ISSN 0040-6015, Thermal Engineering, 2014, Vol. 61, No. 6, pp. 399–405. © Pleiades Publishing, Inc., 2014.
Original Russian Text © N.I. Chernova, S.V. Kiseleva, O.S. Popel', 2014, published in Teploenergetika.

ENERGY SAVING, NEW, AND RENEWABLE ENERGY SOURCES

Efficiency of the Biodiesel Production from Microalgae

N. I. Chernova[a], **S. V. Kiseleva**[a], **and O. S. Popel'**[b]
[a] *Moscow State University, Moscow, 119991 Russia*
[b] *Joint Institute of High Temperatures, Russian Academy of Sciences, Izhorskaya ul. 13, str. 2, Moscow, 127419 Russia*
e-mail: k_sophia_v@mail.ru

Abstract—Biomass of the highly productive algae is a promising nontraditional raw material for biopower engineering, including production of energy and motor fuels from it. The paper presents an analysis of the efficiency of solar energy conversion to microalgae biofuel based both on the general theoretical approaches and on the experimental results obtained in various pilot projects. Some data on the economic efficiency of biofuel production from algae are also discussed. The possible ways to enhance the efficiency of microalgae energy use are formulated.

Keywords: microalgae, biofuel, biodiesel, photosynthesis, energy conversion

DOI: 10.1134/S0040601514060019

Biopower engineering is a rapidly developing sector of the economy based on the energy sources of organic origin used to produce heat, electricity, and motor fuels. In 2012, the total production of ethanol and biodiesel from various types of biomass reached 105 billion L, or about 3% of the total world consumption of motor fuels. As technology advances, the unit costs of liquid biofuel production decline and according to various sources constitute about 1 dollar/L of biodiesel produced from soybean, rapeseed, and wastes of vegetable oils and animal fats; in the United States the production of bioethanol from maize costs about 40 cents/L [1].

In recent years, the bio-energetic potential of photosynthesizing microalgae attracts more and more attention of biofuel manufacturers, and funding for research and development in this area is growing steadily [2–5]. Manufacturing of biodiesel from microalgae aroused an increased interest due to the fact that the lipid content in some of them (e.g., *Botryococcus braunii*, *Dunaliella, Nannochloris, Stichococcus*, etc.) under optimum growth conditions can be high (up to 80%), and their yields in biomass and oils (lipids) are dozen times greater than the corresponding yields of terrestrial plants [6–8]. The technological advantages of microalgae cultivation allow them to compete successfully with terrestrial plants, including food crops (use of the area, water, and fertilizers). It was proven that it is possible to cultivate microalgae on unfertile, recultivated lands, and water areas, as well as to adapt the algae strains to growth in salty waters and to use them as a source of biogenic elements of sewage. Unlike traditional crops, the cultivation and energy use of microalgae do not enhance the food problem. In the present paper we tried to analyze the indicators of energy and economic efficiency of the artificial cultivation of microalgae and the manufacturing of motor fuels, particularly biodiesel, based on our own energy estimates and taking into account the experimental and theoretical data published by other authors.

THEORETICAL ESTIMATES OF THE MAXIMUM PRODUCTIVITY OF MICROALGAE

The following basic questions arise when analyzing the possibilities of using the photosynthesizing microalgae (PM) as a raw material source for biofuels:

What is the ratio of energy costs for lipid (oils) production to the energy of the product obtained;

Are those high yields, which are announced by different authors in principle, possible and determine the feasibility of microalgae as a fuel source on an **industrial scale**.

Let us estimate the efficiency of conversion of light energy to the energy of chemical bonds (biomass and oil) in the microalgae. The buildup of microalgae biomass is due to the conversion of solar radiation energy during the photosynthesis reaction, and in this case, one can assume that its mass M (kg) is proportional to the light energy E (MJ) absorbed by a photosynthesizing organism and can be derived from the energy balance equation

$$qM = KE, \tag{1}$$

where q is the specific energy content of biomass that is equal to 21–22 MJ/kg for photosynthesizing microalgae [6]; and K is the integral coefficient of efficiency of conversion of light energy to organic matter.

