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Productivity of microalgae as biofuel for bioadaptive systems of facades

Продуктивность микроводорослей, как биотоплива для биоадаптивных систем фасадов

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Abstract. Microalgae are one of the promising fuel sources and many specialists associate it with the future of alternative energy. A promising area of application of photobiological devices is their conjugation with the architectural covers of a building and formation of bio-adaptive facades. The determining criteria for the organization of the microalgae biomass production process in the facade structure is solar radiation, ratio of light and dark growth phase and ambient temperature. The goal of this work is to study the productivity of microalgae Chlorella of CALU 157 strain at low temperatures and low illumination, as well as to calculate the amount of biofuel that can be produced under such climatic conditions. In the first stage of the experiment the algae cultivation was studied at different illumination values – 3500 lx, 1750 lx and 930 lx. In the second stage of the experiment cultivation of algae at different temperatures was studied: +2 °C, +10 °C, +19 °C and +25 °C. Total number of cells in the suspension was determined using the method of direct cell counting in Goryaev chamber. As a result of the experiment microalgae productivity data were obtained at different illumination and temperature. It was found that at a temperature of 2 °C and 10 °C, an almost stable state of algae was observed, the concentration increased very slowly, however the culture did not die. Also the calculation of the amount of energy and biogas, which can be obtained from the biomass of microalgae under the growing conditions of 3500 lx and 23 °C was also made.

Аннотация. Микроводоросли являются одним из перспективных топливных источников. Одним из направлений применения фотобиологических устройств на основе микроводорослей является сопряжение их с архитектурными оболочками здания и образование биоадаптивных фасадов. Определяющими критериями для организации процесса производства биомассы микроводорослей в фасадной конструкции является солнечная радиация, соотношение световой и темновой фазы роста, температура окружающей среды. Целью данной работы является изучение продуктивности микроводорослей Chlorella vulgaris Beijer., штамм CALU-157 при различных температурах и различном количестве освещения, а также расчет количества биотоплива, которое можно получить при таких условиях. Первый этап эксперимента заключался в расчете концентрации и продуктивности микроводорослей при освещенности 3500 Лк, 1750 Лк и 930 Лк. Второй этап эксперимента заключался в расчете концентрации и продуктивности микроводорослей при температурах +2 °C, +10 °C, +19 °C и +25 °C. Общее количество клеток в суспензии определялось с помощью метода прямого подсчета клеток в камере Горяева. В результате эксперимента получены данные продуктивности микроводорослей при различной освещенности и различной температуре. Было выявлено, что при температуре 2 °C и 10 °C состояние водорослей было стабильным, концентрация увеличивалась очень медленно, однако гибели культуры не произошло. Также сделан расчет количества энергии и биогаза, которое можно получить из биомассы микроводорослей при условиях выращивания 3500 Лк и 23 °C.

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1. Introduction

In many countries the cost of heat network and boiler plants operation is increasing every year. The known problems of operation of centralized heat supply urgently require accelerated introduction of non-traditional methods of energy supply. The use of biofuel in recent decades has attracted increasing interest. At present, attention is drawn to the use of third-generation biofuel obtained on the basis of microalgae [1–5].

Microalgae are one of the promising fuel sources and many specialists associate it with the future of alternative energy [6]. They are tiny, mostly unicellular organisms about 5 micrometers in size. Like other plants, microalgae use sunlight as a source of energy to create biomass. This process is called photosynthesis which in nature occurs identically in all plants. However, microalgae are much more efficient in converting light energy into biomass than multicellular plants, since the microalgae are unicellular, and each individual cell performs photosynthesis. Microalgae can divide up to once a day doubling their biomass which is an energy carrier. 1 gram of dry biomass contains about 21 kJ of energy [7]. In the work [8] it is justified that microalgae will become the main raw renewable source of technical lipids for biofuel production.

