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Lesia PAVLIUKH[1]
Sergii BOICHENKO[2]
Sergii SHAMANSKYI[3]
Iryna SYROTINA[4]
Olena TODOROVYCH[5]

CASCADE PHOTOBIOREACTOR FOR WASTE WATER TREATMENT BY MICROALGAE

In this paper, we consider the design of an open bioreactor for the cultivation of microalgae. The main feature of this design is a cascade type of tank, which allows you to satisfy parameters such as lightness, mixing, energy efficiency, and economical. The proposed methodology can help to assess all types of bioreactors for microalgae cultivation applying on the waste water treatment. Based on the previous researches, statistical data, modeling and requirement to the bioreactor parameters the construction of cascade bioreactor was proposed. According to proposed methodology of efficiency estimation received that this bioreactor construction is efficient on 85% and offset during the year is positive. The main advantages of the proposed technology and bioreactor construction are environmental, economic and energy-efficient features. These three directions are main proposal to sustainable development which modern world strive for.

Keywords: waste water treatment; energy-efficient benefit; microalgae; bioreactor; economic benefit; biofuel

[1] Lesia Pavliukh, Candidate of Engineering, Associate Prof. of the Ecology Department, Faculty of Environmental Safety, Engineering & Technologies, National Aviation University, Kyiv, Ukraine; e-mail: lesiapavliukh003@gmail.com (corresponding author). ORCID: 0000-0002-7715-4601.

[2] Sergii Boichenko, Doctor of Engineering. Prof., Dean of the Faculty of Environmental Safety, Engineering & Technologies, National Aviation University, Kyiv, Ukraine; e-mail: chemmotology@ukr.net. ORCID: 0000-0002-2489-4980.

[3] Sergii Shamanskyi, Doctor of Engineering. Associate Prof., Leading Researcher of the Research Department, National Aviation University, Kyiv, Ukraine; e-mail: shamanskiy_s_i@ukr.net. ORCID: 0000-0002-6215-3438.

[4] Iryna Syrotina, Student of Faculty of Environmental Safety, Engineering & Technologies, National Aviation University, Kyiv, Ukraine; e-mail: sirotinaio@ukr.net. ORCID: 0000-0002--0420-0654.

[5] Olena Todorovych, Student of Faculty of Environmental Safety, Engineering & Technologies, National Aviation University, Kyiv, Ukraine; e-mail: olenka.lenysia@gmail.com. ORCID: 0000--0002-8692-644X.

1. INTRODUCTION

The high content of biogenic elements, first of all phosphorous and nitrogen compounds, can lead to a decrease of dissolved oxygen, has a toxicological effect on fish, affects the increasing of bioavailable that cause corrosion of water supply systems.

The microalgae treatment of waste water can be a good solution for biogenic elements transferring from water to biomass, and further extraction. That`s why the suitable equipment is required (Geider, Delucia, Falkowski, Finzi, Grime, Grace et al., 2001; Boichenko, Boichenko, Shamanskyi, 2020).

2. PROBLEM STATEMENT

The main problems in the use of microalgae are, first of all, the cost of installation, maintaining the conditions for the growth of culture, the most effective design of tanks. The land resources for tanks are also limited.

The use of wastewater as a substrate for microalgae, and the farthest use of biomass for the production of fertilizers and biofuels, is still at the stage of theory and laboratory research in Ukraine.

3. ANALYSIS OF THE LATEST RESEARCH AND PUBLICATIONS

Significant concentrations of nutrients in reservoirs lead to a decrease in the content of dissolved oxygen, have a toxicological effect on fish, affect the increase of bioavailables that cause corrosion of water supply systems, accelerated growth of water biota and phytoplankton, which, in turn, affects the quality of water. It becomes cloudy, the color changes to green, yellow, brown or red. This prevents its use for recreation, fishing, recreation and domestic needs. The production of phytoplankton toxins, which can cause health problems through exposure to the human body after contact with the skin or the use of contaminated water for drinking, is also a hazard.