Next, we consider the quantitative estimates of factors that determine the value of the integral coefficient K. For the formation of organic substances, plants use only a portion of the solar radiation spectrum: the so-called photosynthetically active radiation (PAR), whose share in the total light energy flow is not more than 50% [9–11]. In the subsequent evaluations, we assume $K_{\mathrm{PAR}} = 0.5$.

According to the commonly accepted equation of photosynthesis

$$6\mathrm{CO}_2 + 6\mathrm{H}_2\mathrm{O} + nh\nu = \mathrm{C}_6\mathrm{H}_{12}\mathrm{O}_6 + 6\mathrm{O}_2, \qquad (2)$$

where $h\nu$ is the energy of a single photon and n is the number of photons. From 8 to 10 photons from the PAR range are required for reduction of one molecule of CO_2 to glucose [11]. Given the energy of one quantum of sunlight, which corresponds to the mean wavelength in the PAR range and is about 680 nm, the energy of 1 mol of photon quanta is about 200 kJ/mol. In a quantum flow rate of 8, approximately 1.6 MJ is required to reduce 1 mol CO_2. If we take glucose having a combustion heat equal to 470 kJ per 1 mol of the reduced CO_2 as the stable product of photosynthesis, the conversion of light energy to the energy of organic substance is carried with the theoretical efficiency $K_{\mathrm{pc}} = 470/1600 \approx 0.3$ (30%) estimated as the **ratio of the energy content of the resulting organic substance to the total energy of all the photons undergoing** the photosynthesis reaction.

It is important to note that the quantum flow of photosynthesis in the shortwave and long-wave PAR is almost identical, therefore, depending on the light spectral composition, the utilization efficiency of the radiant energy may deviate towards both the magnification (when using long-wave flow) and the decrease in the case of the shorter wavelength of the incident radiation. Note that in 1966 V.E. Semenenko et al., managed to significantly improve the efficiency coefficient of photosynthesis of unicellular green microalgae *Chlorella* sp. by increasing the proportion of long-wave radiation ($\lambda = 610$–710 nm) within the range of photosynthetically active radiation [12]. The maximum possible theoretical efficiency of photosynthesis at the molecular level is estimated to be 33% [10, 11].

Taking into account the foregoing, the integral coefficient of efficiency of conversion of light energy to organic matter has the maximum value

$$K = K_{\mathrm{RAP}} K_{\mathrm{pc}} = 0.5 \times 0.3 = 0.15 \text{ (or 15\%)}. \qquad (3)$$

It should be noted that in real situations K_{ps} significantly decreases due to the factors limiting the efficiency of light absorption and to the dissipation losses on respiration and photorespiration. In practice this decrease is 50–65% of the initial values [13], i.e., K_{ps} does not exceed 0.11–0.12. As a result, the maximum value of the integral coefficient K of efficiency of the light energy conversion to the organic substance is decreased to about 0.06 (6%).

Thus, the efficiency of photosynthesizing microalgae (like terrestrial plants) is limited by the value of incident solar radiation E and coefficients K_{ps} and K_{PAR}.

For the sunniest areas of the earth, the annual incoming solar radiation on its surface E is approximately 10 000 MJ/(m^2 year) ([or an average of about 7.5 kWh/(m^2 day)]. Using Eq. (1), it is easy to determine that the maximum possible biomass from 1 m^2 will be equal to $M = 28$ (kg/m^2)/year [280 (t/ha)/year, or an average 75 (g/m^2)/day]. For the southern regions of Russia the incoming solar radiation on the surface of the earth is about 7000 MJ/(m^2 year) [or an average of about 5 kWh/(m^2 day)] [14], and then $M = 20$ (kg/m^2)/year [200 (t/ha)/year, or an average 55 (g/m^2)/day)]. Note that, for example, the maize harvests of 20 (t/ha)/year by the green mass are considered as the record ones, but they are an order of magnitude less than the given limiting theoretical estimates.

To determine the theoretically possible productivity of microalgae biomass by oil, M_{oil}, the energy intensity of oil is taken as $q_{\mathrm{oil}} \approx 35.5$ MJ/kg and the energy intensity of dry biomass after the extraction of lipids, $q_{\mathrm{dry}} \approx 15.6$ MJ/kg. Then, instead of expression (1) the energy balance will have the form

$$\left(q_{\mathrm{oil}} + \frac{1-\alpha}{\alpha} q_{\mathrm{dry}}\right) M_{\mathrm{oil}} = KE, \qquad (4)$$

where α is the fraction of oil (lipids) in the total mass of microalgae.

