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Carbon Dioxide Utilization Using *Chlorella* Microalgae

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Abstract: The problem of the excessive CO_2 emitted into the atmosphere is one of the significant problems for the modern world and ecology. This article examines the dynamics of carbon dioxide absorption from thermal power plants, TPP, and waste gases by three types of microalgae, the most typical for the Russian Federation: *Chlorella kessleri*, *Chlorella vulgaris*, and *Chlorella sorokiniana*. The exhaust gases of the TPP contain up to 39% carbon dioxide. In this work, the rate of absorption of carbon dioxide from model exhaust gases with a CO_2 content of up to 39% was studied. As a result of the study, a species of microalgae (*Chlorella vulgaris*) was identified, characterized by the maximum rate of absorption of CO_2 = 0.412 g/L·day and the maximum volume of CO_2 utilized in 1 day = 8.125 L. The conducted research proved the possibility of utilizing a large content (up to 39%) of carbon dioxide from the exhaust gases of the TPP with the help of microalgae of the genus *Chlorella*. A scheme for the utilization of CO_2 with the help of microalgae is also proposed, which meets the principles of a circular economy (closed cycle).

Keywords: carbon dioxide; microalgae; absorption; uptake rate; *Chlorella*; biomass; cultivation; CO_2 fixation; *Chlorella vulgaris*; fixation

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1. Introduction

The problem of elevated carbon dioxide content in the atmosphere is a serious threat to the environment today [1,2]. The concentration of greenhouse gases, especially carbon dioxide (CO_2) [3–6], has increased in the atmosphere since 1750 [7]. This led to a sharp increase in temperatures around the world [8].

In this regard, the introduction of technologies for capturing, utilizing, and storing carbon (carbon capture, utilization, and storage—CCUS) has become more and more active recently [9,10]. Carbon capture, utilization, and storage (CCUS) technology is considered an effective way to reduce greenhouse gases, such as carbon dioxide (CO_2), which is significant for achieving carbon neutrality [11]. The International Energy Agency (IEA) assessed the emission reduction potential of CCUS, which could reduce 6.9×10^9 t of CO_2 per year by 2070 in a sustainable development scenario, accounting for 19.27% of the total emission reduction [12]. A CCUS technology system covers several key technologies in the following fields: (1) CO_2 capture and transport; (2) CO_2 mineralization; (3) reduction and recycling; (4) biological carbon sequestration; (5) carbon geological storage; and (6) CO_2 enhanced underground resource exploration [13–18]. They involve the use of adsorption, absorption [19], and membrane separation of CO_2 [20], as well as cryogenic technologies [21] and biofixation methods [22]. Hybrid technologies based on a combination of different approaches are also being developed. However, according to a 2016 report by the Global CCS Technology Research Center, energy consumption in carbon sequestration projects is quite high, which creates additional problems [23]. The introduction of various systems for cleaning gases from CO_2 will not be able to completely solve the problem of

the carbon footprint, but it will help to significantly reduce the level of negative impact on the environment. The authors of many scientific papers agree with this statement [11,24].

Biological CO_2 fixation usually occurs through photosynthesis by terrestrial plants and trees. However, they can eliminate only 3–6% of CO_2 because of their slow growth, while other microorganisms, such as eukaryotic algae and cyanobacteria, can fix CO_2 10–50 times faster [25,26].

In microalgae, chloroplasts play a key role in photosynthesis, that is, the process of converting light energy into chemical energy that can be used for life. The photosynthesis of microalgae consists of two types of reactions: light-dependent and light-independent. Light-dependent reactions occur in the thylakoids of chloroplasts and assist in the absorption of light energy, which is used to create high-energy molecules ATP and NADPH. ATP and NADPH, in turn, are used in light-independent reactions. Light-independent reactions occur in the stroma of chloroplasts and involve the fixation of carbon dioxide (CO_2), which is then converted into organic compounds such as sugars, starches, and fats. These compounds are a source of energy and building blocks for microalgae and other living organisms. Thus, microalgae, thanks to their chloroplasts, can use light energy for photosynthesis and the conversion of carbon dioxide into organic compounds, which makes them biofactories. This is important for the ecological sustainability of our planet, as they are able to absorb carbon and reduce the concentration of CO_2 in the atmosphere [27].

The absorption of CO_2 by microalgae has a number of advantages, which are due to the high efficiency of photosynthesis, the growth rate of microalgae, their adaptability to environmental conditions, and the reduction in energy use [28]. The decrease in energy expended is due to the production of energy from biomass by photosynthesis [29]. In addition, these organisms are able to transform the absorbed carbon dioxide into lipids, proteins, pigments, and carbohydrates and can become the basis for obtaining valuable components [30], such as biofuels [31,32], fertilizers, biologically active additives, or be used for cosmetic and pharmaceutical purposes [33,34].

According to approximate data, 100 tons of microalgae fix 183 tons of carbon dioxide during the period of maximum growth of biomass when cultivated for 8–10 days [35]. This value will vary depending on many factors (temperature, cultivator design, CO_2 supply method, type of microalgae, etc.).

The optimal CO_2 requirement for maximum growth enhancement in microalgae is found only when CO_2-enriched gases are supplied. Therefore, air pumping to the medium is required for better microalgal production [36]. Unfortunately, the CO_2 concentration in the atmosphere is only 0.033%, and the extraction energy of 1 mol of CO_2 from ambient air is 19.63 KJ/mol, a rare compound in air [37]. In addition to that, chemically graded CO_2 supply for microalgal production leads to 30% greenhouse gas emissions [36]. However, the feed CO_2 concentration for algae is similar to the flue gas composition [37], which reduces the extraction requirement and associated cost. Therefore, the use of flue gas as a carbon source is a robust complementary approach [38].

Using photoautotrophic organisms to reduce the noxious effects of industrial CO_2 emissions in the atmosphere by sequestration under the form of biomass constitutes a relatively recent solution. This may become valuable if we obtain high-added-value products that can become economically and commercially attractive [39,40]. Due to the price increase in fossil fuel on the international market, this solution may become more and more feasible [41].