Nitrogen, which belongs to biogenic elements, is most needed for the growth of living organisms. An excessive increase in the concentration of nutrients (mainly nitrogen and phosphorus compounds) in water bodies is known as eutrophication. It can be caused by natural processes, when surface waters carry a considerable amount of organic material and nutrients in lakes and oceans, however, this process is mainly caused by a human activity (Ongley, 1996).

The treatment of wastewater subsequent to the removal of suspended solids by microorganisms such as algae, fungi, or bacteria under aerobic or anaerobic conditions during which organic matter in wastewater is oxidized or incorporated into cells that can be eliminated by removal process o5r sedimentation is termed biological treatment (Fluence news team, Feb 12, 2020). The goal of biological wastewater treatment is to create a system in which the results of decomposition are easily collected for proper disposal. Scientists have been able to control and refine both aerobic and anaerobic biological processes to achieve the optimal removal of organic substances from wastewater (Samer, 2015).

The topic of microalgae treatment was first uncovered in the early 70s of the 20th century, but still remains relevant and requires innovation. For microalgae treatment as biological stage of purification must carry out pre-treatment (mechanical), primary (physical) and secondary (if needed chemical) treatment.

The production of biomass in biotechnological production takes place in special capacities of so-called fermenters or bioreactors whose design ensures compliance with the optimal temperature regime for the introduction and removal of gas and liquid streams, control of the composition of the nutrient substrate and conditions inside the reactor.

The bioreactor commonly used for micro of macro algae cultivation. Algae may be cultivated for the purposes of biomass production (as in a seaweed cultivator), wastewater treatment, CO_2 fixation, or aquarium/pond filtration in the form of an algae scrubber (Morrissey, Jones, Harriott, 1988). Algae bioreactors vary widely in design, and can be distinguish into two categories: open reactors and enclosed reactors. Open reactors are exposed to the atmosphere while enclosed reactors, also commonly called photobioreactors, are isolated to varying exposure from the atmosphere. Also bioreactors can be intensive and extensive according to the biomass production purpose.

4. PURPOSE AND OBJECTIVES OF THE WORK

The aim of this scientific investigation is:

- to improve the sewage purification technology from biogenic compounds by microalgae culture.
- to analyze the sewage treatment issues and classic methods of wastewater treatment;
- to estimate bioreactor parameters for waste water treatment;
- to develop ecologically and economically expedient wastewater treatment technology.

Methods of research: analysis, data comparison, statistical data processing, mathematical modeling.

5. RESEARCH RESULTS

In this point we gain an understanding of the bioreactor requirements and factors which influenced on the microalgae production.

The bioreactor requirements for waste water treatment:

1. Speed of biomass production/ biogenic compounds consumption;
2. Ratio between volume of cultivation reservoir and volume of input waste water;
3. Occupied area;
4. Process operation complicity;
5. Purification system for equipment;
6. Ratio between the cost of installation and benefit.

Factors influencing on the biomass production speed:

1. Lighting (L)

Reviewing the previous research of ultrasound on biological effects, Wang et al. (Hsia, Yang, 2014). cultivated Chlorella cells in Petri dishes under ultraviolet irradiation for 0, 20, 40, 60, 80, 100, and 120 sec. in order to study the effects of ultraviolet irradiation on Chlorella growth, reproduction, and chlorophyll content, finding that irradiation for 20–60 sec appeared to stimulate mono-cell division and enhance cell growth. Nevertheless, when ultraviolet irradiation was prolonged for more than 80 sec., cell density was sharply reduced. Ultraviolet irradiation for 20–80 sec did not reveal obvious effects on the

Chlorella chlorophyll content, but obvious and reduced effects did occur after 100 sec. Increasing the solar ultraviolet irradiation time apparently directly affects algal growth, reproduction, and chlorophyll content and indirectly influences photosynthetic efficiency.