For the sunniest regions of the earth the marginal productivity in oil will be about 60 (t/ha)/year at $\alpha = 20\%$, and 150 (t/ha)/year at $\alpha = 80\%$. In the climatic conditions of southern Russia, these values will not exceed 45 and 105 (t/ha)/year, respectively.

Thus, the maximum values of the microalgae productivity in lipids [100 (t/ha)/year] reported in the literature (e.g. [15]) correspond to the limiting theoretical values even in the climatic conditions of the southern regions of Russia. However, to achieve high microalgae productivity in lipids it is crucial to ensure the maximum possible values of K_{ps} and α.

THE PRACTICALLY ACHIEVED EFFICIENCY INDICATORS OF MICROALGAE CULTIVATION AND LIPID PRODUCTION

To date, considerable experimental data on the microalgae cultivation under laboratory conditions and the conditions close to industrial were accumulated. Microalgae cultivation is carried out both in outdoor ponds and in closed photobioreactors (PBRs).

The purpose of the Aquatic Species Program (ASP, USA, 1978–1996) was testing the possibility of biodiesel production from microalgae [16]. Within the project, a collection of algae with more than 3000 strains was created. A prolonged large-scale cultivation of microalgae in outdoor ponds and tubular PBRs under climatic conditions of New Mexico, USA was conducted. In this project, the biomass productivity in outdoor ponds during long periods was on average more than 20 (g/m^2)/day [73 (t/ha)/year], and in

Table 1. Energy balance of systems for microalgae cultivation for the conditions of British Columbia [19]

Baseline characteristics of the cultivation systems	Outdoor cultivators	Photobioreactors
Average daily biomass yield for a dry matter, g/m^2	9.38	15.3
Oil content, %	15	25
Energy balance, MJ/L of oil:		
Electricity consumption	32.0	38.0
Energy equivalent of fertilizer consumption	20.4	12.3
Consumption of additional energy (total)	**52.4**	**50.3**
Energy content of algal oil	37.0	37.0
Energy content of biomass residue (after lipids isolation)	46.7	21
Energy equivalent of the use of CO_2 emissions for biomass cultivation	8.4	3.8
Useful energy (total)	**92.1**	**61.8**
Energy gain	**39.7**	**11.5**
Ratio of useful energy to the additional energy expenditures, %	**1.76**	**1.23**

some short periods it rose to 70 (g/m^2)/day [17, 18]. However, it was shown that it is practically impossible to maintain monoculture microalgae in open systems over several weeks due to contamination of the ponds by other organisms. An important result of the research also established the experimental fact that for most microalgae strains the sufficient supply of the cultures with nitrogen (in the absence of other limiting factors) contributes to the high rate of culture growth, and nitrogen deficiency leads to an increase in lipid content in the cells with simultaneous substantial decrease in their growth rate. In other words, it was shown that it is impossible to simultaneously achieve the high productivity and high lipid content by microalgae culturing. Authors of the project also drew attention to the need to optimize the harvesting and lipid isolation procedures.

The research team from the Japanese Research Institute of Innovative Technology for the Earth (RITE, 1990–1999) came to similar conclusions. The RITE's project, as well as ASP, was aimed at creating a collection of photosynthesizing microalgae as promising biofuel sources, and at studying the possibility of solving the problem of CO_2 sequestration with their use. The main emphasis was placed on the use and improvement of PBR systems, however, the authors concluded that none of the developed PBR types makes it possible to achieve acceptable profitability in the industrial production. As a result, in 1999 RITE ceased the study on the biological fixation of CO_2 and switched to its geological sequestration.

