Implementation of mathematical models and algorithms in task control of the microalgae cultivation processes

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Abstract. This article considers the implementation of mathematical models and algorithms in the problems of controlling the process of chlorella cultivation. When building a control system, the following tasks are solved: collecting and primary processing of information, predicting the course of technological processes, optimizing regime parameters, managing a technological process, etc. One of the necessary conditions for the optimal conduct of the process of cultivating microorganisms is automatic control of the quality and composition of nutrients at the inlet, as well as control of the output indicators of the process. The frequency of solving control problems is set depending on the technological features, the control object, the mode of introducing the process, and also on the availability of a complex of technical means. As a result of the implementation of the proposed control system, the maximum ratio of the concentration of chlorella from its average value decreased by 23.8%. Thus, the control system for the cultivation of chlorella provides timely forecasting of the course 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%.

1. Introduction

Human activity is considerably increasing water contamination, which is impeding our future development. As a result, we need act right away and look for sustainable ways to treat this essential resource. It is commonly recognized that some microorganisms can help clean up polluted water. For instance, microalgae can get rid of organic nitrogen, which is typically the limiting substrate in wastewater.

The modeling and simulation of the bioreaction processes must come before the quantitative description of those processes. There are several knowledge databases and modeling catalogs available nowadays, on which the researcher might base his or her theory and test it with the least amount of active experimentation. The process engineer can construct a comprehensive model of the photobioreactor (PBR) and the culture under autotrophic, mixotrophic, or heterotrophic conditions in order to address optimization and scale-up problems by having knowledge of microalgae kinetics and physiology. The use of modeling methods and optimal control algorithms contributes to a scientifically based choice that is effective in presenting information, substantiating the composition and structure of technical means [1, 2].

Automatic control of the quality and composition of nutrients at the inlet, as well as control of the process's output indicators, is one of the necessary conditions for the optimal operation of the microorganism cultivation process. However, due to the lack of serial sensors, local automatic monitoring and control systems are currently used to stabilize the input and output flows [3, 4].

2. Research Methodology

With optimal control, it is necessary to control and influence the entire set of factors influencing the function of the objective. In practice, the control actions $Y = F(Z, U^*)$ differ from the required U* by:

$$\delta U^* = F(Z, U^*) - \varphi^* \tag{1}$$

here: F - function

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The control correction δU should minimize this value, obviously. In other words, to synthesize the correction δU, it is necessary to solve the minimization problem:

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

where: R - resources allocated for correction

The control system for chlorella cultivation should address the following issues in accordance with the provided mathematical models:

- determining the productivity of the cultivator;
- measuring the productivity of the cultivator; - stabilizing the existing chlorella and nutrient concentrations in the cultivator, etc. [5, 6]. - choosing the best nutritional composition (rate of dilution of the medium in the cultivator).

When controlling, it is necessary to minimize 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 $Z(t) \neq \hat{Z}(t)$, where in the formula (3): $Z\check{}(t)$- the forecast of the behavior of the environment. This task is as follows:

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

The development of systems based on adaptive control algorithms is required because to the increasing quality control requirements for the chlorella cultivation process [7, 8]. The following issues are resolved by the suggested method for implementing a set of control algorithms in the chlorella cultivation process:

-collection and primary processing of information; output current values of controlled variables on call of the operator;
- Timely forecast on the course of technological processes;
- Optimization of the composition of nutrient media;
- finding optimal regime variables;
- Implementing management decisions;
- Analyzing the current situation and predicting the outcome of the process.

To implement control systems, it is also necessary to solve the following technical support tasks:
- Improvement of the work of local control and regulation systems (pH, T, light, etc.);
- management of the composition of nutrients, continuous circulation of the medium, etc.

The frequency of solving control problems is set depending on the technological features, the object of control, the mode of introduction of the process, as well as the availability of complex technical means [9-12].

Based on the following ratios [13, 14], the values of the optimal consumption of nutrients, water, salt solutions, microorganisms, and microelements are established:

$$V_k = \frac{V_p S_k}{C_k}; \qquad (4)$$

$$V_i = \frac{V_p S_i}{C_i}; \quad i = \overline{1, n}; \qquad (5)$$

$$V_\text{в} = V_p(1 - \frac{S_k}{C_k}) - \sum_{i=1}^n S_i/C_i. \qquad (6)$$

Installed actuators, which take control signals produced by a computing device, maintain the nutritional medium's pH at its ideal level in the ammonia water supply line. By generating favorable circumstances in the cultivator with variable pH values of the medium, nutritional salt content, etc., the proposed technique for making a medium for cultivating microalgae allows for greater growth rate and improved conditions for chlorella development [13, 14].

3. Results

Temperature and level sensors for photosensitive substances, chlorella and inhibitor concentration sensors, and other sensors are all connected to the computing device. The actuator of the control circuit for the supply of cold water and nutrient media is connected to the computing device's output. In order to increase the precision and caliber of the prepared nutrient medium, methods for nutrient media preparation and control systems are taken into consideration.

