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THE ROLE OF THE WAVELENGTH OF LIGHT IN THE DYNAMICS OF GROWTH OF CHLOROPHYLLSYNTHESIZING MICROALGAE DUE TO THE ABSORPTION OF CARBON DIOXIDE

Vasyl Dyachok, Viktoriia Katysheva,
Serhiy Huhlych, Roman Dyachok

Lviv Polytechnic National University,
12, S. Bandery Str., 79013 Lviv, Ukraine
dyachokvasil@gmail.com, katyshevakt@gmail.com

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Abstract. The effect of light wave length on the rate of carbon dioxide absorption by microalgae has been studied. The mechanism of transfer of carbon dioxide from the air into the internal environment of the cells of microalgae has been described. The coefficient of microalgae growth based on the mathematical model has been determined. The analytical dependence of the mentioned coefficient on the light wave length has been obtained. The optimum length of light wave has been determined to design the flow chart for eliminating carbon dioxide from industrial gas emissions by the biological method.

Keywords: photosynthesis, light wave length, microalgae, diffusion, mathematical model, kinetics.

Introduction

About 150 world leaders met in the suburb of Paris, in a township of Lai Burzhe, where a world climatic summit concerning continuous growth of carbon dioxide content in the atmosphere began on November 30, 2015. Its main task was to agree on measures, which would allow retaining the growth of temperature in our planet within the limits of 2 °C. Scientists have already alarmed and warned that if this problem is not solved in an urgently, the middle temperature of the Earth will rise by 5 °C till the end of the century and it will cause the threat of global sea level rise and catastrophic consequences for all mankind.

This situation necessitates the development of effective technologies for eliminating this undesirable effect. One of the possible solutions to this problem is to use photosynthesis in industrial environment. The ability to absorb carbon dioxide from the atmosphere by plants and algae and its "storage" in the form of biomass is an objective condition for the implementation of these processes to the treatment of industrial carbon dioxide emissions. This process can be described by a reaction:

$$nCO_2 + mH_2O + \text{solar energy} \rightarrow C_n(H_2O)_m + nO_2 \quad (1)$$

Not only plants, but also microalgae have the ability to perform photosynthesis. Moreover, the advantage of chlorophyll synthesising microalgae is that they grow quickly and absorb much more carbon dioxide than the plants, and are able to adapt to the land of adverse conditions. Photosynthesis can be implemented effectively and efficiently in a light period of a day. There is a problem of photosynthesis at night because it requires artificial lighting making industrial technologies more expensive. Therefore searching ways to reduce the cost of realization of photosynthesis in industrial technologies is the relevant problem.

One of the ways of decreasing the quantity of carbon dioxide in the atmosphere is the development of effective methods for eliminating it from industrial gas emissions, including the use of photosynthesis which is one of the most efficient biological methods. The necessity of additional artificial lighting significantly increases the cost of environmental measures when it comes to continuous cleaning process. A significant reduction of energy costs is possible thanks to the determining the light wavelengths in the visible area of the spectrum at which the maximum absorption of the culture of microalgae is obtained. Therefore, it is reasonable to use microalgae photosynthesis at certain wavelengths of the visible spectrum of the light flux.

The literature contains information about the most important factors influencing the efficiency of algae photosynthesis which include temperature [2], the extent of aeration by carbon dioxide [3, 5], the illumination, the contents of macro and microelements, the alkaline–acid balance, etc. At the same time, there is little information about the impact of certain wavelengths in the visible range on the effectiveness of microalgae photosynthesis. Due to the correlation of physical and chemical values with the biological ones, you can get a deeper understanding of processes in the investigated biological object. Therefore, the study of the influence of light wavelengths in the visible area on the efficiency of photosynthesis is an interesting task.

The aim of this work is to study the influence of light wavelengths on photosynthesis processes, which accompany the absorption of carbon dioxide from the gaseous fluid by the cells of microalgae and increase their biomass.

Theoretical part

Photosynthesis is the only process in the biosphere, which leads to the increase in free energy due to the internal source. The energy stored in the products of photosynthesis is the main source of energy for the mankind. It means that the products of purposeful photosynthesis can be used for recuperation of power. For example, it can be anaerobic biodegradation with the aim of producing methane [4].

Traditionally it is believed that photosynthesis is the process of converting sunlight into energy of chemical bonds and the synthesis of organic compounds (carbohydrates) from inorganic ($CO_2\uparrow$ and H_2O).

$$6CO_2 + 6H_2O + h\nu \rightarrow C_6H_{12}O_6 + 6O_2\uparrow$$

Photosynthesis is a complex multistage process; the reactions of photosynthesis are divided into two groups: reactions of the light phase and the reactions of the dark phase.