In the period from 1997 to 2001, another major research project was carried out in Hawaii [6]. It was aimed at testing and working off the strategy of a two-stage microalgae cultivation to increase the lipid yield, as well as marketing of a new commercial algal product. A green microalga *Haematococcus pluvialis* was chosen as the object of cultivation; it is a producer of oil and valuable carotenoid pigment astaxanthin. The constant optimum conditions conducive to continuous cell division and preventing contamination of the grown microalgae culture by other organisms was maintained at the first stage carried out in a closed (tubular) PBR. At the second stage, the cells of photosynthesizing microorganisms were subjected to limitations in nutrients, excessive light, and other stresses that led to accelerated synthesis of the target products, oil and astaxanthin. The stressful conditions were created by transferring the culture grown from PBRs to outdoor cultivators. The total biomass productivity in a two-stage cultivation ranged from 38.1 (average) to 91.8 (t/ha)/year (maximum). If the energy content of dry biomass was 21.9 MJ/kg, the total energy productivity of *H. pluvialis* was on average 83.4 (MJ/m^2)/year, and in the maximum, 201 (MJ/m^2)/year. At incoming solar radiation at the level of 10 000 (MJ/m^2)/year, in this experiment the coefficient of conversion of solar energy is on average equal to 0.8% for the full range of incident solar radiation and 1.7% for PAR. The oil content in *H. pluvialis* in the outdoor cultivators under stress conditions reached on average 25–30%; as a result, the microalgae productivity for oil was about 11.4 (t/ha)/year (average for the year) and up to 27.5 (t/ha)/year during short periods.

It is important to keep in mind that the processes of microalgae cultivation, harvesting, and oil separation are associated not only with the use of solar energy, but also with additional energy costs. The most significant costs for additional energy are associated with pumping water through bioreactors and CO_2 supply. Furthermore, nutrients are necessary for the microalgae cultivation; their production is also associated with energy costs. A detailed optimization analysis of such costs for the conditions of British Columbia (Canada) was carried out [19]. The calculations were performed both for riverbed outdoor cultivators and for PBRs. The results of evaluations are shown in Table 1.

It is seen that the total energy content of the final products exceeds the additional energy costs even without considering the energy equivalent from "underemission" of CO_2 in cultivating microalgae. At the same time, in these cases the energy of the biomass waste after lipid extraction is a crucial positive factor that provides for complete processing of biomass in almost all projects. Otherwise, from the energy point of view, the production of biodiesel can be "unprofitable": the ratio of the energy content of oil to the additional energy costs is 0.7 for both cultivation schemes.

At the same time, the practical efficiency of introduction of a technology is ultimately determined by economic indicators. In this respect, the economic estimates made on the basis of ASP are of interest. They showed that the cost of biodiesel from PM can be from 39 to 127 dollars/barrel, or 26–86 cents/L depending on productivity. In this case, the biomass production was carried out only in outdoor cultivators, and CO_2 from flue emissions of thermal power plants was used to enrich the medium. Biomass productivity ranged from 30 to 60 (g/m^2)/day at 40% oil content. In the Hawaiian project at two-stage microalgae cultivation the cost price estimate of biodiesel gave 56 dollars/barrel in prices of 2003 (about 40 cents/L), when the oil price on the global market was about $55/barrel.

Unlike these indicators, the economic estimates of production of algal biodiesel made for the conditions of British Columbia gave more pessimistic results [19]. They were made both for outdoor cultivators and for closed PBRs. The year-round and seasonal (from April to September) operation of cultivators were considered. In the second case, the capital costs were decreased twice, and there was no need for heating water. Biomass productivity ranged from 10 to 25 (g/m^2)/year with a lipid content from 15 (cultivation) to 25–35% (bioreactors). It was shown that even under the most optimistic scenario of biodiesel production, none of them led to the parity expenditures for the same climatic conditions as compared to fossil raw materials and fuel from terrestrial oleaginous plants (canola).

In the structure of costs for obtaining algal oil, the capital expenditure for the creation of outdoor cultivators reached 50%, and for PBRs it exceeded 60%; the current costs for fertilizer and additional energy made up about 25%; and the remaining costs were related to wages. As a result, the cost price of 1 L of algal oils was estimated at approximately $2.5 and $7/L for the outdoor cultivators and PBRs, respectively. The authors of the calculations noted that the economic indices of biofuel production from algae can be improved with simultaneous production of energy and valuable byproducts, such as astaxanthin and other pigments. This idea is not new and was discussed by various authors [6 and others]. The obtained results are quite pessimistic for open outdoor cultivators and PBRs and connected largely with climatic conditions of place of the supposed cultivation of microalgae (Canada). This confirms once again the need to consider the characteristics of each project and the region when choosing the strategies for organizing the production.

