

Potential Productivity of Microalgae in Industrial Photobioreactors

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Abstract—Based on the maximum theoretical efficiency of photosynthesis (25%), the potential productivity of microalgae can be estimated as 110–160 g/(m² day) under sunlight and two times higher under artificial 24-h illumination. The actual values achieved in industrial-scale photobioreactors are several times lower. Such a considerable difference between the potential and actual productivity is related to properties of the algal cell cycle and characteristic age distribution in the algal population, light propagation in optically thick suspensions, and shortcomings in the design of photobioreactors and practices of algae growing. The contribution of each of these factors is discussed. The practically attainable efficiency of light-energy use in industrial-scale photobioreactors was shown to be equal to 12–14%, with an algal productivity of 60–80 and 120–150 g/(m² day) under natural and artificial illumination, respectively.

Key words: microalgae - photobioreactor - productivity

INTRODUCTION

The production of algal biomass and valuable substances derived from it is continuously growing, with an expanding list of industrially grown unicellular phototrophs and the fields of their application. In this connection, many researchers aim their efforts at developing open and closed photobioreactors for the large-scale industrial cultivation of microalgae under natural or artificial illumination [1–4]. The application of some or other type of photobioreactor depends on the cultivation purpose. Construction and maintenance costs of open photobioreactors are lower than those of closed ones; however, problems with contamination arise, which considerably limit the utilization of the obtained microalgal biomass. Closed photobioreactors allow for stricter control of the cultivation regime, channeling the synthesis into the selective accumulation of substances required, and production of high-quality biomass for food, pharmaceutical, and medical purposes.

Presently, the productivity of photobioreactors under natural illumination attains about 25–35 g of dry biomass/(m² day) [4, 5], which is about five times higher than the productivity of higher plant stands. Nevertheless, this is far from the potential photosynthetic capacity of microalgae. Calculations show that, on cloudless days, the incident solar energy in the PAR region is sufficient to produce 110–160 g (depending on the region) of dry biomass per day from 1 m² of illuminated area, assuming the photosynthetic efficiency to be equal to 25%. When artificial light is used, the potential productivity of photobioreactors can be increased twofold, due to 24-h illumination. A significant discrepancy between the potential photosynthesis

and the actual productivity can be explained by several factors, the major ones being the growth characteristics of microalgal populations, the peculiarities of their cell cycle, and the shortcomings of cultivation systems and processes. In this connection, it seems appropriate to analyze the factors affecting the productivity of microalgal populations in order to determine the basic principles for the construction of photobioreactors providing for the industrial-scale cultivation of photosynthesizing microorganisms, the development of respective technological specifications, as well as for an estimation of the production efficiency.

Effect of characteristics of cell and population development on the productivity of microalgal cultures. Numerous studies of synchronous cultures [6–9] showed significant variation in cell photosynthetic activity, and, therefore, in the efficiency of light energy conversion, during the cell development cycle. Figure 1 shows light-dependency curves of photosynthesis in a synchronous culture of *Chlorella* IPPAS C-1. During cell development from an autospore (curve 0 h) to the middle of the light development phase (4.5 h), the maximum photosynthetic rate increases and, then, considerably decreases to the end of the cell cycle. Thus, if the maximum theoretical value of the efficiency of light conversion can be attained at all, this may occur only within a rather narrow period of the cell cycle, i.e., in the middle of its light phase. That is why the efficiency of light conversion, when averaged over the whole cell cycle, is lower by at least a factor of 1.5–2.0; therefore, the photosynthetic efficiency of the population as a whole will be below its theoretical value. The value of the photosynthetic efficiency of a population will be the