The biomass of microalgae absorbs CO_2 as a result of photosynthesis, while oxygen is released and the biomass of microalgae increases. Algae convert energy without any evolution beyond the cells and easily adapt to environmental conditions [42]. The absorption of CO_2 by microalgae cells occurs during the photosynthesis reaction, which is presented below:

$$CO_2 + H_2O \rightarrow {}^{\text{light chlorophyll}} C(H_2O) + O_2 + 120 \text{ kcal/mol}, \quad (1)$$

Photosynthesis is a complex process that can be divided into two main stages. The first stage is the photoreaction stage, which occurs in the thylakoid membranes of chloroplasts and involves the conversion of light energy into chemical energy in the form of ATP and NADPH. This process is carried out by two photosystems, PSII and PSI, which work together to produce ATP and NADPH. The second stage is the dark reaction, which occurs in the stroma of chloroplasts and involves the conversion of CO_2 into sugar molecules using the energy and reducing power provided by ATP and NADPH, as shown in Equations (2) and (3).

$$H_2O + ADP + P_i + NADP^+ \rightarrow {}^{light} O_2 + ATP + NADPH + H^+, \quad (2)$$

$$CO_2 + ATP + NADPH + H^+ \rightarrow (CH_2O) + ADP + P_i + NADP^+, \quad (3)$$

This process is known as the Calvin cycle, and it involves a series of enzymatic reactions that convert CO_2 into glucose and other sugars. Together, these two stages of photosynthesis allow plants and other photosynthetic organisms to produce the energy and organic compounds they need for growth and metabolism.

Photosynthetic carbon metabolism in microalgae is mainly dependent on the C_3 cycle [43]. This process involves using ATP as an energy source to lower the energy level, deplete NADPH, and convert carbon dioxide into sugar through a series of steps known as carboxylation, reduction, and regeneration of ribulose-1,5-bisphosphate (RuBP), as shown in Equation (4). Within the carboxysome, RuBP is bound to CO_2 by the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (rubisco) and converted into two molecules of 3-phosphoglycerate (3-PGA). The 3-PGA then diffuses from the carboxysome to the cytoplasm through the pores of the hexamer shell protein. In the reduction phase, catalyzed by an enzyme, 3-PGA in the cytoplasm is converted into glyceraldehyde-3-phosphate (GAP), as shown in Equation (5). The regeneration of RuBP is critical to ensuring the continuous operation of the carbon sequestration cycle [44].

$$3RuBP + 3CO_2 \rightarrow GAP + 3RuBP, \quad (4)$$

$$PGA + ATP + NADPH + H^+ \rightarrow GAP + ADP + NADP^+ + P_i, \quad (5)$$

The rubisco enzyme has the capability of performing two contrasting functions, i.e., carboxylation and oxygenation, and the choice of function is influenced by the relative concentrations of CO_2 and O_2 in the surroundings. Since the atmospheric concentration of O_2 is relatively high, it favors the function of oxygenation and promotes photorespiration, which ultimately reduces the rate of photosynthesis. To overcome this limitation, microalgae have evolved a CO_2-concentrating mechanism that enables them to maximize photosynthetic efficiency even under low CO_2 concentrations or inorganic carbon conditions [45].

Biomass (plants, algae, etc.) annually produces more than 100 billion tons of organic matter as a result of photosynthesis, absorbs about 200 billion tons of CO_2, and releases about 145 billion tons of oxygen into the environment. Studies [46] have shown that the efficiency of photosynthesis in microalgae is 10–20% higher than in plants.

The main ways of utilizing carbon dioxide are absorption and adsorption. Thus far, several chemical and physical materials have been proposed to serve as adsorbents, including carbon fiber monolithic adsorbents [47], activated carbon fiber–phenolic resin composites, melamine–formaldehyde highly porous adsorbent, and amine immobilized adsorbents [26,48]. Typical absorbents commercially available in a chemical absorption system include amine carbonate-based components such as mono-ethanolamine (MEA), diethanolamine (DEA), ammonia, and hot potassium carbonate [26,49]. Purification by these methods causes the generation of waste materials such as sludge and spent adsorbents that must be disposed of. It is impossible to create a waste-free carbon dioxide removal system using adsorbents and absorbents. Therefore, the question of finding the most

effective, cheap, and affordable ways to absorb CO_2 without the formation of by-products that require additional processing still remains relevant. The absorption of CO_2 using a biofilter, where a suspension of microalgae is used as a bioload, is a cheap and affordable way to reduce CO_2 emissions, as well as to provide high-speed biomass synthesis of microalgae of the genus *Chlorella* (C.). Microalgae can use inorganic carbon CO_2 for the synthesis of organic carbon biomass [33].

Therefore, there is an increase in interest in the use of microalgae as a biofilter for removing CO_2 in the world scientific community. Researchers from different countries propose various innovative projects to capture and absorb CO_2 by microalgae.

Indonesian scientists found that the rate of CO_2 absorption depends on the type of microalgae C. [50] and that *C. vulgaris* has the highest potential in the field of CO_2 capture. It has been proven that cultivation with a higher initial cell density (0.325 g/dm^3) demonstrates better resistance to carbon dioxide intake of 48.17 g/h with a carbon fixation of 37.95 g·dm^3/day (58%) and production biomass 0.82 g·dm^3/day [50].

Since the problem of reducing the carbon footprint has been faced by the scientific community for a long time, various researchers in the field of carbon dioxide reduction have already proven the possibility of using microalgae biomass as a biofilter [51]. However, most studies have studied the absorption of gases with a low CO_2 content (no more than 20%) by microalgae [52,53]. So, for example, in the work of V.Yu. Kulabukhov et al., CO_2 concentration was supplied from 0.2% to 16% [53]. This article proves that microalgae *C. vulgaris* and *Scenedesmus* are able to absorb gases with a CO_2 content of up to 16%. However, the work does not reveal the potential of microalgae to absorb gases with a high content of carbon dioxide (up to 39%). Similarly, in the work "Isolation and selection of microalgae from coal-fired thermoelectric power plant for bio-fixation of carbon dioxide" [52], the CO_2 concentration in the supplied gases did not exceed 18%.

Improvement of the nutrient medium for cultivating microalgae is carried out to increase the efficiency of CO_2 capture [54–56]. For example, the initial deficiency of NH_4HCO_3 is more favorable for the growth of microalgae [55,56]. The addition of sodium bicarbonate to the nutrient medium led to a significant increase in the amount of biomass and the productivity of the carbon dioxide utilization process [57–59]. The maximum CO_2 fixation rate and lipid content were recorded at a sodium bicarbonate concentration of 0.4% [59].