A promising area of application of photobiological devices is their conjugation with the architectural covers of a building and formation of bio-adaptive facades [9, 10–12]. Creating such building structures allows to reduce power consumption and to provide comfortable conditions in the premises. This direction is completely new in the world of architecture and has not yet become widespread [13, 14]. The use of such structures can significantly improve biosphere compatibility of modern megalopolises. However, many external factors affect their efficiency such as: level of solar radiation, temperature, amount of available nitrogen and phosphorus compounds and availability of carbon dioxide sources [15-18]. Therefore, one of the main criteria for the high efficiency of the photobioreactor is the choice of a suitable area.

The determining criteria for the organization of the microalgae biomass production process in the facade structure is solar radiation equal to 4.0 kWh/m^2/day or approximately 14 MJ/m^2, ratio of light and dark growth phase is not less than 6:18, ambient temperature is not lower than 12 °C [13]. Analysis of the cartographic material at the research initial stage showed that there are many places in Europe with suitable climate conditions however in the coldest days of the year it can be necessary to use additional heating. [13, 19] The climatic conditions can be found in such places as Nice, Marsel (France), Malta and Cyprus islands, San Remo, Sicily (Italy), Sochi (Russia) and others.

Further research was conducted using the example of climatic conditions of the city of Sochi which is located in Russia. The average annual solar radiation in Sochi is 4.0 kWh/m^2/day. The maximum amount of solar radiation is in July and is 7.24 kWh/m^2/day, the minimum amount is in December – 1.29 kWh/m^2/day. The average annual temperature is 15 °C. The average temperature in the hottest month (August) is 24.9 °C, in the coldest month – 6.95 °C [20]. Thus, this region fully meets the criteria for microalgae cultivation in summer but in winter additional heating may be necessary. To clarify this issue it is necessary to study the behavior of algae at low temperatures and low illumination. For this purpose, two stages of the experiment are planned:

1. Calculation of microalgae productivity with a small amount of illumination;
2. Calculation of microalgae productivity at low temperatures.

The experiment results will allow to determine under what climatic conditions the environment heating for microalgae is mandatory for the algae life.

In articles [21, 22] it is stated that the optimum temperature for chlorella is 33–36 °C. There are no data on the behavior of microalgae at low temperatures. Therefore, in this article, for the first stage of the experiment the following temperature values were chosen: +2 °C, +10 °C, +19 °C and +25 °C. In the article [21-23] it is stated that the optimal illumination for chlorella is 20-30 thousand lx. According to the data [24] the values of 20–30 lx are commensurable with a clear, sunny afternoon at noon in the middle latitudes. When cultivating microalgae in real weather conditions, the illumination will fluctuate from 0.2 lx at night to 30 lx in the daytime. There are no data on the behavior of microalgae with a small amount of illumination (0–5000 lx). Therefore, in this article, for the second stage of the experiment the following values of illumination were chosen: 3500 lx, 1750 lx and 930 lx.

Thus, the goal of this work is to study the productivity of microalgae at low temperatures and low illumination, as well as to calculate the amount of biofuel that can be produced under such climatic conditions. To achieve the goal, the following tasks are set and solved:

- calculation of concentration and productivity of microalgae at illumination of 3500 lx, 1750 lx and 930 lx;

- calculation of concentration and productivity of microalgae at temperatures of +2 °C, +10 °C, +19 °C and +25 °C;
- calculation of amount of energy that can be obtained under the above-described growing conditions, as well as calculation of amount of biogas that can be obtained under the same conditions.

2. Methods

Unicellular green alga Chlorella of CALU 157 strain was used as a test organism in the experiments. This alga was taken from the collection of algae of the Microbiology Laboratory of the Biological Institute of St. Petersburg University. It is not demanding to nutrient medium, carbon dioxide, mechanical stirring and has high productivity [25]. Sterility is not required for cultivation. During cultivation it observes the strain monoculture. In addition, it is widely spread in nature and well studied by scientists. [22, 26, 27].