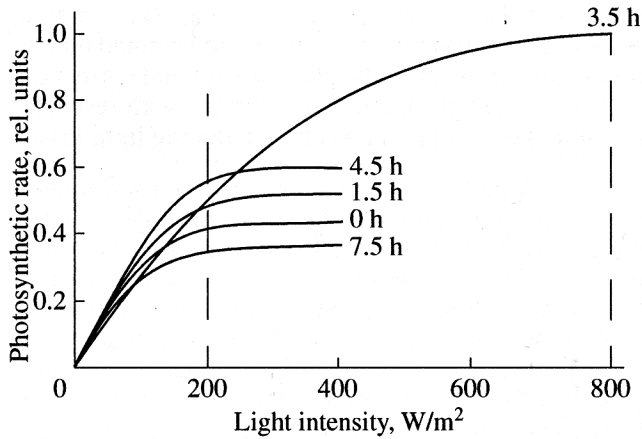


Fig. 1. Light-dependency curves of photosynthesis in *Chlorella* IPPAS C-1 cells at different stages of the cell cycle [8]. Numbers on the curves indicate time periods from the beginning of the cell cycle; the dashed lines indicate the light saturation level of photosynthesis.

highest as the environmental variables (mainly light intensity, temperature, and carbon supply) approach their optimum values.

The effect of individual characteristics of cell development on culture productivity can be estimated using the basic ideas of population dynamics. In a steady-state regime (for example, in the case of prolonged turbidostat cultivation of microalgae), the age distribution of a population can be described by an exponential curve, with an exponent proportional to the specific growth rate of the culture, $n(\tau) = \mu e^{-\mu\tau} / (1 - e^{-\mu T})$ [10], where $n(\tau)$ is the relative number of cells of the τ age; μ is the specific coefficient of culture propagation; e is the base of the natural logarithm; and T is the cell-cycle duration, hours. Figure 2a (curve 1) shows an example of cell age distribution in a *Chlorella* IPPAS C-1 culture under the steady-state regime at $\mu = 0.24 \text{ h}^{-1}$. Curves 2 and 3 in Fig. 2a show the increase in normalized cell biomass and the changes in the specific rate of biomass increase (photosynthetic activity) during a *Chlorella* cell cycle (the data are taken from [8]). Multiplication of curves 1, 2, and 3 gives the total relative value of cell photosynthesis as a function of cell age (Fig. 2b), and the area under the curve gives the relative value of the photosynthetic rate of the whole population. Curve 1 (Fig. 2b) was obtained assuming the constant maximum photosynthetic rate during the whole cell cycle (dashed line 4 in Fig. 2a), whereas curve 2 was obtained by taking into account the actual variation in cell photosynthetic activity. The data imply that the activity variation during the cell cycle and the development of the population reduce culture productivity by a factor of 1.69 as compared to the data for the constant maximum activity.

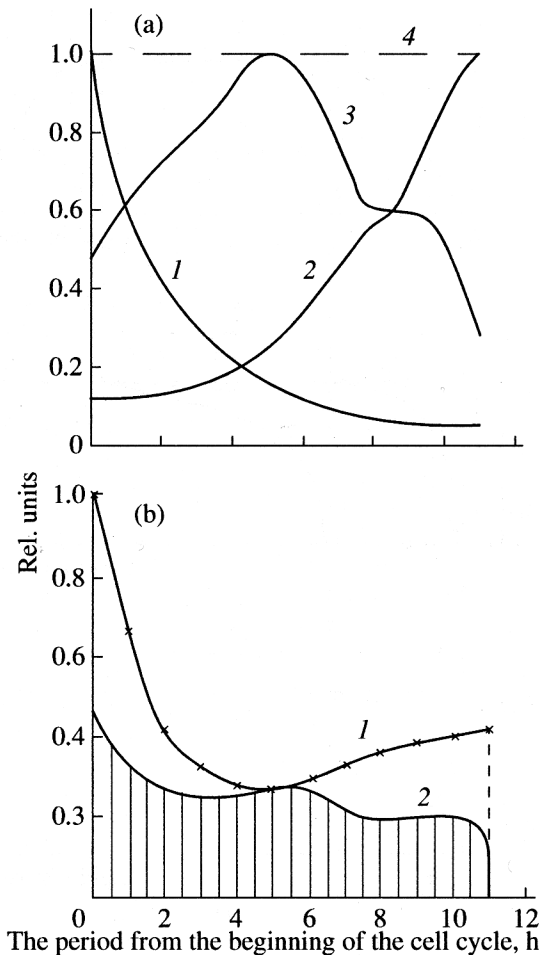


Fig. 2. Effect of cell age distribution and changes in cell physiological characteristics on the productivity of a population of microalgae.