Figure 1 presents a simplified diagram of how microalgae utilize carbon dioxide. Firstly, inorganic carbon is absorbed from the environment, and then CO_2 and HCO_3 are transported to the chloroplast. Inorganic carbon passes through the thylakoid membrane and is converted to CO_2 by carbonic anhydrase (CA) at a higher ambient pH, which increases the CO_2 concentration near the rubisco enzyme and ultimately enhances photosynthetic rates [60]. Microalgae can uptake HCO_3^- through active transport and CO_2 through passive diffusion. CA regulates the concentration of CO_2 and HCO_3^- to maintain proper pH in the chloroplast stroma [44]. HCO_3^- is the preferred form of inorganic carbon storage due to its approximately 1000-fold lower permeability to lipid membranes than uncharged CO_2 molecules.

Since the efficiency of carbon dioxide uptake by microalgae directly depends on the number of cells in the microalgae suspension, some success has recently been achieved in increasing the growth rate of the number of microalgae cells using genetic engineering, random mutagenesis, and adaptive evolution. The improvement of the photosynthesis process is achieved through many mechanisms. The main ones are increasing the efficiency of enzymes involved in CO_2 fixation; strengthening metabolic processes; and reducing the size of the antenna, which can alleviate excessive absorption of sunlight [61,62].

The purpose of the presented studies was to study the effect of various species of algae of the genus *C.* and cultivation conditions on the rate of CO_2 uptake and growth.

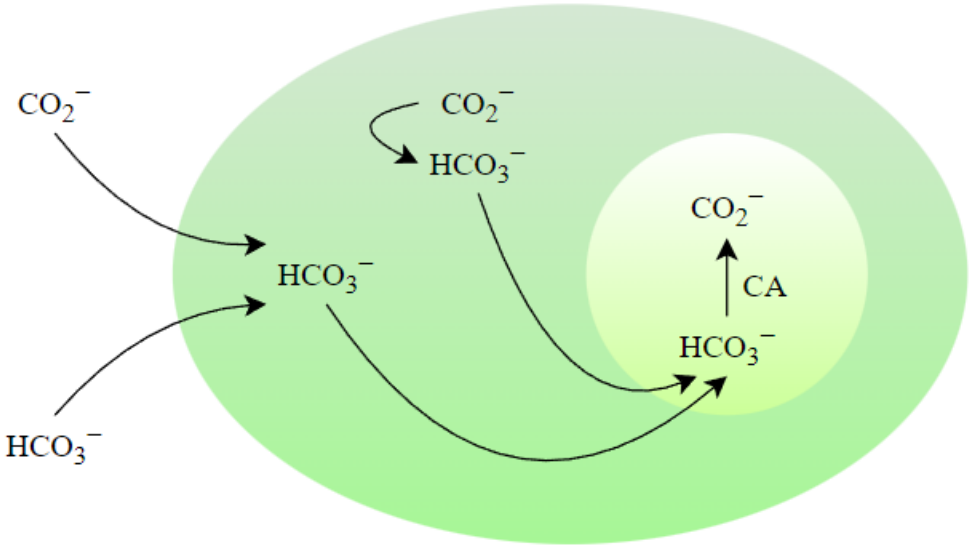

Figure 1. The simplified scheme for the utilization of carbon dioxide with the help of microalgae.

2. Materials and Methods

The objects of the study were various species of microalgae of the genus *C.*: *C. kessleri*, *C. vulgaris*, and *C. sorokiniana.*

The hermetic photobioreactor-biofilter (PhBR-B), with a capacity of 100 L (Figure 2), was created to assess the dynamics of CO_2 uptake by the biomass of various microalgae species.

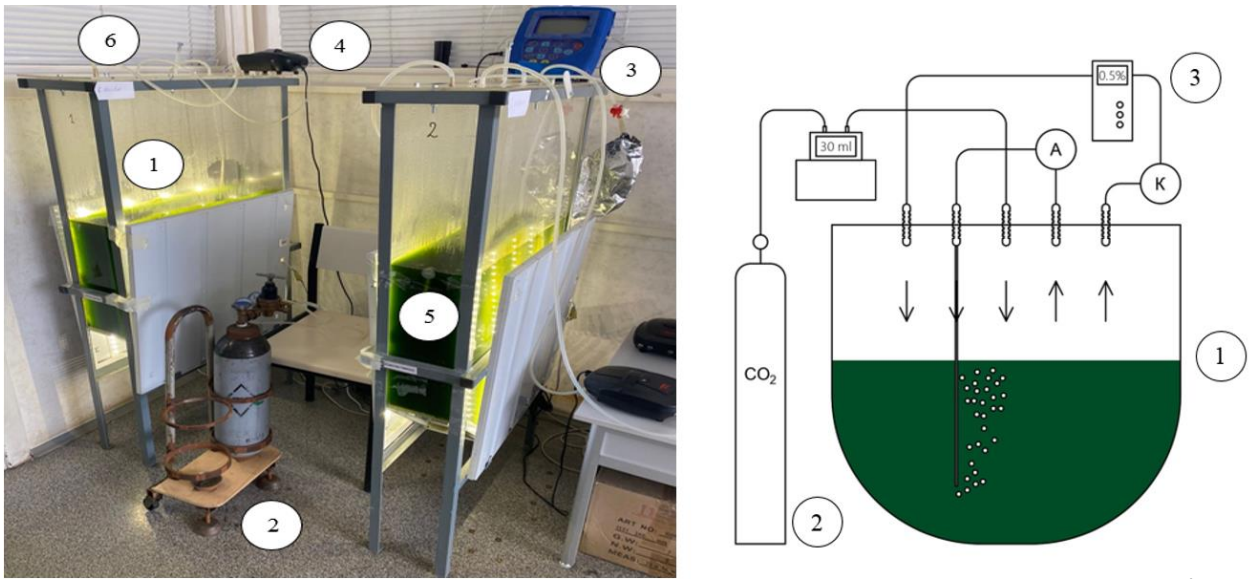

Figure 2. PhBR-B system with CO_2 source: 1—PhBR-B, 2—CO_2 supply system, 3—gas analyzer, 4—aerator, 5—microalgae biomass, 6—PhBR-B space for CO_2 supply.

