

UDC:628.35:620.3 (045)

<https://doi.org/10.31073/ecobezpeka202507-14>

COMPARATIVE ANALYSIS OF PHOTOBIOREACTOR DESIGNS FOR MICROALGAE CULTIVATION

Lesia Pavliukh¹

PhD, Professor of the Environmental Science Department
State University «Kyiv Aviation Institute»

Victor Repeta²

PhD (Mathematics), Associate Professor of the Higher Mathematics Department
State University «Kyiv Aviation Institute»

e-mail: lesia.pavliukh@npp.nau.edu.ua

e-mail: victor.repeta@npp.nau.edu.ua

Abstract. Environmental pollution is a matter of deep concern, especially after the invasion of Ukraine by the Russian Federation. The strategic importance of fresh water is widely recognised, but at the same time, a number of questions arise regarding the sustainable management of water resources in any scientific, social or political programme around the world. The world's water resources face serious quantitative and qualitative threats, despite the fact that environmental legislation is becoming increasingly stringent. This issue is particularly acute in the context of hostilities. The damaged and destroyed infrastructure has led to the degradation of ecosystems due to the inflow of untreated wastewater containing a significant amount of pollutants, including phosphorus and nitrogen compounds, which cause eutrophication of water bodies.

Today, microalgae are a very valuable raw material, as they are not only involved in the removal of nutrients from wastewater in the process of post-treatment, but also a promising biofuel in the context of

the energy crisis. The production of valuable microalgae biomass by cultivating them in closed systems - photobioreactors - is gaining popularity, as open systems do not always cope with the task due to their sensitivity to changes in ambient temperature, which vary significantly in different regions of Ukraine and the world. There are different designs of photobioreactors that have their advantages and disadvantages. The most important parameters that affect the efficiency of photobioreactors are: type of bioreactor; bioreactor shape; temperature control; economical carbon dioxide waste; high-quality simulation of the growing medium; material; terrain; controlled hydrodynamics; and freedom of cultivation.

The combination of biotechnology with innovative approaches to growing microalgae and unicellular organisms opens up new opportunities for sustainable industrial development and environmental safety in the water and wastewater sector.

Keywords: Photobioreactor, Microalgae, Wastewater, Nutrients, Cultivation.

ПОРІВНЯЛЬНИЙ АНАЛІЗ КОНСТРУКЦІЙ ФОТОБІОРЕАКТОРІВ ДЛЯ КУЛЬТИВУВАННЯ МІКРОВОДОРОСТЕЙ

Павлюх Л. І.¹ Репета В. К.²

Державний університет «Київський авіаційний інститут».

Анотація

Забруднення навколишнього середовища викликає глибоке занепокоєння, особливо після вторгнення в Україну російської федерації. Стратегічна важливість прісної води є загальною рисою, але водночас виникає низка питань щодо сталого управління водними ресурсами в будь-якій науковій, соціальній чи політичній програмі в усьому світі. Світові водні ресурси стикаються з серйозними кількісними та якісними загрозами, незважаючи на те, що природоохоронне законодавство стає все більш жорсткішим. Особливо гостро це питання постає в умовах бойових дій. Пошкоджена та зруйнована інфраструктура призвела до деградації екосистем через надходження неочищених стічних вод, які містять значну кількість забруднюючих речовин, зокрема сполук фосфору та азоту, що спричиняють евтрофікацію водойм.

Мікродорості на сьогодні є дуже цінною сировиною, оскільки не тільки беруть участь у видаленні біогенних сполук зі стічних вод у процесах доочищення, а й є перспективним біопаливом в умовах енергетичної кризи. Отримання цінної біомаси мікродоростей шляхом їх культивування у закритих системах – фотобіореакторах, набуває все більшої популярності, адже відкриті системи не завжди справляються з поставленою задачею через чутливість до зміни температури навколишнього середовища, які у різних регіонах України та світу суттєво відрізняються. Існують різні конструкції фотобіореакторів, які мають свої переваги та недоліки. Найважливішими параметрами, які впливають на ефективність фотобіореакторів є: тип біореактора; біореакторна форма; контроль температури; економні відходи вуглекислого газу; якісна імітація живильного середовища; матеріал; рельєф місцевості; керована гідродинаміка; свобода вирощування.