Medium Tamiya was used as a nutrient medium which was singled out by many researchers as the most optimal for the growth of chlorella [28, 29]. The medium is characterized by the following composition of salts and microelements:

Table 1. Composition of nutrient medium Tamiya

No	Components	Per 1 liter of medium
1	K2HPO4	66.6 mg
2	MgSO4 × 7H2O	33.3 mg
3	KNO3	100 mg
4	Solution with microelements × 1000	1 ml

Table 2. Solution with microelements × 1000

No	Components	Per 1 liter of solution
1	NaBO3 × 4H2O	2.63 g
2	MnSO4 × 5H2O	1.81 mg
3	ZnSO4 × 7H2O	0.22 mg
4	(NH4)6Mo7O24 × 4H2O	1.0 ml
5	CuSO4 × 5H2O	0.079 g
6	Co(NO3)2 × 6H2O	0.02 g
7	CaCl2	1.2 g
8	FeSO4 × 7H2O	9.3 g
9	Na2EDTA × 2H2O (Trilon B)	10 g

The nutrient medium and salt solutions were prepared on distilled water and were not sterilized. To avoid precipitation the sample of each substance was first dissolved in a small amount of water, and then the solutions were poured together in the above sequence and the water was added to the desired volume.

To prepare 1 liter of medium, sample of K_2HPO_4 was dissolved in 800 ml of distilled water. Sample of $MgSO_4 \times 7H_2O$ was dissolved separately in 100 ml of water and poured into K_2HPO_4 solution while stirring. Sample of KNO_3 was added to the mixture. After the sample complete dissolution, 1 ml of microelement solution was added. After that the volume was brought to a liter with distilled water. Total number of cells in the suspension was determined using the method of direct cell counting in Goryaev chamber [30] for 10 days. For the biomass cultivation 250 ml conical flasks were used.

The first stage of the experiment was conducted in the educational and scientific center for the utilization of industrial and domestic waste in St.Petersburg Polytechnic University. The algae cultivation was studied at different illumination values – 3500 lx, 1750 lx and 930 lx. For this purpose, 30 W fluorescent lamp LBU 30 (U-shaped) was used. Temperature of all three samples was the same: 23 °C. Initial concentration in all three flasks was 2.125 million of cells/ml. Position of each flask with the suspension was determined with a luxmeter. The first flask was at a distance of 50 mm from the lamp, the illumination was 3500 lx. The second flask was at a distance of 170 mm, the illumination was 1750 lx. The third flask was at a distance of 245 mm, the illumination was 930 lx. All three flasks were illuminated for 12 hours per day.

The second stage of the experiment was conducted in the Microbiology Laboratory of the Biological Institute of St. Petersburg University. Cultivation of algae at different temperatures was studied: +2 °C, +10 °C, +19 °C and +25 °C. Chlorella suspension was placed in a thermostat, while the illumination for all samples was the same: 600 lx (Figure 1). Initial concentration of all samples was 130 thousand of cells/ml. The suspension was illuminated for 24 hours a day.

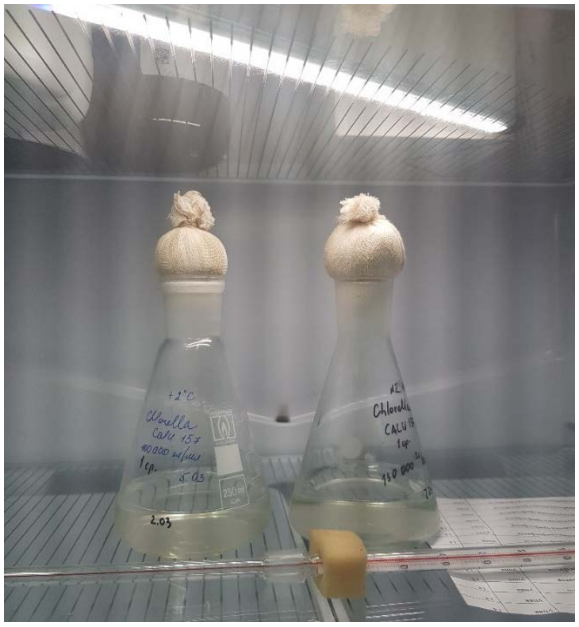

Figure 1. Cultivation of algae at the temperature +2 °C

3. Results and Discussion

The results of the first stage are given in Table 3 and Figure 2.