Optimal culture conditions, based on Taguchi methods, are 25°C, 8000 lux LED irradiation intensity, 24h LED irradiation time, 2000cc/min pumping intensity, 1 MHz ultrasound frequency, 5.5v ultrasound exposure intensity, and ultrasound exposure time of 10 s every 8h (Hsia, Yang, 2014).

2. *Water temperature (t).*

Microalgae growth efficiency depends on temperature of environment and water in reservoir. Indeed, most microalgae species are capable of carrying out photosynthesis and cellular division over a wide range of temperatures generally stated between 15 and 30°C but optimal conditions between 20°C and 25°C (Ras, Steyer, Bernard, 2013).

Below optimal growth temperatures, an increase in temperature has a positive effect on photosynthesis and cell division. This trend is explained by the enhancement of enzymatic activities related to the Calvi cycle (Falkowski, Owens, 1980). The relation between growth rate and below-optimal temperatures has been extensively studied and even modeled, most commonly with the Arrehenius equation (Ahlgren, 1987).

3. *Concentration of phosphorus and nitrogen compounds (Cbio).*

An adequate supply of nitrogen and phosphorus is imperative to ensure high production rates in mass microalgae cultures. High yield coefficients, low crude protein contents and low productivities were measured at low supplies of these nutrients. The highest production rates were measured at N and P concentrations exceeding 25 and 2 mg litre−1 respectively, at which supply the highest crude protein contents were measured. Although the carbohydrate content followed, under certain N supply conditions, an inverse relationship with the crude protein content, it was generally not affected by changes in N and P concentrations (Mostert, Grobbelaar, 1987).

4. *CO_2 concentration (Cco_2).*

Some green algae are reported to easily grown at very high CO_2 concentration. Chlorella species is very common to be used as carbon sequestration. It is fresh water, single cell organism containing chlorophyll a and b and has high photosynthetic efficiency to convert CO_2 to O_2. Chlorella species belong to the Phylum Chlorophyta. C. vulgaris strain was studied under ambient CO_2 concentration (0.036%) and elevated CO_2 concentration (20%) (Mostert, Grobbelaar, 1987).

5. *Concentration of algae (Calgae).*

On the concentration of algae culture in the reservoir depend the lightning capacity, reservoir structure, technological processes, concentration of nutrient and its absorption efficiency.

Maximum growth and nitrate removal rates were 3.6 g L-1 and 16.4 mg L-1 h-1 respectively at a nitrate concentration of 2400 mg L-1 while 3000 mg L-1 nitrate appeared to inhibit growth yield but not nitrate uptake (S.P. Singh, P. Singh, 2014). Nitrite as the sole N source (400 mg L-1) resulted in optimal growth of Chlorella vulgaris with a maximum biomass of 3.16 g L-1. Nitrate and nitrite concentrations of 800 and 150 mg L-1 produced maximum growth rate and biomass production of 7.8 g L-1 biomass (Taziki, Ahmadzadeh, Murry, 2015).

6. *pH of water (pH).*

The pH level can be changing during different phase of microalgae growth, and can influence on the microalgae metabolism.

According to the all above data we prepared the methodology to the bioreactor effectiveness estimation (formula 1):

$$E = \nu + V + s + O + P + B \quad (1)$$

where: E – effectiveness; ν – speed of biomass production/ biogenic compounds consumption; V – ratio between volume of cultivation reservoir and volume of input waste water; s – occupied area; O – process operation complicity; P – purification system for equipment; B – ratio between the cost of installation and benefit.

Maximal effectiveness estimation 60, and refer to the most effective microalgae treatment.

Speed of biomass production is a set of influencing factors (formula 2):

$$\nu = L + t + C_{bio} + C_{CO2} + C_{algae} + pH \quad (2)$$

where: L – lightning; t – water temperature, Cbio – concentration of phosphorous and nitrogen compounds; CCO2 – concentration of carbon dioxide; Calgae – concentration of microalgae in the water; pH – acidity/alkalinity of water.