Поєднання біотехнології з інноваційними підходами до вирощування мікродоростей і одноклітинних організмів відкриває нові можливості для сталого розвитку промисловості та забезпечення екологічної безпеки водо-каналізаційного господарства.

Ключові слова: фотобіореактор, мікродорості, стічні води, біогенні сполуки, культивування

Introduction

Environmental pollution is a matter of deep concern, especially since the invasion of Ukraine by the Russian Federation. The strategic importance of fresh water is widely recognised, but at the same time, a number of questions arise regarding the sustainable management of water resources in any scientific, social or political programme around the world. The world's water resources face severe quantitative and qualitative threats, despite the fact that environmental legislation is becoming increasingly stringent. The water environment, as a fundamental and critical part of the human environment, plays a key role in the food chain. This issue is particularly acute in the context of hostilities. The damaged and destroyed infrastructure has led to the degradation of ecosystems due to the flow of untreated wastewater, which contains a significant amount of pollutants, including phosphorus and nitrogen compounds, which cause eutrophication of water bodies.

Analysis of Recent Research and Publications

Microalgae are cultivated in open, closed and so-called hybrid systems. The synergy of biomass growth efficiency in open natural systems and in photobioreactors can be achieved by using such hybrid systems. The two-stage hybrid cultivation system is an advanced version of algae culture, where the cell medium is transferred when nutrients are found to be decreasing. The hybrid system can operate with small photobioreactors and large ponds and vice versa [1].

There are various designs of photobioreactors for cultivation [2-4]. A significant number of them can be used and are widely used for wastewater treatment by combining biomass cultivation with the removal of nutrients from the culture medium. This reduces the cost of both processes, reduces the amount of unwanted sludge and reduces the risk of eutrophication.

The study [5] emphasized the enhancement of microalgal productivity and quality (e.g., biochemical composition) using different colored photobioreactors (PBRs) exposed to ambient conditions. In this study, a unique approach had been applied to evaluate the microalgae co-culture (*Chlorella vulgaris*, *Chlorella*

sorokiniana, and *Scenedesmus simris002*) growth by exposing the colored transparent photobioreactors (white, blue, and green) to sunlight using a nutrient-rich (N, P) anaerobic reactor effluent produced after the treatment of domestic wastewater. Experimental results suggested that the white PBR increased the microalgae productivity by 2.3 to 3.5 times than blue and green PBRs, respectively. In addition, the FTIR spectroscopy analysis showed better quality microalgae (i.e., higher IR spectra) produced in white PBR compared with that of blue and green PBRs, respectively. Moreover, the microalgae cultivated in white PBR also showed high lipid content (38%) with the dominant biodiesel FAME composition (C16-C18) of 68.6% [5].

Principles of fluid mechanics, gas-liquid mass transfer, and irradiance controlled algal growth are integrated into a method for designing tubular photobioreactors in which the culture is circulated by an airlift pump [6]. A 0.2 m³ photobioreactor designed using the proposed approach was proved in continuous outdoor culture of the microalga *Phaeodactylum tricorutum*. The culture performance was assessed under various conditions of irradiance, dilution rates and liquid velocities through the tubular solar collector. A biomass productivity of 1.90 g l⁻¹ d⁻¹ (or 32 g m⁻² d⁻¹) could be obtained at a dilution rate of 0.04 h⁻¹. Photoinhibition was observed during hours of peak irradiance; the photosynthetic activity of the cells recovered a few hours later. Linear liquid velocities of 0.50 and 0.35 m s⁻¹ in the solar collector gave similar biomass productivities, but the culture collapsed at lower velocities [6].