PhBR-B is equipped with the following systems: aeration, lighting, temperature sensors, carbon dioxide supply, measurement of gas mixture composition, and removal of microalgae biomass suspension. Illumination was carried out with fluorescent lamps, the illumination of which varies in the range of 2500 to 3000 Lx. The temperature of the suspension solution was maintained in the range of 25 to 30 °C by thermostats. PhBR-B was supplied with 50 L of microalgae suspension, and the remaining 50 L was filled with a gas–air mixture with a high CO_2 content and aerated for 648 h (27 days). CO_2 was added daily through aerators in a volume of 7.5–17.5 L (15–39%) of the unoccupied volume

of PhBR-B. Intensive bubbling with gases with a high content of CO_2 (15–39%) of the suspension of *C.* microalgae makes it possible to intensify the processes of absorption of CO_2 by the biomass of microalgae. CO_2 from gaseous emissions is not only a source of inorganic carbon for microalgae but also promotes more rapid reproduction of microalgae *C.* cells and maintains the required pH of the solution in the range of 6.0 to 9.0.

Carbon dioxide was supplied to the PhBR-B from a CO_2 cylinder (imitation of gas emissions from power plants) through an aeration pipe located at the bottom of the PhBR-B with holes. The composition of the gas mixture in PhBR-B was measured using a GEOTECH ga200plus gas analyzer (Geotechnical Instruments (UK) Ltd., Sovereign House, Queensway, Leamington Spa, Warwickshire, CV31 3JR, UK).

The biomass of microalgae was settled during the day and poured into containers after 648 h (27 days) of the experiment.

The cultivation of microalgae biomass was carried out using a nutrient medium (Table 1), the composition of which was selected and described in the literature source [63]. In addition to the nutrient medium, diluted wastewater from food industry enterprises can be used [64] since they contain the elements necessary for the growth of microalgae.

Table 1. The composition of the nutrient medium.

Name of Substances	Concentration, mg/L
$ZnSO_4 \cdot 7H_2O$	100
$CuSO_4 \cdot 5H_2O$	10
$CoSO_4 \cdot 7H_2O$	100
$MnCl_2 \cdot 4H_2O$	500
$H_3BO_3 \cdot WF$	50
$Na_2MoO_4 \cdot 2H_2O$	100
$FeCl_3 \cdot 6H_2O$	4000
$Na_2EDTA \cdot 2H_2O$	6000
KNO_3	3.03
KH_2PO_4	0.32
$MgSO_4 \cdot 7H_2O$	2.4

The increase in biomass was estimated from the change in the optical density of the microalgae suspension at a wavelength of 750 nm, which was carried out using a CPP-3 (KFK-3) spectrophotometer. All measurements were carried out in triplicate. The measurement error was 3–7%.

3. Results

Comparative characteristics of six samples of *C.* microalgae according to various factors of their cultivation are presented in Table 2.

Table 2. Influence of illumination, temperature, and supply volume on the rate of CO_2 uptake and biomass growth of microalgae *C.*

Factors	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5	Sample No. 6
Temperature, °C	25	25	25	30	30	30
Illumination (daylight lamp), Lux	2500	2500	2500	3000	3000	3000
The volume of supplied CO_2, L/%	15.5/31	15.5/31	15.5/31	19.5/39	19.5/39	19.5/39
Optical density on the 1st day, D *	0.481	0.449	0.720	0.481	0.449	0.720

* Tables optical density measurement was carried out at a wavelength of 750 nm. Sample No. 1—*C. kessleri* (temperature (T) = 25 °C, illumination (O) = 2500 Lx, volume (V) of supplied CO_2 = 15.5 L (31%)). Sample No. 2—*C. vulgaris* (T = 25 °C, O = 2500 Lx, V CO_2 = 15.5 L (31%)). Sample No. 3—*C. sorokiniana* (T = 25 °C, O = 2500 Lx, V CO_2 = 15.5 L (31%)). Sample No. 4—*C. kessleri* (T = 30 °C, O = 3000 Lx, V CO_2 = 19.5 L (39%)). Sample No. 5—*C.* vulgaris (T = 30 °C, O = 3000 Lx, V CO_2 = 19.5 L (39%)). Sample No. 6—*C. sorokiniana* (T = 30 °C, O = 3000 Lx, V CO_2 = 19.5 L (39%)).

The initial optical density of the suspension of microalgae *C. kessleri* was 0.481 ± 0.014, *C. vulgaris* was 0.449, and *C. sorokiniana* was 0.720 at a wavelength of 750 nm.

When carbon dioxide was added, the pH shifted to an acidic environment, up to a value of 5.4. As the carbon dioxide was utilized by the suspension of microalgae, the pH turned into an alkaline medium, up to a value of 8.4.

The general graph of the dynamics of CO_2 uptake by a suspension of microalgae *C. kessleri* for 27 days of cultivation and CO_2 utilization is shown in Figure 3 (upper blue dots indicate a new supply of CO_2 to the PhBR-B after the CO_2 value has decreased to 0).

