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To cite this article: Sh Rakhmanov *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **883** 012086

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## Automatic control system for the technological process of chlorella cultivation

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**Abstract.** This article devoted to the implementation of mathematical models and algorithms in control problems of the chlorella cultivation process. The article gives us expanded concepts about the construction of the control functional – algorithmic structure, as well as the automation of various microbiological processes and productions, which based on modern computing devices, creation of a full-fledged complex for the task of chlorella mass cultivation process.

When building the control system, problems are solved: collection and primary processing of information, prediction of technological processes progress, optimization of mode parameters, process control.

Within the framework of these main tasks solutions have been found, which make it possible to facilitate the operator-technologist operational control or to implement reasonable management decisions depending on different production situations. For the considered class of objects, in particular the technological process of microalgae cultivation, the task of synthesis of control systems is to maintain the technological process at an optimal level that meets the technological and ecological standards of production.

One of the necessary conditions for the optimal conduct of the process of cultivation of microorganisms is automatic control of the content and composition of nutrients at the entrance, as well as control of the output indicators of the process.

The following technical tasks are also required to implement the management systems:

- Improvement of local control and control systems (pH, T, light.);
- Nutrient composition control, continuous medium circulation.

Periodicity of control tasks solution is established depending on process features, control object, process introduction mode, as well as the availability of a set of hardware.

As a result of the implementation of the proposed control system, the maximum ratio of chlorella concentration to its average value decreased by 23.8%.

Thus, the control system of the chlorella cultivation process provides a timely prediction of the technological process and the formation of control actions using a computing device, which contributes to an increase in the productivity of the cultivator by 8-12%.

Based on the theoretical and experimental studies performed as part of this work, the following main results were obtained:

1. Based on the developed models and algorithms, a functional-algorithmic structure of a control system for the chlorella cultivation process is proposed, oriented towards



solving the following problems: collecting and primary processing of information, predicting the progress of the technological process, optimizing operating parameters and controlling the course of the technological process.

2. The implementation of the control system made it possible to increase the yield of chlorella from a unit of spent nutrients, to increase the productivity of the cultivator due to the strict maintenance of the optimal value of the residence time of the substrate particles in the apparatus.

3. The results obtained make it possible to draw a conclusion about the adequacy of the constructed models for the real process, the correctness of the selected control actions and optimality criteria, as well as the efficiency and effectiveness of the developed algorithms for optimizing and controlling the technological process of chlorella production cultivation.

## 1. Introduction

In the automation of microbiological processes and production based on the application of modern methods, principles, and techniques of automatic control theory-oriented to the use of control computer equipment, there is a need to solve in a new way a number of issues related to algorithms of initial tasks. Application of modeling methods and algorithms of optimal control contributes to the scientific-reasonable selection of effective methods of information presentation, justification of composition, and structure of technical means [1, 2, 3, 4].

The growth and development of algae primarily depend on the composition and concentration of nutrient media. In the cultivation of chlorella,  $KNO_3$ ,  $KH_2PO_4$ ,  $MgSO_4$ , and others are usually used as nutrients. Their content in the cultivated medium varies widely, but an increase in their concentration does not adversely affect the growth rate of chlorella [5, 6].

Description of the nutrient medium preparation system is given, which makes it possible to increase accuracy and maintain the required ratio of nutrient components and quality of the prepared nutrient medium.

## 2. Methods

The functional-algorithm structure of the control system should be synthesized taking into account the efficiency of the solved task (the ratio of the value of the obtained information to costs).

When building the control system, problems are solved: collection and primary processing of information, prediction of technological processes progress, optimization of mode parameters, process control, etc [7, 8, 9, 10].

Within the framework of these main tasks, solutions can be found that make it easier for the operator-technologist to manage quickly or to implement reasonable management decisions depending on different production situations. For the considered class of objects (microalgae cultivation process), the task of synthesis of control systems is to maintain the process at an optimal level that meets the technological and environmental standards of production [11, 12].