(a) (1) Cell age distribution in a steady-state culture of microalgae with a specific growth rate of $\mu = 0.24 \text{ h}^{-1}$; (2) biomass growth; (3) the changes in photosynthetic activity during the cell cycle of *Chlorella* IPPAS C-1; (4) the maximum level of cell photosynthetic activity in the middle of the light stage of the cell cycle.

(b) Contribution of cells of different age to the productivity of the cell population: (1) as calculated from curve 4 (Fig. 2a); (2) for the actual changes in photosynthetic activity during the cell cycle (curve 3, Fig. 2a). The areas under curves 1 and 2 represent the total productivity of the population.

That is why the efficiency of photosynthetic light use in a suspension of microalgae did not exceed 14–16% even under laboratory conditions, when environmental variables were maintained close to their optimum values. The effect of variation in the cell-cycle efficiency on microalgae productivity can be reduced in the populations comprising the most photosynthetically active cells [11, 12]. Without a particular change in the age structure of populations, the above factors reduce the maximum productivity of cultures to 65–95 g/(m² day) and 130–190 g/(m² day) under natural and artificial illumination, respectively. Nevertheless,

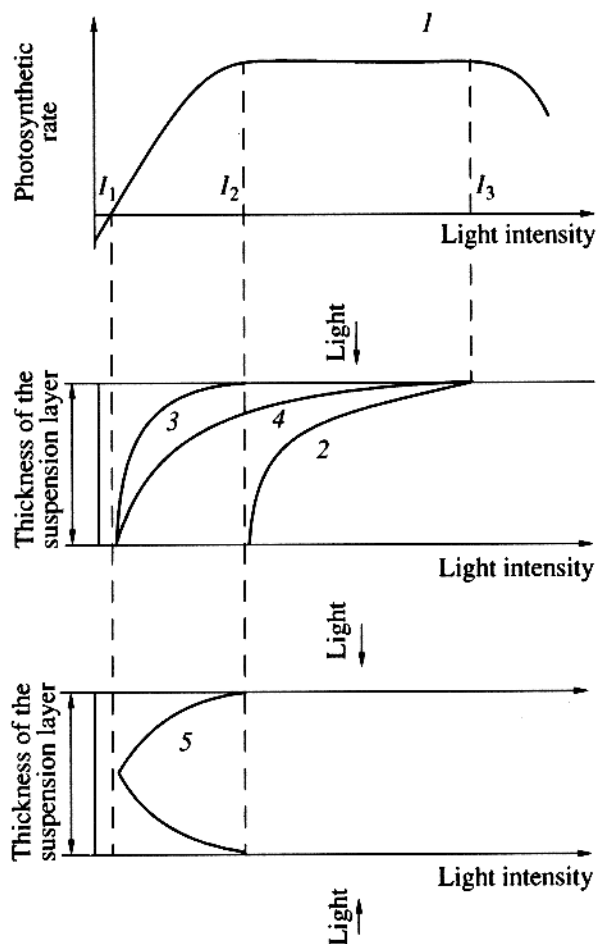


Fig. 3. (1) The generalized light-dependency curve of photosynthesis of microalgal cells and (2–5) light distribution in the suspension under varying illumination and culture density conditions.

One-sided illumination of the suspension: (2) low cell concentration in the suspension; (3) light distribution providing for the maximum efficiency of light utilization and high productivity of the culture; (4) light distribution providing for the maximum productivity of the culture. Two-sided illumination of the suspension: (5) light distribution for the maximum efficiency of light utilization and high productivity of the culture.

(I_1) light compensation point of cell photosynthesis; (I_2) the saturating light intensity for photosynthesis; (I_3) light intensity inhibitory for photosynthesis.

these values are significantly higher than the productivity actually attained, and the major cause for productivity losses seems to come from the drawbacks of cultivation systems and processes.