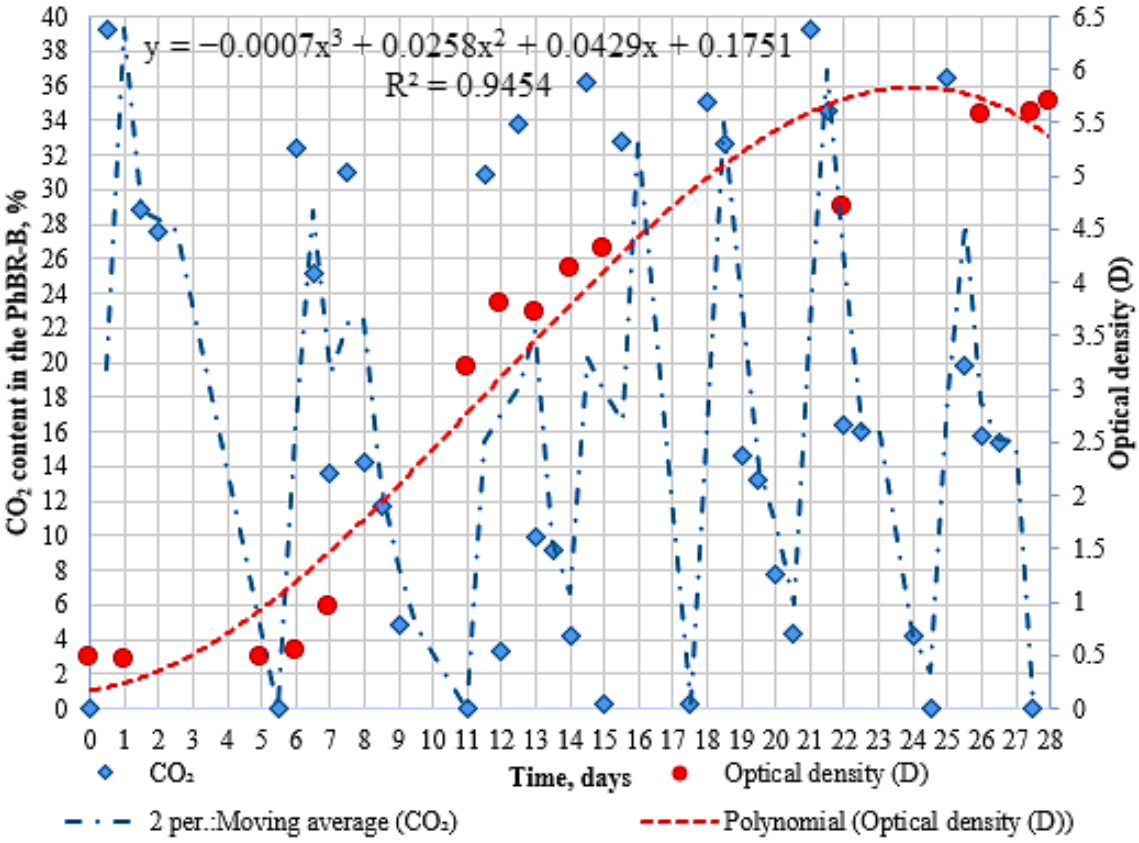

Figure 3. Dependence of CO_2 content and optical density (D) of *C. kessleri* microalgae suspension on cultivation time (27 days).

Figure 3 shows that the absorption of CO_2 by the suspension of microalgae *C. kessleri* most actively occurs at the stage of exponential growth (7–24 days). The optical density of the biomass increased throughout the experiment and corresponded to the classical shape of the growth curve.

The period (Figure 4) from the maximum supply of CO_2 32% (V = 15.5 L) to the complete absorption of 0% was studied to estimate the time of maximum absorption of CO_2 and the dynamics of microalgae biomass. It turned out that 2.8 days are enough for the complete absorption of CO_2 with a content of up to 32% in the air. Research data were recorded starting from the seventh day, which corresponds to the beginning of the exponential phase.

It follows from Figure 4 that 50 L of *C. kessleri* microalgae suspension absorbed 15.5 L of CO_2 in 2.8 days.

The dynamics of CO_2 uptake by a suspension of *C. kessleri* microalgae (initial optical density—0.95) for 9 h (on the seventh day from the start of the experiment) are shown in Figure 5.

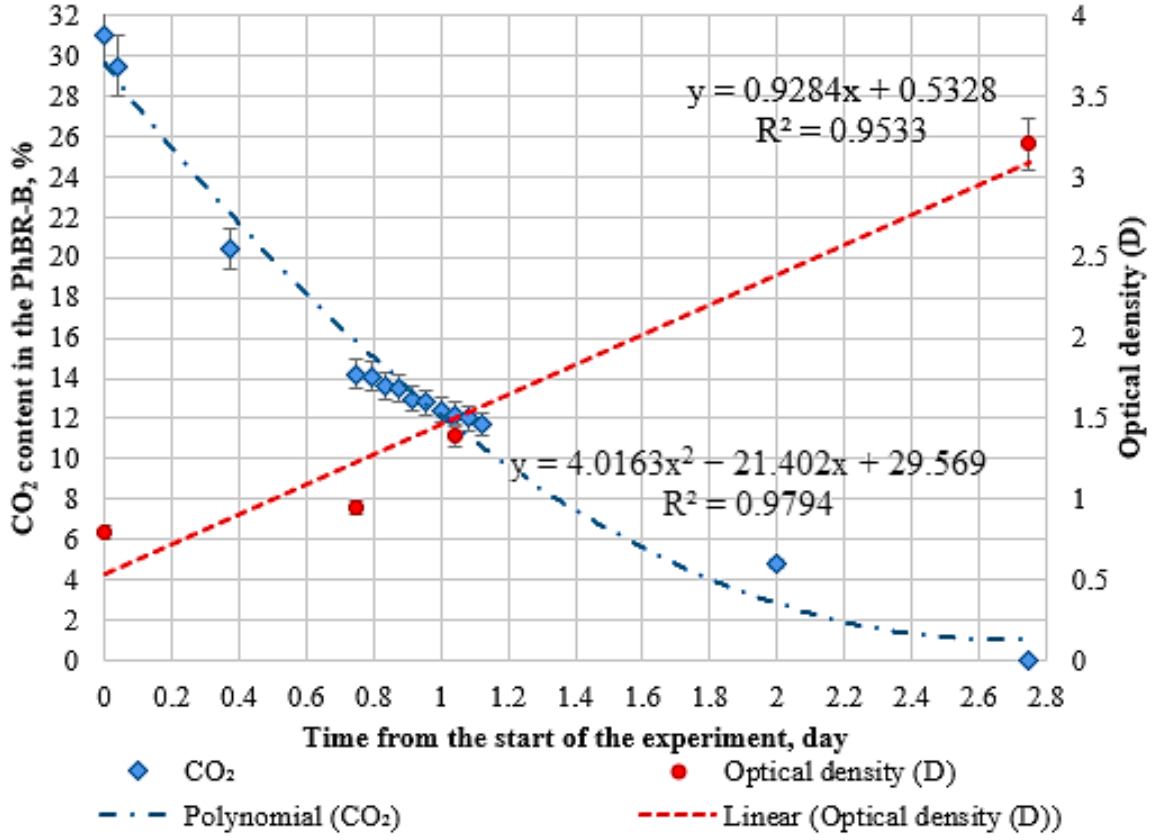

Figure 4. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. kessleri* microalgae suspension on cultivation time (2.8 days).