Make special research in the laboratory and some production conditions, where it is possible to prepare and transport when growing chlorella use standard nutrient media (type 0.4, Tamiya, Myers, Leningrad, etc.)

One of the necessary conditions for the optimal conduct of the process of cultivation of microorganisms is automatic control of the content and composition of nutrients at the entrance, as well as control of the output indicators of the process. However, due to the lack of serial sensors, local automatic monitoring and control systems are currently used to stabilize input and output flows [13, 14].

At optimal control, it is necessary to monitor and influence the whole set of factors affecting the target function. In practice, the control effects  $Y = F(Z, U^*)$  differ from the required  $U^*$  at a size

$$\delta U^* = F(Z, U^*) - \varphi^* \quad (1)$$

In (1)  $F$  is the function.

Obviously, the control correction  $\delta U$  should minimize this value. In other words, in order to synthesize the correction  $\delta U$ , it is necessary to solve the minimization problem

$$Q(\delta U) = |F(Z, U^* + \delta U) - Y^*| \min \delta U \in R(2)$$

In (2)  $R$  - resources allocated for correction.

Based on the proposed mathematical models, the chlorella cultivation control system should solve the following problems:

- Selection of optimal composition of nutrients (rate of medium dilution in cultivator);
- Determining the productivity of the cultivator;
- Stabilization of current concentrations of chlorella and nutrients in the cultivator, etc [15, 16].

### 3. Results and Discussion

When controlling, the discrepancy between the required change in the output of the object  $U^*(t)$  in the control process and what is obtained when controlling in the environment should be minimized  $Z(t) \neq \hat{Z}(t)$ ,

In(3)  $\hat{Z}(t)$  is the forecast of behavior of the environment.

This task looks like

$$\int_0^T [F(t), U^*(t) + \delta U^*(t) - Y^*(t)]^2 \rightarrow \min \delta U^*(t) \in R \quad (3)$$

The increasing requirements for the quality of control of the chlorella cultivation process make it necessary to build systems based on adaptive control algorithms [17, 18, 19, 20].

The proposed system of optimal control of the chlorella cultivation process, which implements a set of control algorithms, solves the following tasks:

- Collection and primary processing of information; Output of current values of monitored variables upon operator call;
- Timely forecast of technological process progress;
- Optimization of nutrient media composition;
- Finding optimal mode variables;
- Implementation of management decisions;
- Situational analysis and forecasting of process results.

The following technical tasks are also required to implement the management systems:

- Improvement of local control and control systems (pH, T, light, etc.);
- Nutrient composition control, continuous medium circulation, etc.

Periodicity of control tasks solution is established depending on process features, control object, process introduction mode, as well as the availability of a set of hardware.

The growth and development of algae primarily depend on the composition and concentration of nutrient media. In the cultivation of chlorella,  $KNO_3$ ,  $KH_2PO_4$ ,  $MgSO_4$ , and others are usually used as nutrients. Their content in the cultivated medium varies widely, but an increase in their concentration does not adversely affect the growth rate of chlorella.

When optimally controlling the process of microalgae cultivation, it is also necessary to take into account the rapid adaptability of the latter to different salt concentrations in the nutrient solution. The composition and amount of trace elements are of great importance in the cultivation of the chlorella. Therefore, it is necessary to determine the optimal content and composition of nutrients that create favorable conditions for the growth and development of microorganisms.

Make special research in the laboratory and some production conditions, where it is possible to prepare and transport when growing cholrella use standard nutrient media (type 0.4, Tamiya, Myers, Leningrad, etc.)

Usually, many semi-industrial and production facilities where many years of chlorella cultivation is practiced do not use standard media, this is due to the absence of special production facilities focused on the preparation of standard media, high cost and difficulties in transporting them.