Light fluence rate and light distribution in suspensions of microalgae. The major factor in cultivating photosynthesizing organisms is light intensity. Under the actual conditions of the large-scale cultivation of microalgae, the amount of light energy absorbed by the cell suspension during daylight hours is always less than the total incident radiation on a horizontal surface. This is mainly due to light reflection from photoreactor

walls and the suspension surface, with the losses as high as 30–60% at this stage. It should be noted that the proper arrangement of the photoreactor and correct orientation of its light-intercepting surface with respect to the Sun play an important role in reducing light losses.

It is difficult to find a general solution for arranging the light-intercepting surface of the photoreactor, which would be applicable for all varieties of microalgae or at least for those that are most often used for large-scale cultivation. Light should enter the suspension at the intensity and specific fluence required by cells. By the "specific fluence" we mean the total light energy, in W, supplied per 1 l of suspension. This problem can be solved in each individual case using the data on light-energy distribution within suspensions and light-dependency curves of photosynthesis for different microalgae.

Figure 3 shows a light-dependency curve of photosynthesis (curve 7) and some types of light distribution within the cell suspension. Of course, the maximum photosynthetic activity in the suspension of microalgae can be attained only when all cells of the culture are in the light-saturation zone of photosynthesis (Fig. 3, curve 2). However, such light distribution requires either a low culture density or very thin suspension layers. This unavoidably involves considerable losses of light energy and a reduction in the efficiency of light use, which is especially important under conditions of artificial illumination. Photosynthetic production of a unit of illuminated surface in a photoreactor, which is defined as the product of cell activity by the cell number (or the activity of unit biomass by its amount), will be rather low. In turn, the maximum efficiency of light utilization attains its highest value when all cells of the culture are exposed to a light intensity corresponding to the linear portion of the light-dependency curve of photosynthesis (Fig. 3, curve 3). Under these conditions, the mean value of cell photosynthesis and the productivity of the population will be two times lower than under saturating light. The intensity of solar radiation is generally much higher than the saturating intensity for the photosynthesis of microalgal cells, even in such light-loving algae as many strains of *Chlorella*, *Scenedesmus*, and *Spirulina*. Such an organization of light distribution within a culture is apparently advantageous under artificial illumination, when the efficiency of light-energy utilization is of critical importance.

The study of light-distribution patterns within the suspensions of microalgae [13] and our experimental data show that to provide for the maximum efficiency of the utilization of artificial light energy (Fig. 3, curve 3), the intensity of incidental light should not exceed 100–120 W/m², and the thickness of the suspension layer in the photoreactor should be within the range of 2–3 cm at a suspension density between 3 and 5 g/l. The specific light fluence should be kept within the range of 3 and 6 W/l of the suspension.

Under sunlight conditions, the optimum light distribution is that shown in Fig. 3, curve 4, which results in virtually complete utilization of the light that enters the suspension and the high overall productivity of a culture. However, such light distribution is admissible only for those cultures in which the light intensity that inhibits photosynthesis is higher than the solar light intensity, and when the optimum temperature and carbon supply are provided during the whole light period.

When artificial light sources are used, the suspension is often illuminated from two surfaces, which results in a twofold increase in the illuminated photoreactor surface and specific fluence rate. Light distribution in the suspension illuminated from two sides, which provides for the highest efficiency of light energy use, is shown in Fig. 3 (curve 5).

It should also be borne in mind that the light-dependency curves of photosynthesis in microalgae are highly dependent on many physical variables of the cultivation process. When the suspension temperature is below the optimum level, solar radiation can be inhibitory even for a light-loving strain. For strains in which photosynthesis is saturated and inhibited at low light intensities, light distribution systems should be used or the light-intercepting surface should be arranged to reduce the intensity of solar radiation at the suspension surface. An example of such a photoreactor is a *Porphyridium* cultivation system (500 l) designed at the Institute of Grain Processing (Potsdam, Germany) [2], which has an area of light-intercepting surface of 20 m² and occupies 5 m² of ground area. The light intensity averaged over the illuminated surface does not exceed 40–50 W/m².