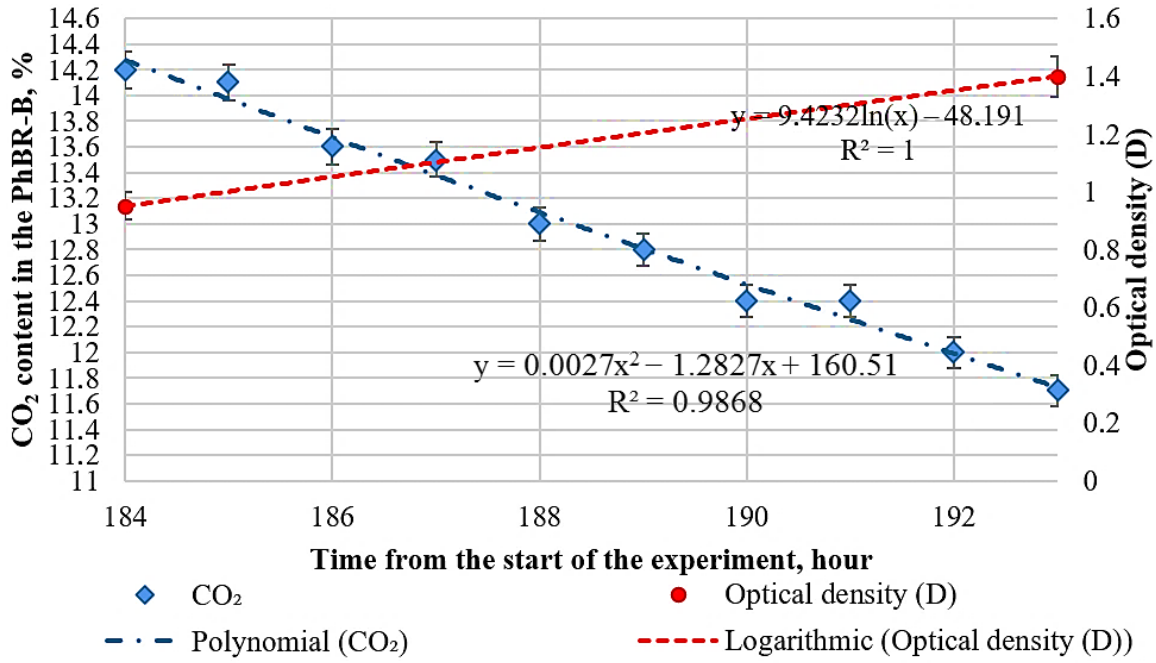

Figure 5. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. kessleri* microalgae suspension on cultivation time (9 h).

It follows from Figure 5 that for 9 h (on the seventh day of cultivation), 50 L of *C. kessleri* microalgae suspension (initial optical density—0.95) absorbed 1.25 L of CO_2.

Thus, 1 L of *C. kessleri* microalgae suspension (initial optical density—0.798) is able to absorb, on average, 0.0046 L of CO_2 in 1 h, and in 1 day, on average, 0.11 L of CO_2.

The mass of utilized CO_2 was determined, taking into account that the density of CO_2 (at a temperature of 27 °C) = 1.773 kg/m^3. A total of 1 L of *C. kessleri* microalgae suspension (initial optical density—0.798) absorbs 0.195 ± 0.001 g of CO_2 per day on average, increasing its absorption capacity as the number of biomass cells (optical density of the suspension) increases.

A similar experiment was carried out with microalgae *C. vulgaris* species.

The general graph of the dynamics of CO_2 uptake by a suspension of microalgae *C. vulgaris* for 27 days of cultivation is shown in Figure 6.

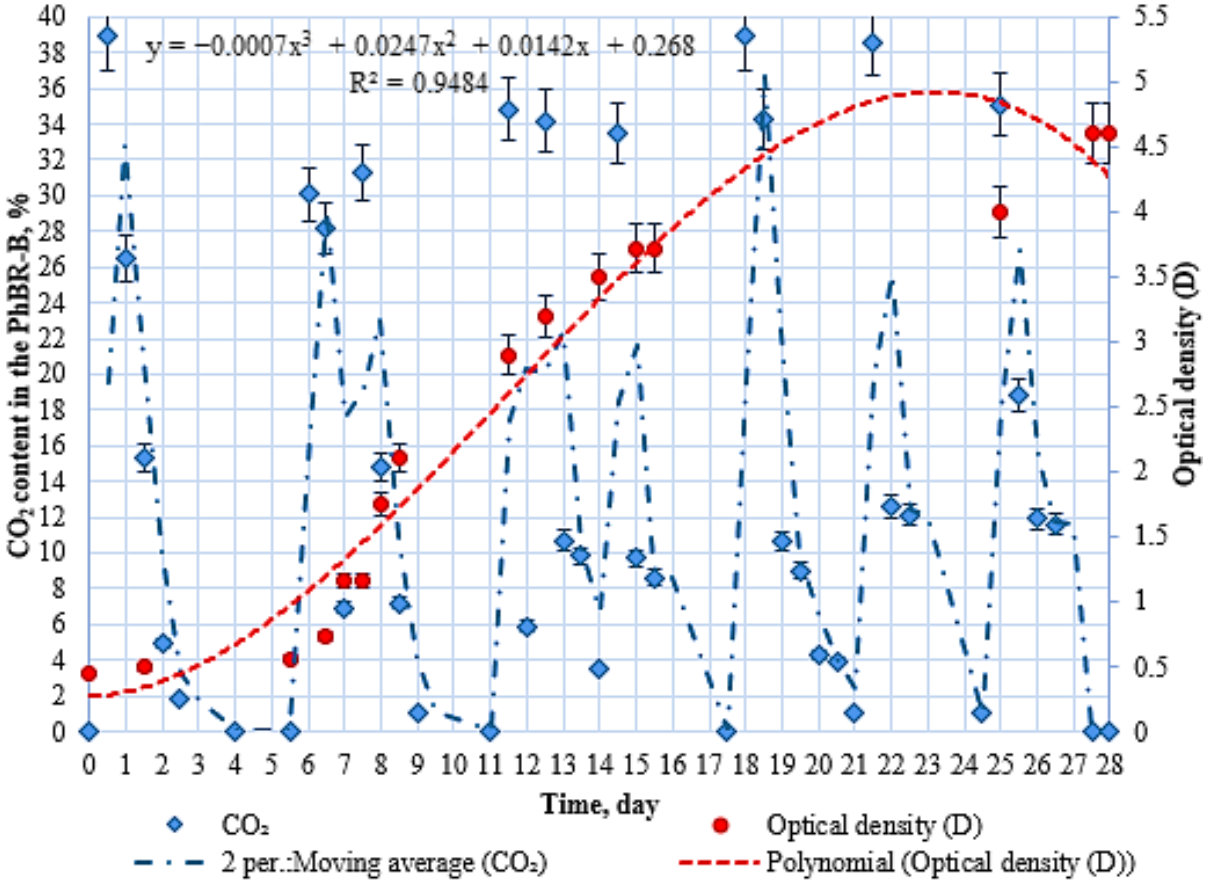

Figure 6. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. vulgaris* microalgae suspension on cultivation time (27 days).