Direct experimental proof that the oxygen in photosynthesis is released from water was found in 40-ies of the last century. In addition, it was found that photosynthesis involves two groups of reactions: one, which is related to photodissociate water, release of O_2, and the electron transfer, is a light phase; and the other, related to the reduction of CO_2 to carbohydrate, which does not depend on the light, is a dark phase.

The process, in which energy-saturated molecules and ATP compositions appear, is called the light phase of photosynthesis. The total equation of the light phase of photosynthesis:

$$12H_2O + 12NADP^* + 12ADP + 12H_3PO_4 \rightarrow 12NADPH_2 + 12\ ATP + O_2$$

Dark phase of photosynthesis occurs in chloroplast. The final equation of photosynthesis:

$$6CO_2 + 24H^+ + ATP \rightarrow C_6H_{12}O_6 + 6H_2O$$

Biological objects, as a rule, are very complex and the processes occurring in them are influenced by many factors which often depend on each other. The absorption of carbon dioxide from the air by microalgae is a subject to the laws of mass transfer. At the heart of the processes of mass-exchange of microalgae cells with the environment lies a complex series arranged in a certain way in time and space of biochemical reactions. As a result of these processes the concentration of the absorbing substance, the number of single cells of the microalgae, the biomass of the microorganisms are changing and other values can also change. Thus, the absorption of carbon dioxide by microalgae is a complex heterophase process in which there occurs the mass transfer of carbon dioxide from the gas phase to conventional solid phase. This processes are characterized by the simultaneous dependence of the rate on diffusion and kinetic factors. The system “gas-liquid-cell” is three-phase, which inevitably creates additional difficulties for the description even in comparison with complex two-phase gas-liquid systems [6].

Penetration of carbon dioxide into the aqueous phase and then the diffusion transfer to the cell membrane with subsequent transfer through the membrane into the cell can be satisfactorily described by the model of mass transfer to the surface of solid particles, as cells are commonly considered to be “conventionally solid” phase. The total resistance in this case can be quite significant, therefore it is important to determine which of the all is limiting and most affects the overall speed of the process.

For the cultivation of microalgae in devices with mixers or column bioreactors the diffusion resistance at the interface “cell-liquid” can be neglected in cases where it comes to separately growing cells.. As shown in several experiments, the system with separately developing cells of the microalgae which are in liquid environment can be influenced by mass transfer at the interface "gas-liquid", but almost never limited by the transfer of substances into the cell or reverse transfer of metabolic products.

With sufficiently good mixing, the microalgae cells are uniformly distributed over the volume of the liquid. With this assumption the mass transfer of carbon dioxide from the gas phase into the liquid phase will flow with the speed:

$$r_Д = \beta_{CO_2} \cdot (\overline{C}_{CO_2} - C_{CO_2}), \quad (2)$$

and carbon dioxide which is turned into the liquid phase is consumed by the culture of microalgae, which grows with the speed:

$$r_{CO_2} = k_{CO_2}[N_K]C_{CO_2}. \quad (3)$$

With constant or little changing concentration of carbon dioxide in the gas phase, respectively, the constant concentration C_{CO_2} in the liquid phase, the system with the culture of microalgae growing in the liquid phase enters a stationary state in which the consumption of carbon dioxide by cells is fully compensated by its income from the gas phase, that is

$$r_Д = r_A.$$

This allows to equate expressions (2) and (3) provided that the β_{CO_2} is the surface-volume coefficient of mass-transfer from the gas phase into the liquid.

$$r_{CO_2} = r_Ä = k_{CO_2}[N_K]C_{CO_2} = \beta_{CO_2} \cdot (\overline{C}_{CO_2} - C_{CO_2}), \quad (4)$$

The total resistance is recorded by the dependence (4), where the law of aggregate resistance is kept:

$$\frac{1}{k_{CO_2}} = \frac{1}{b_{CO_2}} + \frac{1}{k_{CO_2}[N_K]} \quad (5)$$

Since the overall resistance of the process of consumption of carbon dioxide – $1/k_{ef}$ is the sum of the diffusion resistance $1/\beta_{CO2}$ and kinetic, which includes the parameters of the process of metabolism $1/k_{CO_2}[N_K]$.