POSSIBLE WAYS TO ENHANCE THE ENERGY EFFICIENCY USING MICROALGAE

According to the stated facts, to improve the efficiency and competitiveness of the biofuel technology based on the cultivation of highly productive microalgae, the following is necessary:

1. *Providing high efficiency of conversion of light energy to biomass and the achievement of a high lipid content in the microalgae biomass.*

Available solar energy is the main factor in increasing the productivity of microalgae. It was shown that obtaining high yields of the biomass is possible only in areas of maximum solar radiation. At the same time, the ambient temperature conditions, and especially the absence of sharp daily fluctuations are an important factor. In some cases only the seasonal cultivation of microalgae is profitable. For a given spectrum of solar radiation, apparently, it is hardly possible to significantly increase the proportion of photosynthetically active radiation (K_{PAR}). At the same time, there are considerable opportunities for increasing the efficiency of conversion of light energy to the energy of organic matter (K_{ps}), which is still far from the theoretical limit. The main directions to enhance K_{ps} are:

—decrease in losses of solar radiation entering the bioreactor, which are related to shading and reflection of radiation, the non-optimal spatial geometric characteristics, as well as the peculiarities of the technology used to grow algae in open and closed cultivators;

—increasing the efficiency of the incoming photons by spreading the incident solar energy over the entire surface of the cell, as well as by breeding by mutation or genetic engineering, which increases the tolerance of algae to high levels of radiation;

—improving the efficiency of energy storage in the biomass, i.e., an increase in the proportion of energy received by the cell, which is spent on direct storage of it in the form of biomass and not on the functioning of the cell. It requires more detailed studies; however, it is known that the amount of such energy directly

Table 2. The main types of energy costs of the microalgae cultivation process and methods of their reduction

Type of energy costs	Methods for reducing the energy costs
Manufacturing the biogenic elements for microalgae cultivation	Use of animal wastes; the methane fermentation products; marine and geothermal water; and CO_2, NO_x, and SO_x of the flue emissions from thermal power plants for preparation the culture media
Mixing	Use of renewable energy sources (solar, wind, and combined installation)
Harvesting	Application of methods of filtration, flotation, flocculation, and drying with the use of renewable energy sources
Maintaining an optimal temperature and light regime of microalgae cultivation	Use of LED sources; reducing energy costs by waste heat from thermal and nuclear power plants, and renewable energy sources
Major construction	Use of cheap and available reusable materials
Water supply	Use of marine and geothermal water and breeding of microalgae strains adapted to environments on marine and geothermal water. Using municipal wastewate and cooling ponds of NPP and CHP

depends upon factors, such as the algae type and the conditions of their cultivation. In [20] analysis of the "cost of living" was made on the basis of experimental data, where either only respiration was taken into account or the energy needs of the cell were more fully considered. Thus, the efficiency of the energy storage by biomass was equal to 65% according to [13]; it was estimated in the range of 47–86% for the various algae species in [21], 87.5% in [17], from 11 to 79% in [22], and 34% in [23];

—providing high lipid content in the microalgae biomass, which depends not only on the incoming energy, but also on the algae type and selected cultivation conditions. Theoretically, the maximum value of this magnitude is still unknown. For example, in [7], the most comprehensive review of studies of lipid content in the algal cells, it varies from 15 to 77%. It was shown that the simultaneous achievement of high productivity and high lipid content in microalgae cultivation is impossible. The induction of lipid biosynthesis can be achieved by creating a physiological stress: starvation for nitrogen and/or phosphorus, heavy metals exposure, osmotic stress, intense or reduced illumination with a certain spectral composition, pH, temperature, etc. The value of 46% of the dry matter was substantiated for oleaginous green algae grown under stress conditions [24].

2. *Lower costs of additional energy at ensuring the cultivation of algae.* These costs are related to the basic technological stages of the cultivation process, such as mixing and pumping the suspension of microalgae in open cultivators and PBRs, microalgae harvesting, extraction, purification, and other operations for oil isolation. Additional energy is spent on a continuous supply of carbon dioxide to an aqueous solution, the products of fuel combustion of the energy plants serve as one of the most promising sources of it. Biogenic elements (chemical reagents) are used to create the optimum nutrient medium; their production also requires significant electric power costs. In this connection, the use of waste water and/or geothermal water sources containing a broad spectrum of chemical substances is of interest. On the whole, there are significant opportunities for reducing these additional energy costs, and some of them were tested in a number of studies (Table 2). In this case, utilization of waste in the biofuel production and extraction of associated valuable components are an important aspect of the problem, which has a significant impact on energy and economic indicators.