The absorption of CO_2 by the suspension of microalgae *C. vulgaris* most actively occurs at the stage of exponential growth (7–22 days), as can be seen in Figure 6. The optical density of the biomass increased throughout the experiment.

The dynamics of absorption of 15.55 L of CO_2 by a suspension of *C. vulgaris* microalgae (the suspension volume was 50 L) is shown in Figure 7. CO_2 was supplied on the seventh day from the start of the experiment, which corresponds to the beginning of the exponential phase.

Thus, it follows from Figure 7 that 50 L of *C. vulgaris* microalgae suspension absorbed 15.55 L of CO_2 in 2.16 days.

The dynamics of CO_2 absorption by a suspension of microalgae *C. vulgaris* (initial optical density—1.73) for 9 h (the seventh day from the beginning of the experiment) are shown in Figure 8.

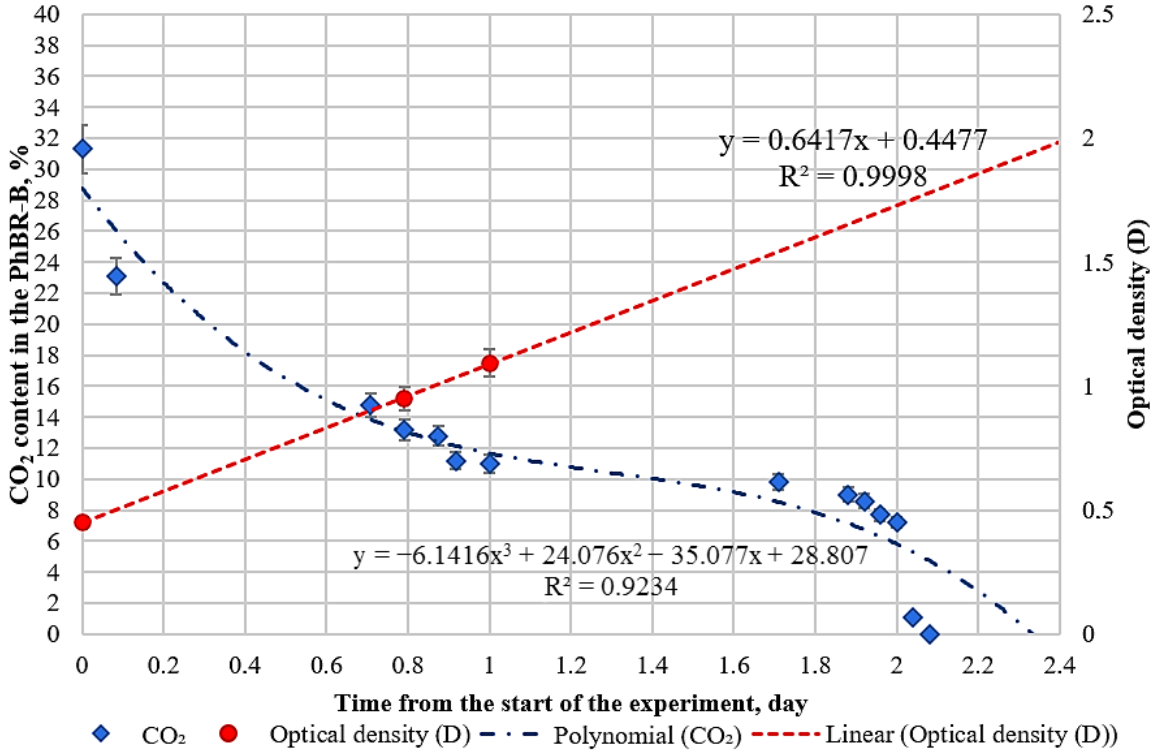

Figure 7. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. vulgaris* microalgae suspension on cultivation time (2,4 days).

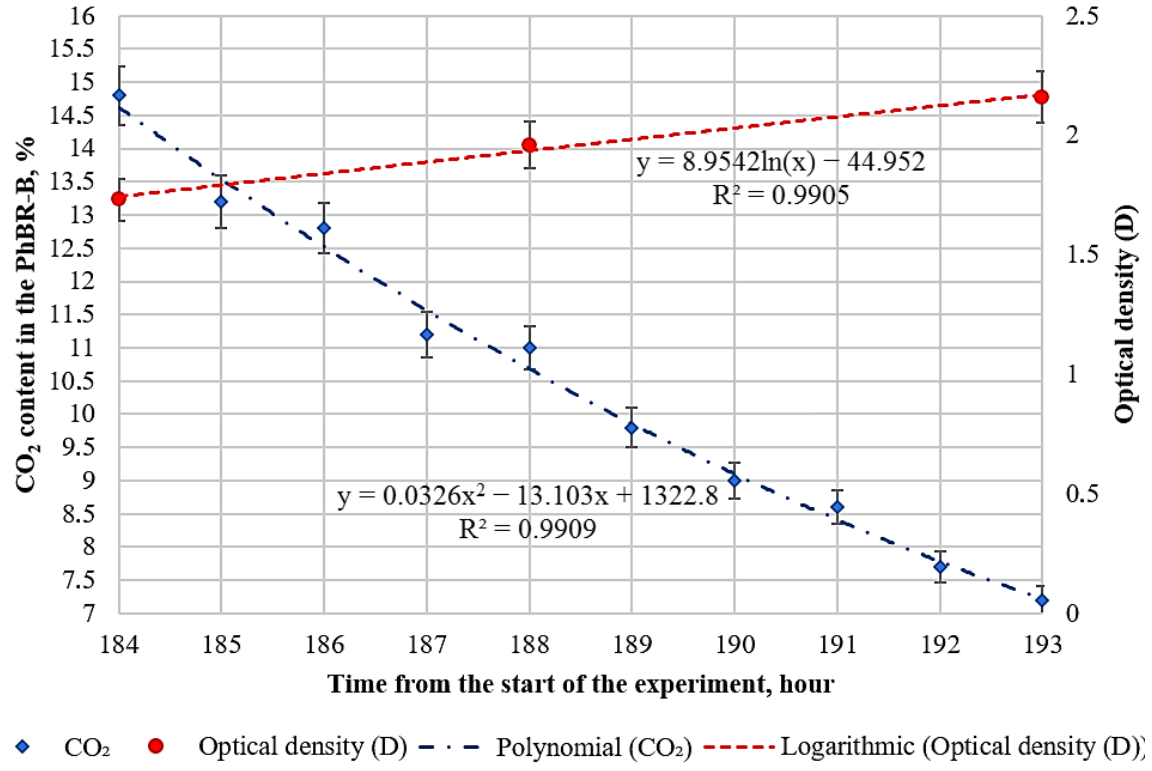

Figure 8. Dependence of CO_2 content in PhBR-B and optical density (D) of *C.vulgaris* microalgae suspension on cultivation time (9 h).