The process model includes a sequential component transfer from phase to phase and its consumption by the cells in the volume of the liquid phase. This leads to the conclusion about the existence of a stationary concentration of carbon dioxide, which is transferred in the phase, where its consumption occurs, namely about the constancy C_{CO_2} in time, which is determined by the expression (3). During the time when the cell concentration $[N_K]$ does not change much, the concentration of C_{CO_2} will be constant, if C_{CO_2}, is also an invariable value, which is acceptable in practice.

The cases which are possible with significant differences in the resistances are of practical interest (5).

If the speed of the metabolism of carbon dioxide is significant due to the large quantity of k_{CO_2} or high concentrations of cells $[N_K]$, then $k_{CO_2}[N_K] >> \beta_{CO_2}$ for the inverse values the inequality is:

$$\frac{1}{\beta_{CO_2}} << \frac{1}{k_{CO_2}[N_K]}. \quad (6)$$

Then (5) can be simplified because the small resistances in the amount can be neglected, in that case $k_{ef} \approx \beta_{CO_2}$ and the overall speed of the process is:

$$r_{CO_2} \cong \beta_{CO_2} \cdot \overline{C}_{CO_2} = \beta_{CO_2} \cdot \frac{1}{\gamma_{CO_2}} \cdot C_{CO_2}. \quad (7)$$

This extreme case corresponds to the diffusion regime of the process, and the nature of the dependence (7) indicates that in such circumstances $C_{CO_2} \cong 0$, in that case microalgae consume carbon dioxide, which diffuses from the gas phase while it is nearly of absent in the liquid phase. It is clear that all the factors which contribute to the increase of the coefficient of mass transfer β_{CO_2} will accelerate the overall process of cultivation due to improvement of supply the cells by the limiting substrate and carbon dioxide. This will result in an increase of the carbon dioxide concentration or its partial pressure in the gas phase.

The second extreme case is when $\beta_{CO_2} >> k_{CO_2}[N_K]$ is achieved in the slow consumption of carbon dioxide by microalgae culture or its low concentration. Inequality

$$\frac{1}{\beta_{CO_2}} << \frac{1}{k_{CO_2}[N_K]} \quad (8)$$

in this case (4) can be written as:

$$r_{CO_2} \cong k_{CO_2}[N_K] \cdot \overline{C}_{CO_2} = k_{CO_2}[N_K] \cdot \frac{1}{\gamma_{CO_2}} \cdot C_{CO_2}, \quad (9)$$

The rate of consumption of carbon dioxide according to (9), is determined only by kinetic factors, therefore this mode can be called kinetic.

In these circumstances, the mass transfer ensures the maximum possible supply of carbon dioxide, which comes from the gas phase to the cells, and the current concentration of carbon dioxide is almost identical with equilibrium, which responds to saturation. Among other factors intensifying the kinetic processes are: temperature, concentration of reagents, and for photo-kinetic, as in this case, the source of light energy.

The main material and discussion of the results

The spectrum of absorption in the visible area of the aqueous solution of Chlorella microalgae is presented in Fig. 1.

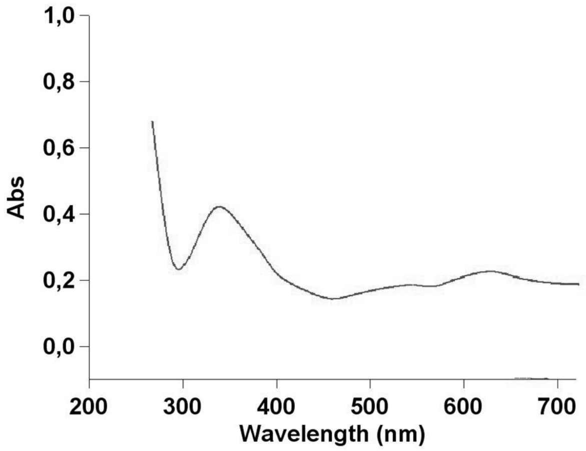

Fig. 1. The spectrum of absorption of the aqueous solution of the studied microalgae

According the shown spectrum, it is possible to say that the greatest area of absorption has (340–400 nm) and (650–700 nm). These spectra correspond to approximately violet-blue and red light, therefore it is useful to study the absorption of the carbon dioxide in these two areas.

The object of laboratory research was the culture of green microalgae of Chlorella vulgaris, which is cultivated with different colours of light during 14 days in four photobioreactors with a 1.5 L volume. In the first photobioreactor the colour of the light was blue, in the second – green, in the third – yellow and in the fourth one it was red. An equal amount of inoculum with the culture of the Chlorella vulgaris microalgae was placed into the basic nutrient environment. The algae received the same amount of the corresponding spectrum of light and bubbling carbon dioxide in all the four photobioreactors. In the further cultivation of algae, their number increased. The pH was 6.5. The temperature of cultivation was 20±1°C. Very quickly from almost transparent content a liquid of dark green colour was formed. The selection of the solution of biomass of algae was carried out every day. The concentration of algae biomass was determined by a photocolorimetric method.