For the conditions of solar illumination and algae with a high level of light-saturation plateau, such as many strains of *Chlorella*, *Scenedesmus*, and *Spirulina*, the light-distribution pattern shown in Fig. 3 (curve 4) can be obtained at the suspension layer of 3–5 cm and culture densities from 4 to 6 g/l. The optimum specific light fluence rate is somewhat higher than for cultivation under artificial light and is between 10 and 20 W/l of suspension. Under such illumination conditions and optimum values of other cultivation variables (temperature, carbon supply, and composition of the nutrient medium), the utilization efficiency of light absorbed in the suspension can be as high as 12–14%. Therefore, the productivity (taking into account 30% losses of light energy due to reflection from the photoreactor and suspension surfaces) can reach about 40–65 g of dry weight from 1 m² of illuminated surface per day. These values approach the best results obtained in the large-scale cultivation of microalgae, although then exceed them almost by a factor of two.

In-process losses in the productivity of microalgae grown in photoreactors. One of the important factors that reduce culture productivity is the build-up of high oxygen levels in the suspension [2, 14], which results in the inhibition of photosynthesis and the alteration of

the chemical composition of the cell biomass [15–17]. On large-scale cultivation of microalgae, the partial pressure of oxygen dissolved in the suspension can be as high as 45–50% in open reactors [5] and even higher in closed photoreactors. High O₂ concentrations can reduce biomass production in photoreactors (particularly in tube-type reactors) by two or more times. As yet, there are no reliable and simple methods for degassing suspensions, and this remains one of the major cultivation problems.

One of the important causes for productivity losses on cultivation under conditions of solar illumination is a discrepancy between light intensity and suspension temperature. The curves of daily variation in temperature and light intensity show a significant phase shift [18]. Generally, in the morning, the suspension temperature does not exceed 18–20°C (otherwise, there are significant respiratory losses at night), whereas the light intensity is rather high at this time. In addition to reducing the suspension photosynthetic activity, such an imbalance in the most important cultivation variables would also affect the physiological condition of cells. The resulting prolonged lag-phase, especially in cells that are most sensitive to environmental changes (dividing cells and cells at the second half of the light phase of their development), will decrease culture productivity during the subsequent hours of cultivation.

It is noteworthy that the daily course of the intensity of solar radiation and the changes in the photosynthetic activity and light-saturation plateau of photosynthesis during their cell cycle (Fig. 1) are similar, which can be regarded as an evolutionary adaptation of unicellular algae. Under the conditions of natural periodic illumination, the synchronous cultivation of microalgae may be of significant advantage, as the light regime matches cell demands. In addition, the processes that occur at the light-independent phase of the cell cycle and do not require a light-energy supply could take place during the night. Such a cultivation regime could significantly increase culture productivity, because the mother cells, in which autospores are formed, and dividing cells have low photosynthetic activity, and, during the day time, they only shade photosynthetically active cells.

Synchronization of the culture in industrial-scale photoreactors is a difficult task because of variable weather conditions, first of all, due to the changing suspension temperature, which determines the cell-cycle duration, and the variable day length during the cultivation season. Nevertheless, even partial culture synchronization can result in significant advantages.

The productivity of photoreactors is affected to a certain degree by the “dark” volume of the suspension, which results in biomass losses for the dark respiration of cells. On the “light–darkness” transition, the rate of cell respiration gradually decreases from the light to dark respiration level, a process which can take from several minutes to an hour. In addition, the high temperature of the suspension in the dark volume also contrib-

utes to the high respiration level. In the case of high dark-to-light volumes of the suspension, respiratory losses can reach 20–30% of the photosynthetic production of the culture.

To provide for mass exchange of a culture in both open and closed photobioreactors, mechanical stirring devices or suspension circulation systems are applied, which negatively affect the physiological state of cultures and often lead to the mechanical cell destruction of some species, such as *Spirulina*, *Dunaliella*, and *Porphyridium*. This can result in a significant reduction in the photobioreactor productivity.

Considerable losses in productivity can arise in closed reactors due to the fouling of the light-intercepting surface with nutrient salts and cells, which should also be accounted for in designing microalgae cultivation systems.

We accounted for the above processing causes of the low productivity of microalgae in designing photobioreactors Priboi and Luxfors [19], which allowed us to obtain an efficiency of light-energy use as high as 11–12%.