For the microalgae cultivation, the cost-effective sources of artificial light, e.g., LEDs, can be used. In this case, the selection of the spectral composition of radiation mainly in the PAR region is possible. The use of allocated artificial light sources makes it possible to obtain uniform irradiation directly inside the bioreactor and to eliminate optical losses (reflection, shading) characteristic of the external solar radiation. Study of the influence of different spectra of light flux and its intensity on productivity and accumulation of lipids by microalgae was conducted earlier in our country and abroad. However, the specialized lamps with replaceable filters were used mainly as light sources. Using the LED technology, the most "productive" irradiation ranges within PAR can be selected for microalgae, and the stressful conditions (high insolation level in a narrow range of wavelengths) allowing one to increase the lipid content in biomass can be created. In comparison with earlier studies the results indicate that the response to change in the spectrum of irradiation and light intensity is species- and even strain-specific. Furthermore, it is very important to study the impact of the spectrum on the qualitative composition of biomass (content of lipids, proteins, and carbohydrates).

At the same time, the principle question of the primary power source arises when using artificial light sources. It may be relatively inexpensive electric power of conventional or nuclear power plants, which is selected during the period of the minimum daily consumption. In the future, it seems possible to use electric power generated by electric installations operating on renewable sources (wind, solar, and other). The use of artificial light to grow algae in order to obtain motor fuels requires special technical and economic analysis. However, in the future, with continued rise in oil prices and a reduction in the cost of energy from renewable sources, such technology can be quite attractive.

3. *Optimization of the cultivator and bioreactor constructions to reduce the capital cost of their creation.*

As already noted, the proportion of capital costs in the cost of the final product can be 50% for open cultivators and more than 60% for closed bioreactors. In this regard, optimizing the design of these devices is a task of utmost importance.

Thus, the analysis of energy balances of solar energy conversion to biomass of oleaginous microalgae confirms the principled possibility of achieving the record productivities of biomass and oil, which can determine the prospects of competitiveness of algal biodiesel. At the optimum organization of the process, the energy content of the final products may exceed the costs of additional energy for microalgae cultivation even without considering the energy equivalent of CO_2 “underemission” in cultivating microalgae. In this case, the energy of biomass waste after lipid extraction constitutes a significant portion in the total energy content of the products obtained. Production of the valuable associated products with high added value (astaxanthin, β-carotene, phycocyanin, and chlorophyll) can also significantly increase the profitability of production. There are significant opportunities to improve the technology; they are associated with the improvement of efficiency of light energy conversion to biomass, the increase in lipid content in the microalgae biomass, reducing costs of additional energy for their cultivation, and the optimization of cultivator and bioreactor constructions with reduced capital cost of their design. The extended studies in this interdisciplinary area involving experts from different fields of science and technology are required to implement these opportunities.