The results of experimental studies of the growth of microalgae biomass by the corresponding wavelengths are presented in Fig. 2. These are the curved lines of growth of so-called S-shaped form and allow to identify four phases of growth which take place in a specific sequence and are expressed to a greater or lesser extent: the initial, or adjustment phase, linear and stationary phases Fig. 2. Phase of settling of microalgae culture is clearly seen in Fig. 3. It is important to note that the adaptation phase for the bioreactor, which was covered in blue and red light has the lowest amount of dying culture and the highest intensity of its growth in the subsequent phases. This confirms the effectiveness of these wavelengths in the spectra of illumination during implementation of the technologies of photosynthesis in the dark period of time.

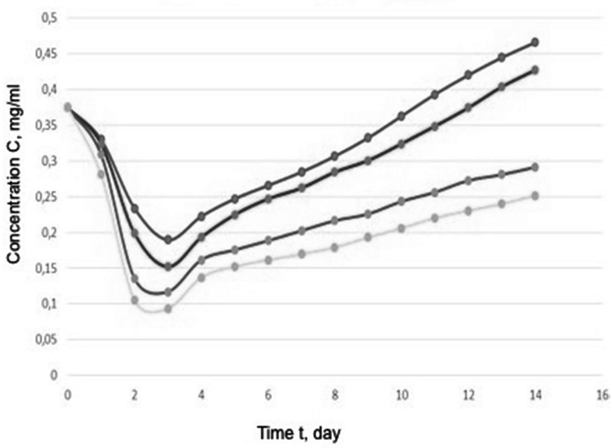

Fig. 2. Kinetic curve lines of microalgae concentration growth

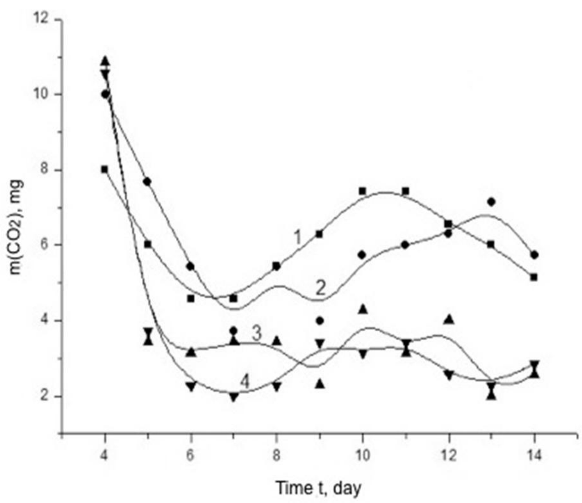

Fig. 2a. The dependence of the mass of absorbed carbon dioxide in appropriate wavelengthes in the investigated limits

The basis of the processes of the cell exchange with the environment and internal metabolism is created by complex series organized in a certain way in space and time by biochemical reactions. As a result of these transformations the concentration of the target substances, the number of individual cells, biomass of microalgae and other quantities are changing. A mathematical model which describes the dependence of modification of cell concentration in the culture medium on time N = N(dt) is given in [6].

As shown in Fig. 2, 3, the dynamics of growth, and thus the intensity of the absorption of carbon dioxide by microalgae significantly depend on the wavelength of light. The experimental curves are well described by the famous equation:

$$N = N_o e^{-k_M t} \qquad (1)$$

where N is current cell concentration in the biomass of microalgae, N_0 is cell concentration in the microalgae biomass at the initial time t = 0, k_M is the coefficient of increasing microalgae biomass.

In logarithmic coordinates (1) describes a straight line, tangent of inclination of which allows to determine the growth rate k_M. The results of the transformations are shown in Fig. 3.