Problem Statement

Methods of additional treatment of nutrients involve converting them to an insoluble state, followed by sedimentation and disposal of the sediment. This requires additional costs. At the same time, demand for microalgae biomass is constantly growing. It is a raw material for the production of various commercial products [7, 8]. Different cultivation methods are used to produce it. However, they all have in common the use of biogenic elements.

Combining biomass cultivation with nutrient removal from the culture medium with wastewater treatment processes reduces the cost of both

processes, reduces the amount of unwanted sludge and reduces the risk of eutrophication.

Since microalgae are able to operate both in open systems (natural water bodies) and in closed systems (photobioreactors), an innovative approach that significantly reduces water pollution and improves water quality, in particular its organoleptic properties, is the bioremediation of water bodies with microalgae suspensions, which is based on algalization and maintaining ecological balance.

There is also an **urgent task** of finding microalgae cultures for use in photobioreactors and improving their efficiency, as well as developing methods for calculating the technological parameters and operating modes of the photobioreactors themselves.

The Main Research

Special containers, so-called fermenters or bioreactors, are used in biotechnology production to increase biomass. The combination of biotechnology with innovative approaches to growing microalgae and unicellular organisms opens up new opportunities for sustainable industrial development, namely:

1. *Growing algae near power plants*: This technology is innovative and efficient, as it uses heat from power plants to provide the energy needed for algae growth. This not only increases the efficiency of production, but also reduces energy consumption from other sources.

2. *Environmental and economic benefits*: using heat from CHP to cover up to 77% of the algae cultivation needs can reduce energy costs while also reducing environmental impact. This increases the sustainability of production, helping to reduce emissions of carbon dioxide and other pollutants.

3. *Development prospects*: the development of bioreactor technologies and optimisation of microbial cultivation conditions can help to increase productivity, reduce costs and improve the quality of the products.

Photobioreactors are important tools for intensifying the production of biomass and valuable compounds from microalgae. Due to their advantages, they can become a key element in the development of sustainable biotechnological processes, in particular in the fields of bioenergy, wastewater treatment and food additives. Photobioreactors are devices designed

for the cultivation of photosynthetic microorganisms (microalgae, cyanobacteria) that use light as an energy source to synthesise organic compounds from inorganic ones. Closed-type photobioreactors were created as opposed to open-type ponds. The advantages of closed photobioreactors are:

Controlled conditions: closed systems allow for precise control of parameters such as temperature, pH, light intensity and CO₂ concentration, which significantly increases the efficiency of the photosynthetic process.

Higher product yields: intensive cultivation under controlled conditions can lead to significantly higher yields of the target product (biomass, oils, bioactive compounds) compared to open systems.

Protection against contamination: closed photobioreactors reduce the risk of contamination from the outside, as microorganisms are cultivated in an isolated environment.

Photobioreactors operate in the following modes:

1. *Accumulation mode:* In this mode, cultivation takes place during one production cycle. The microorganisms are grown until the desired biomass level is reached and then harvested. 2. *Accumulation mode with feeding:* In this mode, new substrate is continuously added to support the growth of microorganisms, allowing for higher productivity within a single cycle. 3. *Continuous Cultivation Mode:* This mode allows for the continuous introduction of new substrate and discharge of finished products, ensuring a stable production capacity.

In most cases, continuous cultivation of microalgae is carried out in a turbidostat, a photobioreactor in which a constant density of the microalgae suspension is maintained by periodically removing part of the culture and adding a nutrient solution. This allows for optimal conditions for microalgae growth without overloading the system. Bioreactors are rather complex engineering systems due to their multimodality and the use of special materials. Ensuring optimal conditions for microalgae growth requires constant monitoring and maintenance of a number of parameters: temperature, pH, redox potential of the medium, dissolved oxygen concentration, carbon dioxide and basic nutrients, liquid flow rate, mixing intensity, and sterilisation conditions. Modern bioreactors are equipped with automatic control systems that allow for real-time monitoring and regulation of temperature,

pH, concentration of dissolved gases and other parameters.