Estimation of the potential productivity of photoreactors. An approximate estimate of the potential biomass productivity (P) of a photoreactor can be obtained based on the total light energy passing through its light-intercepting surface. Under the conditions of 24-h illumination with artificial light, determination of the incident daily light energy presents no difficulty, and the potential productivity can be presented by the following equation:

$$P = 14.4\eta IS(1 - 0.2(V_d/V_l))/Q,$$

where η is the efficiency of light utilization, which (as follows from the above) can be assumed to be equal to 0.1–0.12 for estimation of the potential productivity; I is the light intensity W/m^2 ; S is the area of the photobioreactor light-intercepting surface; m^2 , V_l , and V_d are the illuminated and dark volumes of the suspension; Q is the calorific value of 1 g of biomass, kcal; and 14.4 is the coefficient for the conversion of daily incident radiation in kcal, with account taken for the 30% loss of light energy due to the reflection from the photobioreactor and suspension surfaces.

When solar illumination is used, estimation of the total light energy is much more difficult due to constant variations in the light intensity and the angle of incidence with respect to the solar light-intercepting surface of the photobioreactor. In this case, an approximate formula for the estimation of the potential productivity can be written as follows:

$$P = \frac{0.6\eta TS(1 - 0.2V_d/V_l)}{Q} \int_{t_1}^{t_2} I(t) \cos \varphi(t) dt,$$

where c is the day length, hours; φ is the angle of incidence with respect to the photobioreactor light-inter-

cepting surface at the time t ; t_1 is the beginning and t_2 is the end of the light day; and 0.6 is the coefficient for conversion of incident radiation in kcal with account taken for 30% losses. Of course, the value of η significantly depends on the cultivated strain of microalgae. The above formulas apply to the mass culturing of thermophilic algae, such as *Chlorella*, *Scenedesmus*, and *Spirulina*, under the optimum regimes of cultivation and light distribution in the culture. In turn, a considerable deviation in the values of the actual and calculated productivity can indicate design or process errors in the cultivation system or process.

Thus, with the productivity losses due to imperfect cultivation equipment and processes excluded, the potential productivity of microalgae can be estimated within the range of 60–80 g of dry weight from 1 m^2 of the illuminated surface per day under the conditions of solar illumination and about 120–150 g under 24-h artificial illumination (with the achievable efficiency of light-energy utilization of 12–14%).

REFERENCES

1. Tredici, M.R., Carozzi, P., Zinelli, G.C., and Materass, R., A Vertical Alveolar Panel (VAP) for Outdoor Mass Cultivation of Microalgae and Cyanobacteria, *Bio. Technol.*, 1991, vol. 38, pp. 153–161.
2. Ratchford, I.A. and Fallowfield, H.J., Performance of a Flat Plate, Air-Lift Reactors for the Growth of High Biomass Algal Cultures, *J. Appl. Phycol.*, 1992, vol. 4, pp. 1–9.
3. Richmond, A., Open Systems for the Mass Cultivation of Photoautotrophic Microalgae Outdoors: Physiological Principles, *J. Appl. Phycol.*, 1992, vol. 4, pp. 281–289.
4. Pulz, O., Laminar Concept of Closed Photobioreactor Designs for the Production of Microalgal Biomass, *Fiziol. Rast. (Moscow)*, 1994, vol. 41, pp. 292–298 (*Russ. J. Plant Physiol.*, Engl. Transl.).
5. Tsoglin, L.N., Avramova, S., Gabov, A., Dilov, Kh., and Semenenko, V.E., Study on O₂ Exchange and Optimization of Microalgal Culture Conditions for the "Shetlik"-Type Open Installation, *Fiziol. Rast. (Moscow)*, 1981, vol. 27, pp. 644–652 (*Sov. Plant Physiol.*, Engl. Transl.).
6. Senger, H., Quantum Yield of Photosynthesis in Synchronous Cultures of Algae, *Proc. 1st Eur. Biophys. Congr.*, Baden Near Viena, 1971, p. 33.
7. Berkova, E., Doucha, J., Kubin, S., Zachleder, V., and Setlik, I., Variation in Photosynthetic Characteristics of *Scenedesmus quadricauda* during Cell Cycle, *Abstracts 2nd Int. Cong. Photosynthesis*, vol. 3, Forti, G., Ed., The Hague: Stresa, 1972, pp. 2619–2627.
8. Tsoglin, L.N. and Klyachko-Gurvich, G.L., Changes in Functional Activity of the Chloroplast in the *Chlorella* Cell Cycle, *Fiziol. Rast. (Moscow)*, 1980, vol. 27, pp. 1172–1179 (*Sov. Plant Physiol.*, Engl. Transl.).
9. Akyev, A.Ya. and Tsoglin, L.N., O₂ Exchange and Biomass Accumulation in the *Chlorella* IPPAS C-1 Cell Cycle as Related to O₂ Content in the Medium, *Fiziol. Rast. (Moscow)*, 1994, vol. 41, pp. 203–208 (*Russ. J. Plant Physiol.*, Engl. Transl.).