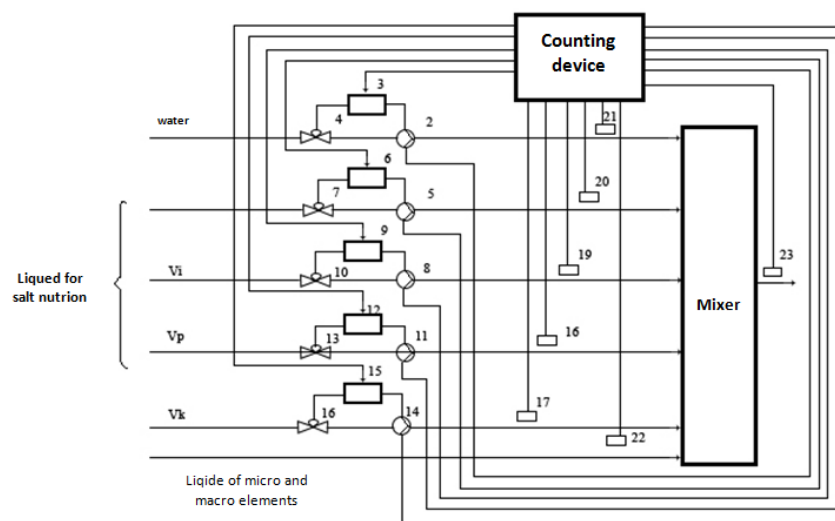
Therefore, many farms themselves prepare nutrients in the required amount. Their composition depends on the presence of nutrient salts. To this end, a solution of trace elements necessary for culture growth is added (8).

Consider the methods of preparation of nutrient media and the control system designed to improve the accuracy and quality of the prepared nutrient media, as shown in Figure 1.

The system for preparation of nutrient medium is necessary for the growth of chlorella, contains: mixer - 1 for preparation of nutrient medium, measuring sensors of water consumption and salt solutions ( $KNO_3$ ,  $KH_2PO_4$ ,  $KNO_3$ ) - 58,11, as well as a sensor of microelement solution consumption - 14, sensors of dissolved nutrient concentration 15-19. All necessary information is supplied to the input of the computing device - 20 for processing and generation of control interactions (6).

Sensors 2, 5, 8, 11 produce information on current values of water flow and dissolved nutrients ( $KNO_3$ ,  $KH_2PO_4$ ,  $KNO_3$ ), and sensors 15-19 – on the concentration of nutrient salts.

On the computing device research processes the received information and, based on a mathematical model, using one of the optimization methods determines the value of the optimal nutrient consumption. To do this, you must first have information about the value of the concentration of salts.



**Figure 1.** Nutrient medium preparation process control system.

The values of the optimal consumption of nutrients, water, solutions of salts, microorganisms, and microelements are determined based on the following ratios:

$$V_k = \frac{V_p S_k}{C_k};$$

$$V_i = \frac{V_p S_i}{C_i}; \quad i = \overline{1, n};$$

$$V_B = V_p \left(1 - \frac{S_k}{C_k}\right) - \sum_{i=1}^n S_i / C_i.$$

Maintenance of optimum value PH of nutrient medium in the ammonia water supply line is performed by installed actuators, which receive signals of controlled actions, generated by the computing device (Fig.1).

The proposed method for preparing the medium for the cultivation of microalgae allows increasing the growth rate and improving the conditions for the development of chlorella by creating favorable conditions in the cultivator with varying pH values of the medium, composition of nutrient salts, etc.

Prepared nutrient medium accumulates in mixer wherefrom it is fed in the required amount to cultivator (25).