Table 3. Concentration of microalgae as a function of illumination, mln. of cells/ml

Illumination\t, days	1	2	3	4	5	6	7	8	9	10
3500 lx	2.125	2.76	3.56	4.61	5.12	5.41	6.3	7.02	6.75	6.61
1750 lx	2.125	2.48	3	3.55	3.78	4.02	4.7	5	4.9	5
930 lx	2.125	2.34	2.68	2.96	3.07	3.3	3.6	4.11	4.02	4

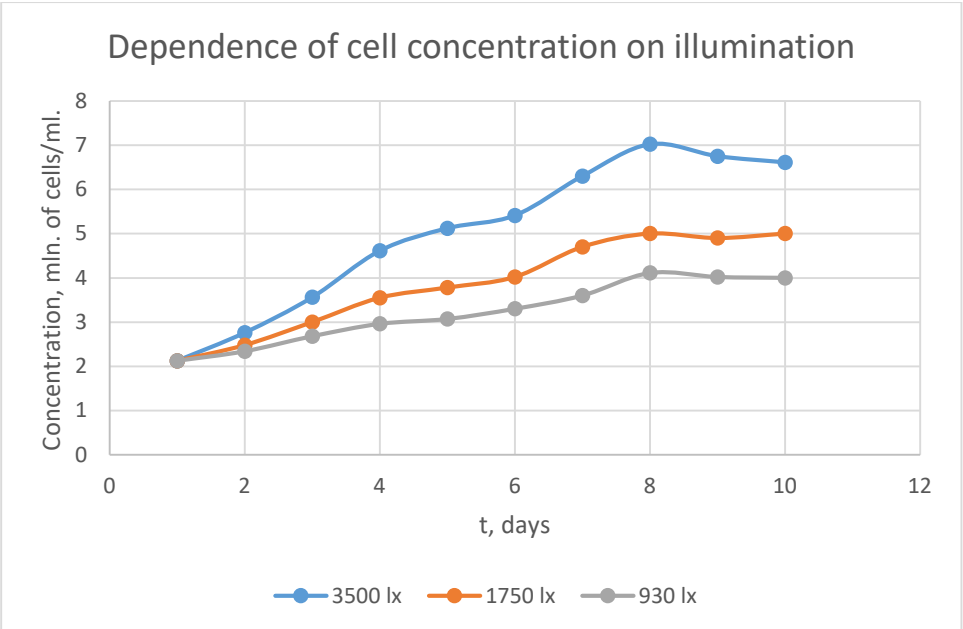

Figure 2. Dependence of cell concentration on illumination

Figure 2 shows that as the amount of illumination increases, the growth rate of microalgae increases, which coincides with the results of other investigators [22]. It can also be noted that the maximum concentration was observed on day 8, after which it began to decrease. This may be due to the onset of a stationary phase of growth. On day 8, the number of algae under illumination of 3500 lx was 7.02 million of cells/ml, with illumination of 1750 lx – 5 million of cells/ml, with illumination of 930 lx – 4.11 million of cells/ml.

In the article [16] it is said that the optimal illumination of chlorella lies within 20–25 klx, the threshold of light saturation is (25…90) $\cdot 10^3$ lx. Also, the authors note that chlorella can adapt to different light intensities, while the value of optimal illumination is closely related to the design of the photobioreactor. In the article [22] it is noted that the strain growth occurs more intensively with uniform illumination and a small thickness of the suspension. In our experiment illumination was carried out from one side of the flask, the diameter of the flask was 12 cm, i.e. the results can be improved by uniform illumination and by choosing a vessel with a smaller diameter. Another way to optimize the insolation can be to maintain intensive bubbling of the suspension so that all cells were in the area with a high level of illumination for sufficient time.

The microalgae biomass productivity was calculated based on the results of the first stage.

Productivity (P) is the amount of biomass formed by growing and multiplying microalgae cells per 1 day in 1 liter of cell suspension. [PRODUCTIVITY OF MICROALGAE CULTIVATION SYSTEM AT NATURAL LIGHTING]

$$\mathrm{P} = \frac{\mathrm{B}_2 - \mathrm{B}_1}{\mathrm{t}},\ [\mathrm{P}] = [\text{million of cells}/(\mathrm{l} \cdot \text{day})],$$

where B_1 is the suspension density on the first day of measurement, million of cells/l; B_2 is the suspension density on the last day of measurement, million of cells/l; t is the duration of measurements, days.