10. Tsoglin, L.N., The Analysis of Physiological Characteristics of Microalgal Populations Based on Their Cell Cycles and Age-Dependent Cell Distribution, *Fiziol. Rast.* (Moscow), 1973, vol. 20, pp. 532–538 (*Sov. Plant Physiol.*, Engl. Transl.).
11. Tsoglin, L.N. and Bakulin, V.A., The Effect of the Age-Dependent Structure of a Population on the Physiological Parameters and Productivity of Microalgal Cultures, *Fiziol. Rast.* (Moscow), 1977, vol. 24, pp. 1295–1300 (*Sov. Plant Physiol.*, Engl. Transl.).
12. Tsoglin, L.N., Akyev, A.Ya., Shapiguzov, Yu.M., and Klyachko-Gurvich, G.L., Control of the Biomass Chemical Composition and Gas Exchange in the Microalgal Cultures by Changing the Age Structure in a Population, *Fiziol. Rast.* (Moscow), 1995, vol. 42, pp. 576–581 (*Russ. J. Plant Physiol.*, Engl. Transl.).
13. Filippovskii, Yu.N., Semenenko, V.E., Nichiporovich, A.A., Lebedev, V.M., and Tsoglin, L.N., Irradiance Energy Distribution in Algal Populations and Its Relation to Algal Photosynthetic Productivity, *Bioenergetika i biologicheskaya spektrometriya* (Bioenergetics and Biological Spectrometry), Moscow: Nauka, 1967, pp. 231–241.
14. Benemann, J.R., Microalgal Biotechnology: Products, Processes and Opportunities, *OMEC. Int. Inc.*, 1989, vol. 6.
15. Akyev, A.Ya. and Tsoglin, L.N., The Effect of Oxygen on the O₂ Exchange and Cell Biomass Accumulation during the Developmental Cycle of *Chlorella*, *Fiziol. Rast.* (Moscow), 1992, vol. 39, pp. 495–502 (*Sov. Plant Physiol.*, Engl. Transl.).
16. Springer, M., Examination of the Influence Parameters of the Apparent CO₂/O₂ Gas Exchange as Limiting Factors of the Biomass Production of Plants at the Example of Microalgae, Berholz-Rebrucke: *Intermed. Rep.*, 1993.
17. Akyev, A.Ya., Rogova, N.B., and Tsoglin, L.N., Effect of O₂ on the Biochemical Composition of *Chlorella* IPPAS C-1 Cells in the Course of Their Developmental Cycle, *Fiziol. Rast.* (Moscow), 1994, vol. 41, pp. 269–274 (*Russ. J. Plant Physiol.*, Engl. Transl.).
18. Livanski, K. and Doucha, J., An Estimation Method for CO₂ and O₂ Photosynthetic Rates in Outdoor Algal Cultures, *Proc. 1st Eur. Workshop on Biotechnology*, Potsdam, 1992, p. 77.
19. Tsoglin, L.N., Gabel', B.V., Fal'kovich, T.N., and Semenenko, V.E., Closed Photobioreactors for Microalgal Cultivation, *Fiziol. Rast.* (Moscow), 1996, vol. 43, pp. 149–155 (*Russ. J. Plant Physiol.*, Engl. Transl.).