Any bioreactor is designed to create comfortable conditions for the life and cultivation of microorganisms, or rather, to provide them with breathing, nutrition and excretion of waste products, a comfortable temperature, etc.

The main part of the bioreactor is the fermenter. The fermenter is a tank that creates comfortable conditions for the cultivation of microorganisms, synthesis of products and accumulation of biomass. The main material used to make bioreactors is high-quality steel or titanium, as they are the most resistant and less susceptible to corrosion, and the inside of the bioreactor is also polished. Mass transfer and hydrodynamics are prerequisites for a bioreactor. Fermenters are equipped with all the necessary parts, such as stirrers, pumps, air filters for sterilisation and others, to maintain the required temperature, gas conditions and proper mass movement in the reactor. The sampler is also an essential part of bioreactors for sampling liquid during the biosynthesis process. Depending on the purpose and specifics of the bioreactor, additional parts may also be used. Bioreactor operation is monitored using instruments that measure the acidity of the medium, temperature, pressure, gas flow, aeration, etc. The details of the bioreactor, as well as the control of all its processes, directly affect the cultivation of microorganisms.

A bioreactor is not just an apparatus, but also complex physical, chemical, physicochemical and biological processes that take place to achieve maximum efficiency of the goal. Bioreactors should be in an accessible location to ensure easy access to replace the necessary parts in case of failure. In addition, the procedure should be as sterile as possible, and the necessary safety precautions must be taken to minimise negative effects on the cultivation process.

High-pressure steam is used to clean bioreactors, as the main contaminants of the reactor are fungi, bacteria and viruses, protozoa and yeast, which appear as a result of dust, working solutions or employees. Bioreactors must meet certain criteria: absolute tightness, stable volume of culture fluid, access to all parts of the bioreactor, and sterilisation.

Bioreactors are also divided into types depending on the volume of fermenters. Before use, the culture liquid or raw material is stored frozen and a small number of microorganisms are grown in the

The principle of operation of different types of photobioreactors [9-12]

Type	Action type
Mechanical	Mixing of the bioreactor contents is performed by a mixer, but leads to uneven mixing and death of microorganisms.
Airlift	Mixing is done by using the gas phase through the liquid, which leads to undesirable foam formation.
Gas-vortex	Mixing is performed by a quasi-stationary flow with axial countercurrent, which is created by gas swirling due to changes in pressure and friction force of the air flow on the liquid surface.
Aerobic	It occurs due to an active biological process with the supply of oxygen (aeration) and purifies water from biological substances, solid particles and other impurities.
Anaerobic	Based on fermentation, the invention relates to ecological processes of water purification from small particles and droplets with flocculation and coagulation and can be used to remove surfactants, fats, oils, petroleum products and other encumbered substances, suspensions and emulsions.
Membrane	It works on the basis of biological purification and membrane separation to purify water from organic substances, bacteria, viruses, and pesticides.
Cascade	It works on the basis of biological treatment of water, organic matter, nitrogen, phosphorus, and is designed to grow microalgae for use as biofuel.
Mixed	Used as both anaerobic and aerobic cultivation to produce biogas and heat simultaneously, which is trained to heal the microbial cultivation environment.

laboratory to the required volume and maximum efficiency in the bioreactor.

After that, the microorganisms are placed in a sterilised bioreactor in comfortable conditions to eventually produce biomass or nutrients from the metabolism of microalgae.

The Table 1 below shows how different types of photobioreactors work.

The efficiency of a photobioreactor also depends on the following parameters:

1. Type of bioreactor. There are two types: open and closed. The closed form of the bioreactor is the most common and is often used in the cultivation of microalgae.

2. Bioreactor form. Photobioreactors come in different shapes, which determine the working area of the photobioreactor. The shape of the bioreactor (e.g., in the form of pipes or flat) affects the intensity of lighting, the rate of passage of wastewater through the photobioreactor and the mode of operation of the fermenter.