Estimation of influencing factors you can find in the Table 1.

Table 1. Influencing factors on biomass production speed

Lightning (L)		
24 hour of artificial lightning	12 hour of artificial lightning	Without artificial lightning
2	1.5	1
Water temperature (t)		
15°C – 20°C	20°C – 25°C	25°C – 30°C
1	2	1.5
Concentration of biogenic compounds (C_{bio})		
N >25 mg/l and P > 2 mg/l	N =25 mg/l and P = 2 mg/l	N < 25 mg/l and P < 2 mg/l
2	1	0
Concentration of carbon dioxide (C_{CO2})		
20% and more	20% – 10%	Less than 10%
1.5	1	0
Concentration of microalgae in the water (C_{algae})		
From 3 to 4 g/l	More than 4 g/l	Less than 1 g/l
1.5	0.5	0.5
Acidity/alkalinity of water (pH)		
Less than 6	6–8	More than 8
0	1	0

Volume of reservoir must satisfy the amount of input waste water on the sewage treatment plant. The reservoir can be flow type and with periodical work.

If the volume of reservoir ≥ than amount of input waste water the volume ratio (V) equals 10. And if meets the condition: volume of reservoir ≤ amount of input waste water, that is volume ratio (V) equals 0.

For the area estimation by the formula 3:

$$S = \frac{S_e}{S_t} \cdot 100\% \quad (3)$$

where: S – percentage of occupied area from the total area, S_e – area for microalgae treatment equipment; S_t – area of all treatment complex.

For the occupied area estimation (s) use the Table 2.

Table 2. Occupied area estimation (s)

№	S	s
1	More than 50%	1
2	50–40%	2
3	40–35%	3
4	35–30%	4
5	30–25%	5
6	25–20%	6
7	20–15%	7
8	15–10%	8
9	10–5%	9
10	Less than 5%	10

Process operation complicity (O) depends on the parameters and construction features of equipment for treatment. For this estimation use the Table 3.

Table 3. Process operation complicity (O)

Don`t require special personnel	Don`t require special personnel, but needed training for correct working	Require special personnel
10	9	5

Table 4. Purification system for equipment (P)

Simple system and easy operation	Medium complicity system and needed special devices	Complex system and needed special devices
10	5	0

Purification system for equipment (P) can be installed and improved the system in a whole because of the longer exploitation time period. This an important issue for the bioreactors with transparent walls because of growing turbid with time and losing the light carrying capacity. For the open bioreactors with no-transparent walls the cleaning system for equipment is easy to apply and not require special devices. Use table 4 for P estimation.

Benefit ratio (B) between installation cost and offset can be calculated according to the cost of all equipment, energy expense, wage costs and costs to other needs, in the relation to the benefits which received after installation (like benefits from the biomass selling to the biofuel of biofertilizers production). This ratio very depends on the cost of materials which were used in the equipment, and amount of energy which needed on the operation.

For the assessment of profit must meet a condition (formula 4):

$$I - E_n + M \leq P_r \tag{4}$$

where: I – investments per year, E_n – energy explicit cost per year, M – material explicit cost, P_r – profit cost per year.

Table 5 present the value for benefit ratio (B).

Table 5. Benefit ratio (B)

$I - E_n + M < P_r$	$I - E_n + M = P_r$	$I - E_n + M > P_r$
10	5	0

In the first situation the profit from the technology applying more than input investments, and equals the highest value. Second situation shows the zero profit, that means the input investments equal output profit. Third situation means the profit less than input investment, and has negative economic effect.

The proposed methodology can help to assess all types of bioreactors for microalgae cultivation applying on the waste water treatment.

After consideration the influencing factors and requirements for bioreactor we proposed the design of an open bioreactor for the cultivation of microalgae. The main feature of this design is a cascade type of tank, which allows you to satisfy parameters such as lightness, mixing, energy efficiency, and economical.