Based on the results of the experiment, the average productivity of microalgae at an illumination of 3500 lx before the onset of the stationary phase (day 8) is:

$$\mathrm{P} = \frac{7.02 - 2.125}{7} \approx 0.7 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 700 \text{ million of cells}/(\mathrm{l} \cdot \text{day})$$

The average productivity of microalgae at an illumination of 1750 lx before the onset of the stationary phase is:

$$\mathrm{P} = \frac{5.0 - 2.125}{7} \approx 0.411 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 411 \text{ million of cells}/(\mathrm{l} \cdot \text{day})$$

The average productivity of microalgae at an illumination of 930 lx before the onset of the stationary phase is:

$$\mathrm{P} = \frac{4.11 - 2.125}{7} \approx 0.283 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 283 \text{ million of cells}/(\mathrm{l} \cdot \text{day})$$

The results of the second stage are given in Table 4 and Figure 3.

Table 4. Concentration of microalgae as a function of temperature, thous. of cells/ml

Temperature\t, days	1	2	3	4	5	6	7	8	9	10	11
2°C	130	300	360	460	210	420	500	450	510	540	500
10°C	130	320	430	520	370	550	600	620	700	750	800
19°C	130	500	700	880	870	1300	1700	2500	2900	3100	3470
25°C	130	560	800	940	1150	1480	2230	2850	3340	3670	4100

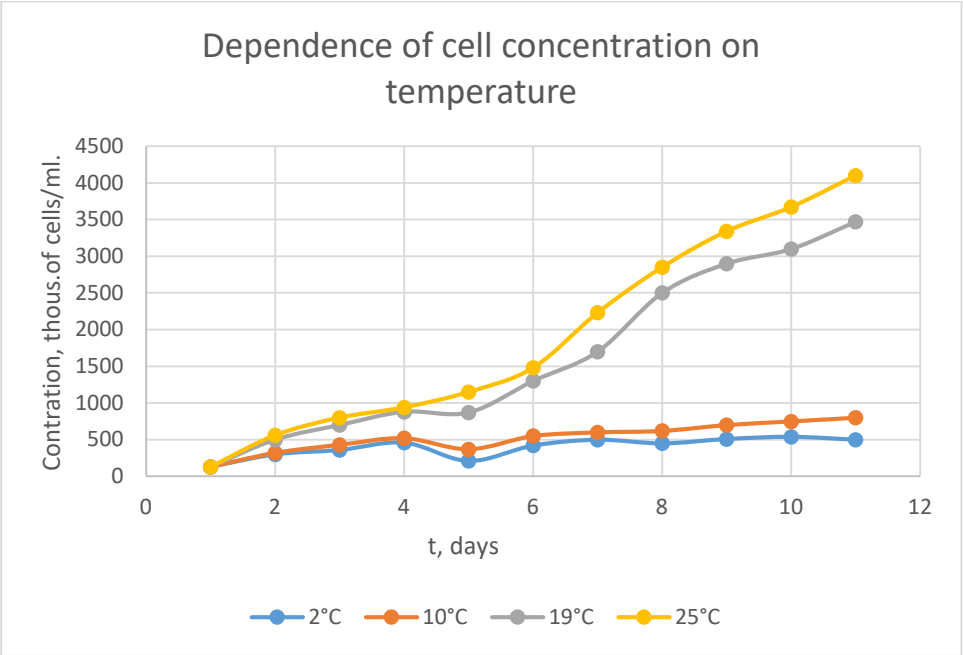

Figure 3. Dependence of cell concentration on temperature

Figure 3 shows that as the temperature increases, the growth rate of biomass increases, which coincides with the results of other investigators [21]. The maximum increase in biomass was at a temperature of 25 °C and amounted to 4.1 million of cells/ml. on day 11 of cultivation. At a temperature of 2 °C and 10 °C, an almost stable state of algae is observed, the concentration increases very slowly but the cells remain active, the culture does not die. In the article [27] it is stated that different species of microalgae grow in a wide range of temperatures, but as a rule, they are all sensitive to freezing, and therefore, the temperature shall not drop below 0 °C, at which the culture will die.