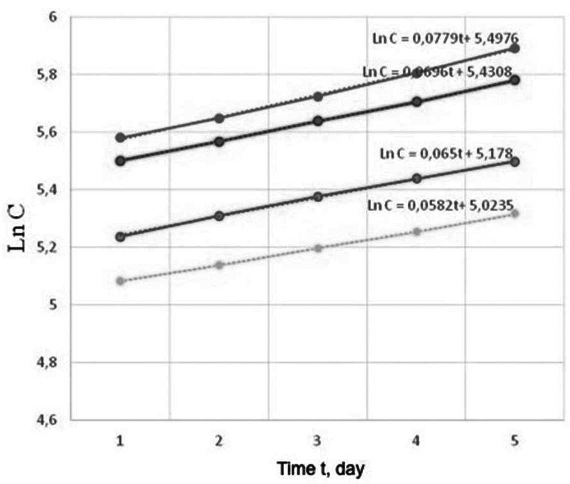

Fig. 3. Kinetic curves of increasing microalgae concentration in logarithmic coordinates with the appropriate light wavelength

Thanks to the graphic dependences, the coefficient of growth for the corresponding spectrum of light was determined, as the tangent of inclination of the experimental curves shown in Fig. 3, and recorded as analytical dependences. Accordingly, for the blue spectrum, the dependence is written: $C = C_0 e^{0,0779t}$;

– for the red spectrum: $C = C_0 e^{0,0696t}$;

– for the green spectrum: $C = C_0 e^{0,065t}$;

– for the yellow spectrum: $C = C_0 e^{0,0582t}$.

Based on the obtained values, the graph of dependence of the growth rate on the wavelength was built and the corresponding dependence was obtained (Fig. 4).

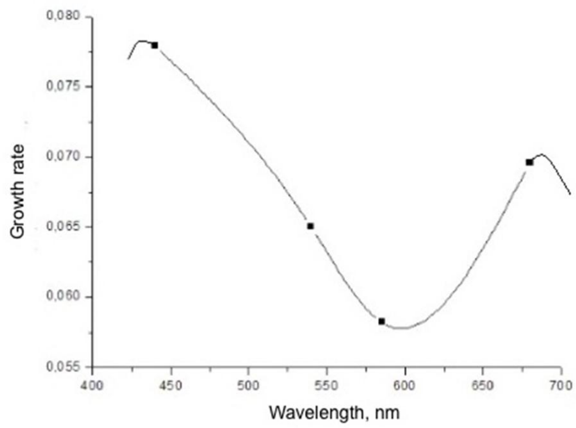

Fig. 4. The dependence of the growth rate on the wavelength

$$k = 3{,}2 \cdot 10^{-3}\lambda + 0{,}0756,$$

where λ is the light wavelength.

Conclusion

The influence of light wavelength on the dynamics of absorption of carbon dioxide by microalgae was studied. The analytical dependence k = f (λ) of the coefficient of growth rate of microalgae on the light wavelength has been obtained.

References

[1] Netrusov A. Y., Bonč-Osmolovskaja E. A., Horlenko V. M. y dr.; Pod red. Netrusova A. Y.: Ekolohyja mykroorhanyzmov: Učebnyk, dlja stud. Vuzov. Yzdat. centr "Akademyja", Moskva 2004, 272. (in Russian)

[2] Djačok V. V., Katyševa V. V., Levko O. B.: Vyvčennja vplyvu temperatury na kinetyku pohlynannja vuhlekysloho hazu mikrovodorostjamy. Visnyk Nacional'noho universytetu "L'vivs'ka politechnika". Chimija, technolohija rečovyn ta ïch zastosuvannja., 2015, 812, 365–372.

[3] Djačok V. V., Huhlyč S. I., Levko O. B.: Vyvčennja procesiv masoobminu pid čas realizaciï biolohičnych metodiv očyščennja hazovych vykydiv vid vuhlekysloho hazu. Visnyk Nacional'noho universytetu "L'vivs'ka politechnika". Chimija, technolohija rečovyn ta ïch zastosuvannja, 2014, 787, 313–319.

[4] Djačok V. V. Levko O. B.: Vyvčennja procesu masoobminu pry peretvorenni vuhlekysloho hazu u metan biolohičnym metodom. Ekolohična bezpeka, 2014, 1, 31–35.

[5] Djačok V. V., Levko O. B.: Masoobmin v biolohičnych procesach. Visnyk NU “L'vivs'ka politechnika” Chimija, technolohija rečovyn ta ïch zastosuvannja, 2013, 761, 289–293.

[6] Dyachok V., Huhlych S. Mathematical design of biological processes of complicated mass transfer Sciens and Education a New Dimension. Natural and Technical Sciences, III(5), ISSUE 41, 2015, 91–94.

[7] Zolotar'ova O. K., Šnjukova Je. I., Syvaš O. O., Mychajlenko N. F. Pid red. Zolotar'ovoï O. K.: Perspektyvy vykorystannja mikrovodorostej u biotechnolohiï. Al'terpres, Kyiv 2008, 234. (in Ukrainian).