The cascade type of a tank implies a certain number of tanks of small diameter and height of the walls, which are arranged on top of each other in such way as to cover the area of the reflecting surface of the lower tank as little as possible.

Let`s consider the construction of open cascade bioreactor for microalgae cultivation. The graphical material presented in Fig. 1–3.

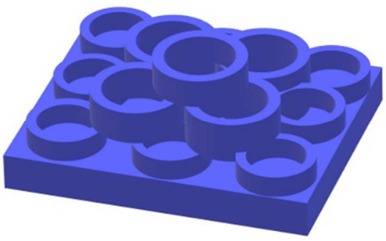

Fig. 1. Cascade reservoir for microalgae cultivation on the sewage treatment plant

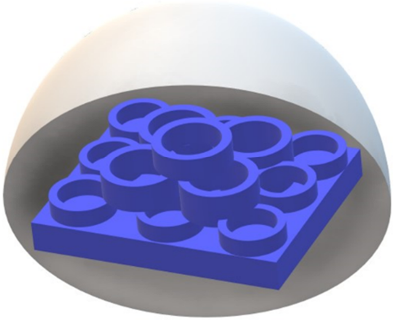

Fig. 2. Proposed bioreactor construction with round-arch greenhouse

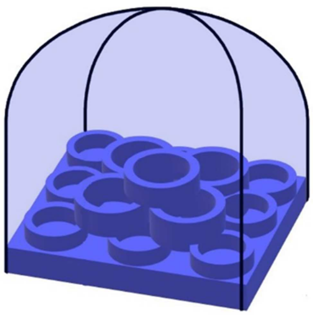

Fig. 3. Proposed bioreactor construction with trapezium greenhouse

Basic features:

1. Small occupied area in comparison with relatively big volume which satisfy the condition of high light reflection area.
2. This is flow-type bioreactor. Water circulate from the bottom to the top and then freely flow down. For this process needed just a pump. The necessary movement and lightning for microalgae metabolism are satisfy.
3. The material from which reservoir building can be concrete or other non-transparent material for the investment economy, and this is no effected on the efficiency because of high reflection area and low height of walls.

4. The greenhouse plays the role of heat accumulator and can be two types as on Figure 2 or Figure 3 depending on the territory. The waste water average temperature on the summer if 20–25°C, in winter 15–20°C and because of that the greenhouse installation is effective. Although, microalgae needed the disperse light and this condition can be satisfied with greenhouse.
5. On the beam of the greenhouse can be installed the lightning for increasing algae growth speed in the night time and in the cloudy days.

It should also be noted that the proposed technology is the next stage after mechanical and biological purification, that is, pre-treatment of wastewater. After rough cleaning (pre-treatment), the concentration of phosphorus and nitrogen compounds is equal to that found in the primary contaminated wastewater.

6. DISCUSSION

According to the proposed the methodology of the effectiveness estimation of bioreactor was calculated by the formula 1. Estimation of speed of biomass production/ biogenic compounds consumption:

$$\boldsymbol{\nu 1 = 1.5 + 2 + 2 + 1 + 1.5 + 1 = 9}, \textit{(in summer)} \tag{5}$$

$$\boldsymbol{\nu 2 = 1.5 + 1 + 2 + 1 + 0.5 + 1 = 7}, \textit{(in winter)} \tag{6}$$

$$\nu = \frac{\boldsymbol{\nu 1 + \nu 2}}{\boldsymbol{2}} = \boldsymbol{8}. \tag{7}$$

Ratio between volume of cultivation reservoir and volume of input waste water equal 10, because of the flow type reservoir and high volume according small occupied area (V).

Area estimation calculated according formula 3. If the S_e = 108 000 m^2, S_t = 1 200 000 m^2 (data about area of treatment complex was retrieved from the Bortnychy aeration station).

$$\boldsymbol{S = \frac{108\,000}{1\,200\,000} \cdot 100\% = 9\%} \tag{8}$$

Value of the occupied area estimation (s) was retrieved from the Table 2.