The microalgae biomass productivity was calculated based on the results of the second stage.

The average productivity of microalgae at a temperature of 25 °C is:

$$P = \frac{4.1 - 0.13}{10} = 0.397 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 397 \text{ million of cells}/(\text{l} \cdot \text{day})$$

The average productivity of microalgae at a temperature of 19°C is:

$$P = \frac{3.47 - 0.13}{10} = 0.334 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 334 \text{ million of cells}/(\text{l} \cdot \text{day})$$

The average productivity of microalgae at a temperature of 10 °C is:

$$P = \frac{0.8 - 0.13}{10} = 0.067 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 67 \text{ million of cells}/(\text{l} \cdot \text{day})$$

The average productivity of microalgae at a temperature of 10 °C is:

$$P = \frac{0.5 - 0.13}{10} = 0.037 \text{ million of cells}/(\text{ml} \cdot \text{day}) = 37 \text{ million of cells}/(\text{l} \cdot \text{day})$$

After that the amount of biofuels that can be obtained from the microalgae biomass was calculated. To calculate the maximum amount of biofuel under the conditions tested in the experiment, we take the results of growth of microalgae from the first stage with an illumination of 3500 lx. As it was already calculated above, the productivity in this case was 700 million of cells/(l·day).

In the publication [27] it is said that 100 million of cells in a dry form weigh 1.3 gram, which allows these calculations:

$$P = \frac{700}{100} \cdot 1.3 = 9.1 \text{ g of dry biomass}/(\text{l} \cdot \text{day})$$

Thus, 700 million of cells is 9.1 grams of dry biomass. The average caloric value of 1 gram of dry biomass of microalgae Chlorella, Spirulina, Synechococcus and Platymonas is 5 kcal (21 kJ) [7], then the amount of energy will be:

$$9.1 \cdot 21 = 191.1 \frac{\text{kJ}}{\text{l} \cdot \text{day}} = 191100 \ \frac{\text{kJ}}{\text{m}^3 \cdot \text{day}} = 53083 \frac{\text{kWh}}{\text{m}^3 \cdot \text{day}}$$

Taking into account all losses during processing of biomass into biogas, it can be assumed that 1 g of dry biomass corresponds to 0.68 liter of methane [31, 32]. Thus, the amount of biogas will be equal to:

$$9.1 \cdot 0.68 = 6.188 \frac{\text{l of methane}}{\text{l of medium} \cdot \text{day}}$$

4. Conclusions

1. As the illumination increases, the growth rate of microalgae increases. On day 8, the number of algae under illumination of 3500 lx was 7.02 million of cells/ml, with illumination of 1750 lx – 5 million of cells/ml, with illumination of 930 lx – 4.11 million of cells/ml. The productivity of microalgae at an illumination of 3500 lx is 700 million of cells/(l·day), at an illumination of 1750 lx is 411 million of cells/(l·day), at an illumination of 930 lx is 283 million of cells/(l·day).

2. As the temperature increases, the biomass increases. The maximum concentration of biomass was at a temperature of 25 °C and amounted to 4.1 million of cells/ml. on day 11 of cultivation. At a temperature of 2 °C and 10 °C, an almost stable state of algae is observed, the concentration increases very slowly, however the culture does not die. The productivity of microalgae at a temperature of 25 °C was 397 million of cells/(l·day), at a temperature of 19 °C – 334 million of cells/(l·day), at a temperature of 10 °C – 67 million of cells/(l·day), at a temperature of 2 °C – 37 million of cells/(l·day).

3. The amount of energy that can be obtained from the microalgae biomass under the growing conditions of 3500 lx and 23 °C is 53083 (kWh)/(m^3·day). The biogas amount that can be obtained from the same amount of biomass is 6.188 l of methane/(l of medium·day).

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