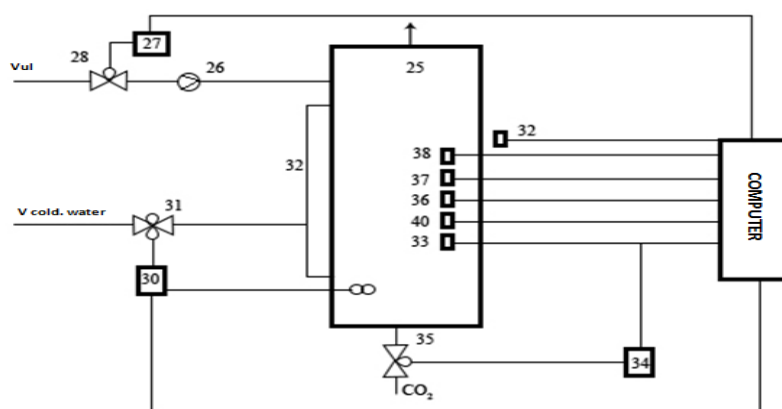
The proposed system of automatic control of chlorella cultivation, which is presented in Fig.2, is intended to provide increased productivity of the cultivator. It has a circuit for regulating the supply of nutrients to the inlet of the cultivator (25). The circuit consists of a flow sensor (26) connected to a regulator (27), the output of which is connected to an actuator (28), installed on a feed line of nutrient salts.

The proposed system also comprises a medium temperature control circuit in cultivator 25 consisting of the temperature sensor (29), connected with the regulator (30) whose output is connected with the actuator (31) fitted on the cooling agent feed line fed into the cooling jacket (32).

Since the process of chlorella cultivation takes place with the direct participation of the  $CO_2$ , a  $CO_2$  concentration sensor (33) connected to the regulator (34) whose output is connected to the actuator (35) is installed on the  $CO_2$  supply line. The system also contains a sensor of pH (36), the concentration of chlorella (37), and inhibitor (38), as well as a photosensitive element (39), which is connected to an actuator through a computing device. The device also receives information from other sensors (e.g., the level sensor 40, etc.).

The computing device is connected to chlororella and inhibitor concentration sensors, temperature and level sensors to photosensitive elements, etc. The output of the computing device is connected to the actuating mechanism of cold water supply control circuit and nutrient media.

The computing device enables timely prediction of the plant efficiency index and generates control actions applied to actuators, which provides the necessary conditions for the implementation of the optimal process. As a result, the productivity of the culture and the yield of the chlorella from the unit of nutrient salts ( $V_{ps}$ ) is increased.



**Figure 2.** System for automatic control of chlorella cultivation process

The increase in the volume consumption of nutrient salts ( $V_{ps}$ ) above the permissible limit (the growth rate of the chlorella is less than the yield) leads to the constant pouring of the chlorella from the cultivator, which leads to losses of nutrient salts, which reduce the productivity of the process plant.

Based on current values of  $T$ ,  $pH$ ,  $H$ ,  $V_{ps}$ , etc., supplied to the computing device from sensors 26, 29, 33, 36, 37, 33, 39, etc., the specific growth rate of chlorella in the cultivator is calculated.

$$\mu = \frac{\mu_p S}{K_S + S} * \frac{I}{K_I + I} - \left[ \frac{(pH - pH_{opt})^2}{\sigma_{pH}^2} - \frac{(T - T_{opt})^2}{\sigma_T^2} - \frac{(C - C_{opt})^2}{\sigma_C^2} \right].$$

Since the process of culturing the chlorella is carried out in a continuous circulation mode, the average residence time of the medium particles within one cycle is

$$\tau = \frac{V}{v}$$

$V$  is the cultivator volume,  $m^3$

$v$  is the flow rate at the inlet and outlet of the cultivator,  $m^3/g$ .

Information on the change in the conditions of use of the chlorella stamp or the quality of the applied nutrient salts, fixed by experimentally determined coefficients of the corresponding equations of the model, is entered into the computing device.

The chromostat mode of chlorella cultivation is carried out under the condition of  $\mu = D$ , when the initial concentration of chlorella remains constant throughout the process. The computing device calculates based on the equation and determines the misalignment wire

$$\sigma = \mu - D$$

Depending on value  $\sigma$  the computer develops the corresponding operating influence given on the actuator (28) installed on a supply line of vegetable salts in a cultivator and providing a change of  $V_{ps}$  at a size  $\Delta V = \sigma * H * Q$ , in  $Q$  is the section of a zone of a channel of nutrient medium.