3. Temperature control. Microorganisms should be cultivated at a temperature that is comfortable for them, as this directly affects the rate and amount of biomass and the efficiency of wastewater treatment.

4. Economical carbon dioxide waste. With sufficient CO₂ saturation, microalgae are intensively cultivated, their composition and life cycle changes. However, many microorganisms require high gas consumption, so low carbon dioxide inputs compared to the resulting higher biomass growth will be effective.

5. High-quality simulation of the culture medium. The creation of appropriate conditions directly affects the development and vital activity of microorganisms. The use of wastewater is a great advantage, as it is rich in many nutrients that accelerate the development of microorganisms.

6. Material. The material for creating a bioreactor is very important, most often glass is used, which is not a budget option. The disadvantage of such a bioreactor is its rapid contamination, which means

Table 2

Comparative analysis of different types of photobioreactors

Type of bioreactor	Advantages	Disadvantages
1	2	3
Plane-parallel	Large illumination surface area maximises solar energy utilisation	Gas and mass transfer in microbial or microalgal cultivation systems increases with increasing gas mixture feed rate (usually air or CO ₂), but only up to a certain limit due to solution saturation, media turbulence and culture stress
	Low dissolved oxygen concentration	External light source makes the photobioreactor bulky
	The continuous cultivation method has proven to be particularly useful for studying the physiological characteristics of unicellular microalgae, cyanobacteria and purple bacteria. It allows cell culture to be maintained in a state of steady growth, which facilitates the study of their metabolic processes under controlled conditions	This design is not suitable for a wide range of microalgae, especially those that tend to form sediment or create a film on the reactor walls, which makes it difficult to mix evenly and maintain a homogeneous environment for their growth
	Simplicity of design makes it easy to increase the volume of cultivation without significant costs for equipment upgrades	Due to their design, flat-parallel reactors cannot be effectively sterilised by autoclaving or flowing steam, which is a critical aspect in the cultivation of microalgae
Tubular	Exceptionally productive system for highly efficient cultivation of many microalgae	Insufficient mixing turbulence in the upper part of the reactor leads to overgrowth of the walls with microalgae culture, which reduces access to light and creates problems with gas exchange
	The system operates in continuous mode	Possibility of accumulation of high concentrations of O ₂ (poison for microalgae) in the culture medium if the tubes are too long
	Large illumination surface area	Reducing the CO ₂ concentration along the tube can cause the microalgae to lose their carbon source
Large areas are required because long tubes are used		
		A certain fraction of the crop is beyond the illumination limit due to the spatial separation of the photosynthesis process inside the illuminated tube and the gas and mass exchange in the gas exchanger
Reactors based on coaxial cylinders	The annular gap allows for the efficient use of mechanical stirring devices	Scaling up to volumes over 20 litres is not easy due to the uneven distribution of conditions
Vertical	High mass transfer rate with good mixing	Small surface area for illumination
	Compact, easy to operate and relatively inexpensive	If the elevator system is not used, cell settling may occur

expensive maintenance. The efficiency criterion is the use of cheap and affordable materials, as well as slow contamination.

7. *Terrain*. The area for the use of a bioreactor must meet many requirements, which affects the number of bioreactors and their versatility. A bioreactor that does not care about location and terrain has a strong advantage. Accordingly, a photobioreactor installed near or in sewage plants will be effective.

8. *Controlled hydrodynamics*. The efficiency criterion is met by a bioreactor in which it is possible to control the flow of liquid.

9. *Freedom of cultivation*. Not all bioreactors are suitable for growing microalgae that can reduce the level of pollutants in wastewater. For example, gas-vortex or mechanical, as many microorganisms have a fragile structure. A photobioreactor is also effective, as it can cultivate different strains of microalgae without harming the microorganisms. The Table 2 below shows the advantages and disadvantages of different types of photobioreactors.

