated surface at the photobiosynthetic efficiency equaled 0.15% over a summer period from 21 March to 21 September.

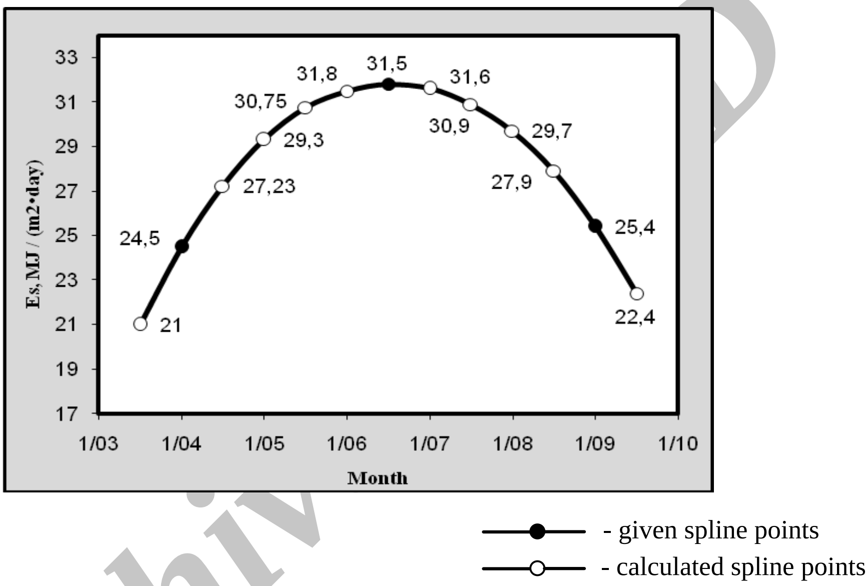

Figure 2: Dispersal of the falling solar radiation on the ground surface in the Isfahan suburbs over a summer period

Discussion

The total solar radiation flux on the ground surface depends on many factors like season, latitude and longitude of a locality, optical characteristic of atmosphere, relief and so on. Detailed maps of distribution of solar radiation flux were composed for many countries (http://www.nrel.gov/gis/solar.html.; http://re.jrc.ec.europa.eu.) since this is important for many research works.

The greatest influx of solar energy arriving to the earth's surface observes according to research centers of different countries in latitudes from 30 to 40 in summer (Khromov and Petrosyants, 2001; http://www.nrel.gov).

The presented calculations of extreme productivity values of microalgae show that the maximal productivity will make 37.90 g. d. w. per square meter of the illuminated reactor surface under condition that efficiency factor of photobiosynthesis equals to 5%; and there is 113.71 g. d. w. per square meter when photobiosynthetic efficiency is 15%. It is clear that even in the full solar maintenance of cell it is practically impossible to receive these productivity values because they will be reduced through other limiting factors as mineral supply of cells, inhibition of growth by metabolism products and so forth.

It is noteworthy to note that all improvements of a reactor design as form and orientation concerning an influx direction of solar radiation are possible to increase productivity nothing more than 21% in comparison with a reactor which has active (illuminated) surface located parallel to ground surface (open pond). Extreme (ideal) productivity value will make 18.5 kg of a dry biomass per one square meter of an illuminated surface (at the photobiosynthetic efficiency of 0.15%) over a summer period from 21 March to 21 September.

We underline that it is necessary to distinguish two definitions as the productivity per unit of illuminated surface and the productivity per unit area occupied by the culturing system on the ground (footprint) in calculations of the productivity values for different photobioreactor designs. Some developers of culturing systems give an report of reaching a record high productivity up to 174 g.d.w.· m^{-2}·day^{-1} referring to a unique photobioreactor form of 3D Matrix System (Pulz and Scheibenbogen, 1998). Moreover, all calculations are relative to the area occupied by the reactor on the ground rather than the illuminated surface that it introduces confusion in the comparisons.

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