The productivity of the cultivator is determined from the expression

$$B = \mu x + H * Q = V^* X \quad (4)$$

In (4)  $V^*$  is the design value of nutrient salt consumption,  $m^3/s$ .

Thus, based on the processing of information from the sensors and based on the results of laboratory analyses, the computing device calculates the main indicators of the process of chlororella cultivation, including the values of  $\mu$  and  $V^*$ . At the same time, the control computing device predicts the progress of the cultivation process from such parameters as  $X$ ,  $pH$ ,  $T$ ,  $CO_2$ , etc., simultaneously calculating  $V$  and as a result, determines the productivity of the cultivator when the flow rate is equal to the flow rate of continuous cultivation. The computing device helps to predict as well as calculate  $B$  values in a timely manner and generate control actions on the mechanism (28), which provides optimal control of the flow rate of the nutrient salts  $V_{ps}$ .

Increased consumption of nutrient salts  $V_{ps}$  compared to  $V^*_{ps}$  leads to removal of culture change, loss of nutrient salts, and as a result - to the reduction of apparatus productivity and reduction of chlorella yield from a unit of nutrient salts. If the nutrient salt consumption is reduced, there is a decrease in the concentration of  $X$  and therefore a decrease in the productivity of the cultivator.

Experimental studies carried out in a cultivator with a volume of  $10 m^3$  on the growth of chlorella in a medium of 04 nutrient salts showed that what  $N = 10 mg/l \div 45 mg/l$ ;  $P = 5 \div 14 mg/l$ .

The initial concentration of sowing chloe is 3-4 million/l, and the maximum value reached 80-10 million/l. The content of  $CO_2$  fed into the cultured medium is 25-30 mg/l, pH of the medium is 6-8, the volume flow rate of the medium is  $1.4 m^3/day$ . The specific productivity was 150 mg/l.

Environment temperature was maintained in a cultivator equal 25-30 °C, the illumination of the environment was 17-30 thousand luxury.

As a result of the implementation of the proposed control system, the maximum ratio of chlorella concentration to its average value decreased by 23.8%.

Thus, the control system of the chlorella cultivation process provides timely prediction of the technological process and the formation of control actions using a computing device, which contributes to an increase in the productivity of the cultivator by 8-12%.

#### 4. Conclusions

The proposed system of optimal control of the chlorella cultivation process, which implements a set of control algorithms, solves the following tasks:

- Collection and primary processing of information; Output of current values of monitored variables upon operator call;
- Timely forecast of technological process progress;
- Optimization of nutrient media composition;
- Finding optimal mode variables;
- Implementation of management decisions;
- Situational analysis and forecasting of process results.

Periodicity of control tasks solution is established depending on process features, control object, process introduction mode, as well as the availability of a set of hardware.

The proposed method of preparing medium for mass cultivation of microalgae makes it possible to increase growth rate and improve conditions of development of chlorella due to the creation of favorable modes in cultivator at a variation of values of pH medium, the composition of nutrient salts. This model allows us, with the help of modern computing devices, to improve and improve the state of production and mass cultivation of microalgae in real time, so that we can also develop software for more accurate control and automation of this model.

Analysis of control system tests allows us to draw the following conclusions:

- 1) The system allows you to reliably stabilize the flow of nutrients.
- 2) During the operation of the control system, the main process indicators (N, P, CO<sub>2</sub>, T, Ph, C, V) and others did not go beyond the permissible limits, and the time to regeneration (using chlorella as a seed material) was more than doubled.
- 3) The control system made it possible to increase the technical and economic indicators of production, ensuring an increase in the yield of chlorella per unit of the spent substrate by an average of 18%.

Based on the results obtained, we can conclude that the proposed models are adequate to the real process, that the selected control actions and criteria are correct, and that the developed optimization algorithms work. Thus, the control system of the chlorella cultivation process makes it possible to improve the quality of management and increase the overall culture of economic planning and analysis through the use of more reliable and timely information on the progress of a complex technological process, as well as through more rational use of available resources (raw materials, useful volume cultivator, etc.).

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