REFERENCES

1. Rakesh Narala, Kalpesh Sharma, Sourabh Garg, Skye Robin Thomas-Hall (2016). Comparison of Microalgae Cultivation in Photobioreactor, Open Raceway Pond, and a Two-Stage Hybrid System. *Frontiers in Energy Research* .Vol. 4. <https://doi.org/10.3389/fenrg.2016.00029>
2. Lesia Pavliukh, Sergii Shamanskyi. A photobioreactor for micro-based wastewater treatment. *Proceedings of the National Aviation University*. 2021.Vol. 87 (2). P. 57-64. <https://doi.org/10.18372/2306-1472.87.15721>
3. Boichenko S. V., Pavliukh L., Shamansky S., Syrotina I., Todorovych O. Cascade Photobioreactor for Waste Water Treatment by Microalgae. *Modern Management Review*. 2020. Vol. XXV. No 27 (3). P. 17-29.
4. L. Pavliukh, S. Shamanskyi, O. Zaiats. A flat-parallel photobioreactor design for sewage water treatment. *Science-based technologies*. 2021.Vol. 51. No 3. P. 237-244. <https://doi.org/10.18372/2310-5461.51.15689>
5. Khalekuzzaman, M., Kabir, S.B., Islam, M.B. et al. (2021). Enhancing microalgal productivity and quality by different colored photobioreactors for biodiesel production using anaerobic reactor effluent. *Biomass Conv. Bioref.* Vol. 11. P. 767–779. <https://doi.org/10.1007/s13399-020-00852-5>.
6. Molina E., Fernandes J., Acien F. G., Chisti Y. (2001). Tubular Photobioreactor Design for Algal Cultures. *Journal of Biotechnology*. Vol. 92. P. 113–131.
7. L. Pavliukh, H. Tsysar. Microalgae as a sustainable energy source. *Сучасні проблеми екології. XVII Всеукраїнської наукової on-line конференції здобувачів вищої освіти і молодих учених з міжнародною участю: 15 квітня 2021 р.: тези доп., Житомир, 2021. С.136.*
8. A.L. Ahmad, N.H. Mat Yasin, C.J.C. Derek, J.K. Lim (2011). Microalgae as a sustainable energy source for biodiesel production. *Renewable and sustainable energy reviews*. Vol.15. Issue. P. 584–593. <https://doi.org/10.1016/j.rser.2010.09.018>.

Conclusion

The cultivation of microalgae requires knowledge of their physiology, especially their ability to capture light and related metabolism, as well as their behaviour in accordance with limiting factors.

The article substantiates the scientific and technological foundations of wastewater remediation processes and the development of tools for phytoremediation of wastewater through the use of developed photobioreactors of various designs. A comparative analysis of different types of photobioreactors was carried out. Criteria for the efficiency of photobioreactors have been developed. It is established that the type of bioreactor, bioreactor form, temperature control, economical carbon dioxide waste, high-quality imitation of the culture medium, reactor manufacturing material, terrain, controlled hydrodynamics, and freedom of cultivation are the most important parameters for calculating the efficiency of closed culture systems.

9. Jack Legrand, Arnaud Artu, Jeremy Pruvost (2021). A review on photobioreactor design and modelling for microalgae production. *Reaction Chemistry & Engineering*. P. 299. <https://doi.org/10.1039/d0re00450bff>

10. A. P. Carvalho, L. A., Meireles and F. Xavier Malcata (2008). Microalgal Reactors: A Review of Enclosed System Designs and Performances. *Biotechnol. Prog.* Vol. 22(6). P. 1490–1506. <https://doi.org/10.1021/bp060065r>

11. O. Pulz (2001). Photobioreactors: Production Systems for Phototrophic Microorganism. *Appl. Microbiol. Biotechnol.* Vol. 57(3). P. 287–293. <http://dx.doi.org/10.1007/s002530100702>

12. M. Morweiser, O. Kruse, B. Hankamer and C. Posten (2010). Developments and perspectives of photobioreactors for biofuel production. *Appl. Microbiol. Biotechnol.* Vol. 87(4). P. 1291–1301. <https://doi.org/10.1007/s00253-010-2697-x>