The nutrient medium preparation system is necessary for the cultivation of chlorella [15, 16]. This system contains a mixer for preparing the nutrient medium (see Figure1); 2, 5, 8, 11- measuring sensors for the flow of water and salt solutions (KNO3, KH2PO4, KNO3); 14-microelement solution flow sensor; 15, 16, 17, 18,19- dissolved nutrient concentration sensors. All the necessary information is fed to the input of the computing device (20) for processing and generating control interactions (in formula 6).

Sensors 2, 5, 8, 11 generate information on the current values of water consumption and dissolved nutrients (KNO3, KH2PO4, KNO3), and sensors of the concentration of dissolved nutrients 15, 16, 17, 18, 19 - on the concentration of nutrient salts.

The smart system evaluates the information that has been received and calculates the value of the optimal nutrient consumption based on a mathematical model and one of the optimization approaches. To do this, knowledge of the salt concentration value must be known beforehand.
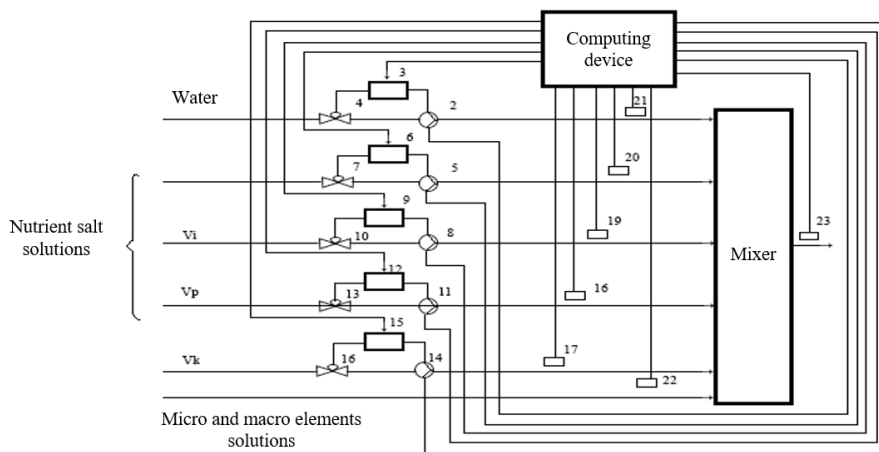

Fig. 1. Control system for nutrient medium preparation processes

The computational device generates control actions that are applied to the actuators and enables timely prediction of the installation's performance indicator, creating the ideal conditions for the implementation of the best process. As a result, the culture is more productive and produces more chlorella per volume of nutritional salts(V_{nc}).
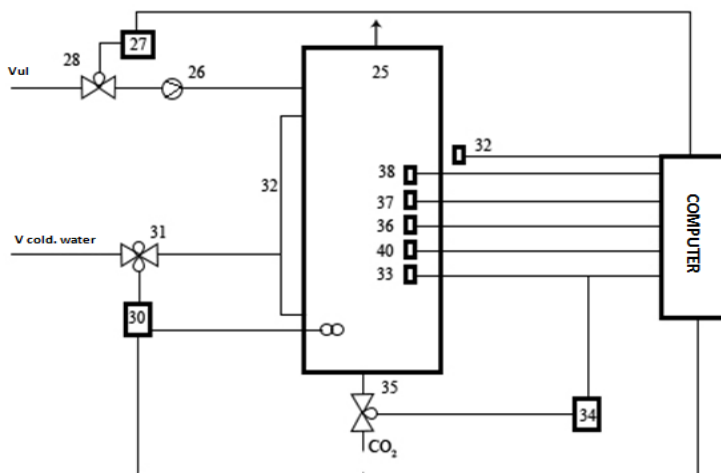

Fig. 2. Automatic control system for the cultivation of chlorella

An increase in the volumetric consumption of nutrient salts (V_{nc}) above the permissible limit (the growth rate of chlorella is less than the debit) leads to the constant outflow of chlorella from the cultivator, which is fraught with loss of nutrient salts and reduces the productivity of the process plant. Based on the current values of T, *pH, H, V_{nc},* etc., entering the computing device (Figure 2.) from sensors 26, 29, 33, 36, 37, 33, 39, etc., a calculation is made for the specific growth rate of chlorella in a cultivator:

$$\mu = \frac{\mu_p S}{K_S + S} * \frac{I}{K_I + I} - \left[\frac{(pH - pH_{opt})^2}{\sigma_{pH}^2} - \frac{(T - T_{opt})^2}{\sigma_T^2} - \frac{(C - C_{opt})^2}{\sigma_C^2} \right] \tag{7}$$