The values process operation complicity (O) and purification system for equipment (P) were retrieved from the Tables 3 and 4 respectively.

For the assessment of benefit ratio will needs the future practical data and because of that we calculate two variant of future events, when the profit equal 0 and profit cost more than investments.

In the Table 6–8 present the effectiveness estimation for proposed technology.

Summarizing, the effectiveness estimation equal 46 that means 76% efficiency of technology applying with zero profit and the effectiveness estimation equal 51 or 85% efficiency of technology applying with positive profit, and 68% efficiency in the situation with negative profit.

Table 6. Effectiveness estimation with positive profit

Variable	Value
v	8
V	10
s	9
O	9
P	5
B	10
E	Σ=51

Table 7. Effectiveness estimation with zero profit

Variable	Value
v	8
V	10
s	9
O	9
P	5
B	5
E	Σ=46

Table 8. Effectiveness estimation with negative profit

Variable	Value
v	8
V	10
s	9
O	9
P	5
B	0
E	Σ=41

Micro-algae wastewater treatment is a method that allows waste processing to be separated into clean liquid and solid fractions. The hard part contains a significant amount of pollutants, therefore it is disposed of, and in the case of microalgae (after purification), the latter can be used as biofuel (phosphate) and biofuels raw material.

We have proposed list of recommendations for technology applying concerning needed material, equipment and initial data.

Set of initial data:

- Volume of waste water discharge on the sewage treatment plant;
- Occupied area of sewage treatment plant;
- Initial concentration of biogenic elements;
- Temperature before treatment and temperature during microalgae cultivation;
- pH level before treatment.

Needed equipment for process monitoring:

- Equipment for temperature monitoring;
- Equipment for microalgae concentration monitoring;
- Equipment for biogenic elements concentration monitoring;
- Equipment for CO_2 concentration monitoring;
- Equipment for pH monitoring.

Needed materials and means for construction:

- Money investment;
- Building materials (choosing according to correlation of money investment and microalgae growth speed);
- Pump;
- Lightning system;
- Biomass separation system (we recommended hydrocyclones, but it can other separation technology).

We recommended application of this technology because of (Table 9):

Table 9. Advantages of proposed technology

Environmental benefit	Economic benefit	Energy-efficient benefit
No chemicals	Without the additional nutrient environment	More cheaper biomass for biofuel production
Oxygen production	Efficient economic using of remain biomass	Usage the minimal energy-consuming equipment
Biogenic elements bounding and decreasing eutrophication potential	Open reservoir bioreactor cheaper than closed bioreactor	The greenhouse on the top of proposed reservoir save the heat and energy on the additional heating

7. CONCLUSIONS

After analysis of the problems of sewage treatment and classic methods of wastewater treatment, we can conclude that the main problems in the use of microalgae are, first of all, the cost of installation, maintaining the conditions for the growth of culture, the most effective design of tanks. The land resources for tanks are also limited. The use of wastewater as a substrate for microalgae, and the farthest use of biomass for the production of fertilizers and biofuels, is still at the stage of theory and laboratory research in Ukraine.

After the bioreactors parameters defining and proposing the effectiveness estimation methodology we can say that this methodology can help to assess all types of bioreactors for microalgae cultivation applying on the waste water treatment.

Based on the previous researches, statistical data, modeling and requirement to the bioreactor parameters the construction of cascade bioreactor was proposed. The cascade type bioreactor means that the reservoir implies a certain number of tanks with small diameter and height of the walls, which are arranged on top of each other in such way as to cover the area of the reflecting surface of the lower tank as little as possible.

The main advantages of the proposed technology and bioreactor construction are environmental, economic and energy-efficient features. These three directions are main proposal to sustainable development which our country strive for.

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