REFERENCES

1. *Renewables 2013 Global Status Report. REN21 Renewable Energy Policy Network for the 21st Century*. http://www.ren21.net/REN21Activities/GlobalStatus-Report.aspx.
2. Preview of Oilgae Digest. http://www.oilgae.com/ref/report/digest/Oilgae_Digest_Preview.pdf.
3. Algae 2020: Vol. 2: Global Biofuels, Drop-In Fuels, Biochems and Commercial Market Forecasts (2011 Update). http://www.emerging-markets.com/algae/Algae2020StudyandCommercializationOutlook.pdf.
4. N. I. Chernova, T. P. Korobkova, and S. V. Kiseleva, “Use of biomass for producing liquid fuel: current state and innovations,” Therm. Eng. **57** (11), 937–945 (2010).
5. A. E. Solovchenko, “Physiological role of neutral lipid accumulation in eukaryotic microalgae under stresses,” Russ. J. Plant Physiol. **59** (2), 167–176 (2012).
6. M. E. Huntley and D. G. Redalje, “CO_2 mitigation and renewable oil from photosyntetic microbes: a new appraisal,” Mitigation and Adaptation Strategies for Global Change **12**, 573–608 (2007).
7. Y. Chisti, “Biodizel from microalgae,” Biotechnol. Adv. **25**, 294–306 (2007).
8. N. I. Chernova, T. P. Korobkova, S. V. Kiseleva, and S. I. Zaitsev, “Microalgae as raw material for obtaining biofuel,” Al’tern. Energ. Ekol. (9), 68–74 (2008).
9. V. Larkher, *Plant Ecology* (Mir, Moscow, 1978) [in Russian].
10. V. V. Kuzhetsov and G. A. Dmitrieva, *Plant Physiology: Textbook for Universities* (Vysshaya Shkola, Moscow, 2005) [in Russian].
11. J. Edwards and D. Walker, *C_3,C_4: Mechanisms, and Cellular and Environmental Regulation of Photosynthesis* (Blackwell Scientific, Oxford, 1983; Mir, Moscow, 1986).
12. V. E. Semenenko, M. B. Zimin, M. G. Vladimirova, G. L. Klyachko-Gurvich, M. V. Sokolov, and A. A. Nichiporovich, “Study of photosynthetic productivity and efficiency of radiant energy utilization of chlorella depending on the spectral energy distribution in the equal-energy laser field,” Russ. J. Plant Physiol. **13** (6), 949–957 (1966).
13. A. Sukenik, R. S. Levy, Y. Levy, P. G. Falkowski, and Z. Dubinsky, “Optimizing algal biomass production in outdoor pond: a simulation model,” J. Appl. Phycol. **3** (3), 191–201 (1991).
14. O. S. Popel’, S. E. Frid, Yu. G. Kolomiets, S. V. Kiseleva, and E. N. Terekhova, *Atlas of Solar Energy Resources in the Territory of Russia* (MFTI, Moscow, 2010) [in Russian].
15. I. I. Moiseev, V. Tarasov, and L. I. Trusov, “Evolution of bioenergy. time of algae,” Chem. J., 24–29 (2009).
16. J. Sheehan, T. Dunahay, J. Benemann, and P. Roessler, “Look back at the US Department of Energy’s aquatic species program – biodiesel from algae” (National Renewable Energy Institute, 1998), NREL/TP_580_24190.

17. J. C. Goldman, “Outdoor algal mass cultures—II. Photosynthetic yield limitations,” Water Res. **13** (2), 119–136 (1979).
18. E. A. Laws, S. Taguchi, J. Hirata, and L. Pang, “High algal production rates achieved in a shallow outdoor flume,” Biotechnol. Bioeng. **28** (2), 191–197 (1986).
19. A. O. Alabi, M. Tampier, and E. Bibeau, *Microalgae Technologies for Biofuels/Bioenergy Production in British Columbia: Current Technology, Suitability and Barriers to Implementation*, Final Report to the British Columbia Innovation Council by Seed Science. http://www.globalbioenergy.org/bioenergyinfo/background/detail/fi/c/10661. Cited January 14, 2009.
20. K. M. Weyer, D. R. Bush, A. Darzins, and B. D. Willson, “Theoretical maximum algal oil production,” Bioenergy Res. **3**, 204–213 (2010).
21. P. G. Falkowski, Z. Dubinsky, and K. Wyman, “Growth-irradiance relationships in phytoplankton,” Limnol. Oceanogr. **30**, 311–321 (1985).
22. C. Langdon, “The significance of respiration in production measurements based on oxygen,” ICES J. Mar. Sci. Symp. **197**, 69–78 (1993).
23. X.-G. Zhu, S. P. Long, and D. R. Ort, “What is the maximum efficiency with which photosynthesis can convert solar energy into biomass?,” Curr. Opin. Biotechnol. **19**, 153–159 (2008).
24. Q. Hu, M. Sommerfield, E. Jarvis, M. Ghirardi, M. Posewitz, M. Seibert, and A. Darzins, “Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances,” Plant J. **54**, 621–639 (2008).
25. N. I. Chernova, T. P. Korobkova, N. V. Radomskii, S. V. Kiseleva, C. I. Zaitsev, and O. Yu. Gainanova, “Experimental module of photobioreactor for two-stage cultivation of microalgae, producers of lipids,” in *Physical Problems of Ecology (Ecological Physics)* (MAKS Press, Moscow, 2012), No. 18, 396–407.

Translated by G. Levit