Because the cultivation of chlorella is done in a continuous circulation mode, the average residence time of the medium particles within one cycle is:

$$\tau = \frac{V}{v}, \tag{8}$$

here: *V*- cultivator volume, м^3

V' - is the concentration in one m3/g of chlorella suspension, the flow rate at the inlet and outlet of the cultivator. Information about changing the conditions for using the chlorella stamp or the quality of the applied nutrient salts, fixed by experimentally determined coefficients of the corresponding model equations, is entered into the computing device. The chromostatic mode of chlorella cultivation is carried out under the condition μ=D, i.e. when the initial concentration of chlorella remains constant throughout the process. The computing device performs a calculation based on the equation and determines the mismatch value:

$$\sigma = \mu - D; \tag{9}$$

Depending on the value of σ, the computing device generates the appropriate control action applied to the actuator [9, 10], installed on the line of supply of vegetable salts to the cultivator and providing a change in V_{ps} by the value ΔV=σ*H*Q, where: Q is the cross-section zone of the duct of the nutrient medium.
The performance of the cultivator is determined from the expression:

$$B = \mu x + H * Q = V^* X, \tag{10}$$

here: V^* - The calculated value of the consumption of nutrient salts, м^3/c.
Thus, the computing device, based on the processing of information coming from the sensors and based on the results of laboratory analyzes, calculates the main indicators of the chlorella cultivation process, including the values of μ and V^*. At the same time, the control computer predicts the course of the cultivation process according to parameters such as X, pH, T, CO_2, etc., simultaneously calculating V and, as a final result, determines the performance of the cultivator when the flow rate is equal to the runoff rate during continuous cultivation. The computing device helps to predict in time, as well as calculate the values of B and develop control actions on the mechanism, which ensures optimal control of the consumption of nutrient salts V_{nc}.
An increase in the consumption of nutrient salts V_{nc} compared to V^*_{nc} leads to the removal of culture changes, the loss of nutrient salts, and, as a result, a decrease in the productivity of the apparatus and a decrease in the yield of chlorella per unit of nutrient salts. In the case of a decrease in the consumption of nutrient salts, a decrease in the concentration of X is observed and, consequently, a decrease in the productivity of the cultivator.
Conducted in a cultivator with a volume of 10 м^3, experimental studies on the cultivation of chlorella in a medium of 04 nutrient salts showed that:

$$N = 10 \ mg/l \div 45 \ mg/l; \ P = 5 \div 14 \ mg/l.$$

The initial concentration of seed chlorella was 3-4 million/l, and the maximum value reached 80-10 million/l. The content of CO2 supplied to the cultivated medium was 25–30 mg/l, the pH of the medium was 6–8, and the volumetric flow rate of the medium was 1.4m3/day. At the same time, the specific productivity was 150 mg/l per day.
The temperature of the environment in the cultivator was maintained at 25-30°C, and the illumination of the environment was 17-30 thousand lx.
As a result of the implementation of the proposed control system, the maximum ratio of the concentration of chlorella from its average value decreased by 23.8%.
Thus, the control system for the cultivation of chlorella provides timely forecasting of the course 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%.
Certain parameter values were established by laboratory analyses during the experiments. Every hour, including the period for sampling and laboratory analysis, sampling was done concurrently.
It was possible to increase the yield of chlorella per unit of nutrients consumed, increase the productivity of the cultivator due to optimal maintenance of the flow rate, etc. by implementing the control system based on the developed mathematical models, optimization and control algorithms, as well as tested software systems.
The type of change in the primary characteristics of the chlorella cultivation process (nutrient consumption G_i, chlorella X concentration, and CO2 content) that happens during the use of the CS based on the suggested models and algorithms (under manual control, with a local automatic regulation and control system).
The following key findings were attained based on the theoretical and experimental studies conducted within the context of this work:

a) Under specific production conditions and nutrient composition, the developed algorithm for predicting and controlling the chlorella cultivation process allows for increased productivity and quality of the target product, as well as the prevention of various unforeseen and emergency production situations in advance.

b) Based on developed models and algorithms, a functional-algorithmic structure of the control system for the chlorella cultivation process was proposed to address the issues of information gathering and primary processing, technological process prediction, regime parameter optimization, and technological process control.

c) By carefully preserving the ideal value of the residence duration of the substrate particles in the apparatus, the control system's installation allowed for an increase in chlorella yield per unit of nutrients used as well as an increase in cultivator productivity.

4. Conclusions

By producing favorable conditions in the cultivator with varied pH values of the medium and nutritional salt composition, the proposed technique of preparing the medium for mass cultivation of microalgae accelerates growth and enhances conditions for chlorella development. We can grow and, more significantly, enhance the state of mass microalgae cultivation using this technology and modern computing devices, which leads us to create software for more accurate control and automation of this model.

The evaluation of control system tests led to the following conclusions: :

a) The system will make it possible to consistently stabilize nutrient consumption.

b) The time to regeneration (using chlorella as a seed) rose by more than two times while the control system was in operation, even though the leading indicators of the processes (N, P, CO2, T, Ph, C, V, and others) did not exceed the permitted limits.

c) A control system allowed for an increase in the technical and financial production indicators, resulting in an average 18% increase in the yield of chlorella per unit of substrate consumed.

By using more accurate and timely information about the development of a complex technological process, as well as by making more judicious use of the resources at hand, the chlorella cultivation process management system enables management quality and the culture of economic planning and analysis to be improved (raw materials, useful volume cultivator, etc.).

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