It follows from Figure 8 that in 9 h (on the seventh day of the experiment), 50 L of *C. vulgaris* microalgae suspension (initial optical density 1.73) absorbed 3.9 L of CO_2.

Thus, 1 L of *C. vulgaris* microalgae suspension (initial optical density—1.16) is able to absorb, on average, 0.006 L of CO_2 in 1 h, and in 1 day, on average, 0.144 L of CO_2.

To determine the mass of utilized CO_2, the density of CO_2 used (at a temperature of 27 °C) was equal to 1.773 kg/m^3. A total of 1 L of suspension of microalgae *C. vulgaris* (initial optical density—1.16) absorbs 0.255 ± 0.001 g of CO_2 per day, increasing its absorbing capacity as the number of biomass cells (optical density of the suspension) increases.

A similar experiment was carried out for *C. sorokiniana* algae. The general graph of the dynamics of CO_2 uptake by a suspension of *C. sorokiniana* microalgae over 27 days of cultivation and CO_2 utilization is shown in Figure 9.

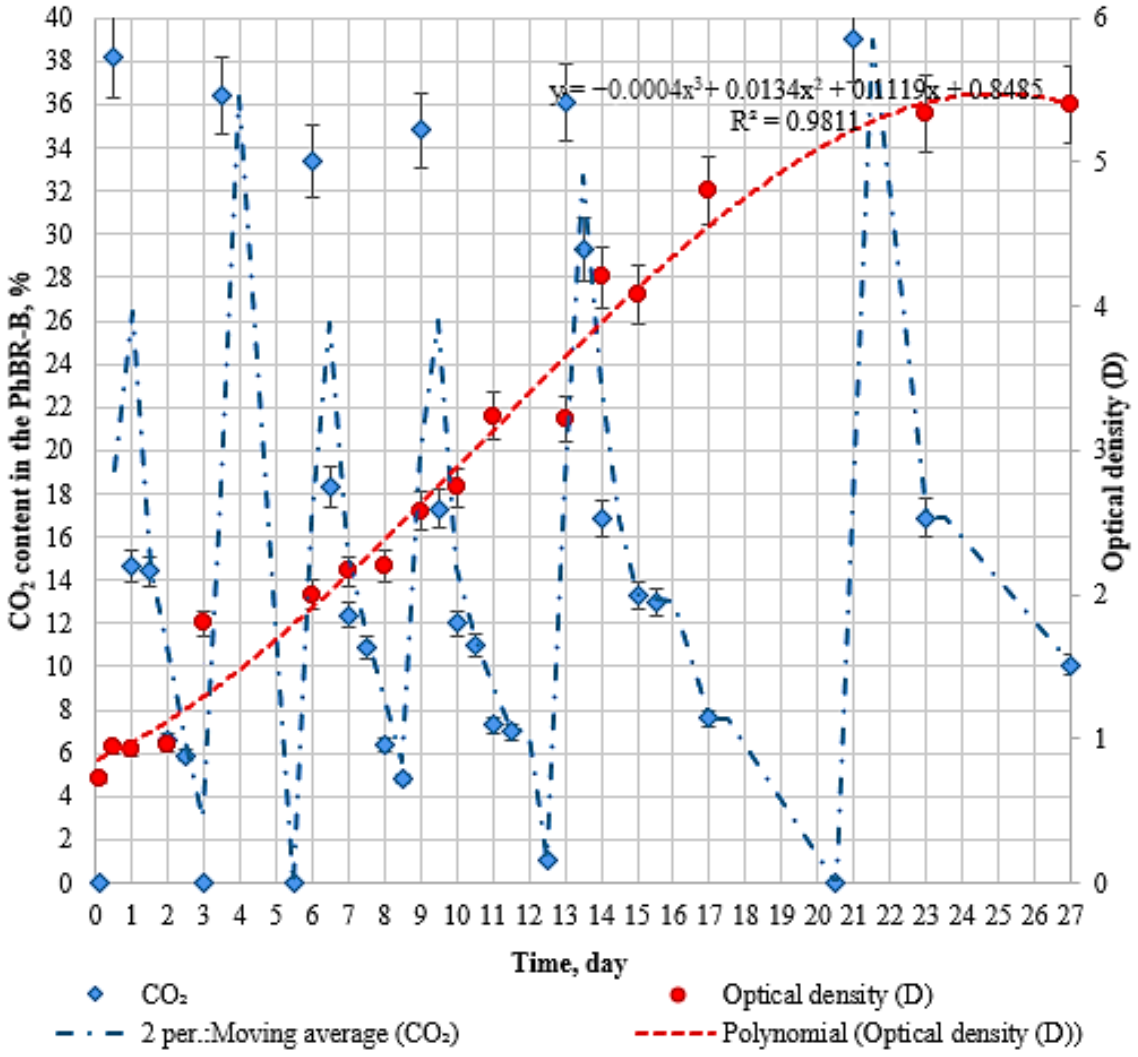

Figure 9. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. sorokiniana* microalgae suspension on cultivation time (27 days).

The absorption of CO_2 by the suspension of *C. sorokiniana* microalgae occurs most actively during the initial phase of exponential growth (days 2–10), as can be seen in Figure 9. The exponential phase begins faster (on the second day) than in the previous species. The biomass optical density increased throughout the experiment.

The dynamics of absorption of 14.3 L of CO_2 by a suspension of *C. sorokiniana* microalgae (CO_2 supply was carried out at 144 h (day 7 from the start of the experiment)) are shown in Figure 10.

Thus, it follows from Figure 10 that 50 L of *C. sorokiniana* microalgae suspension absorbed 14.3 L of CO_2 in 2.24 days.

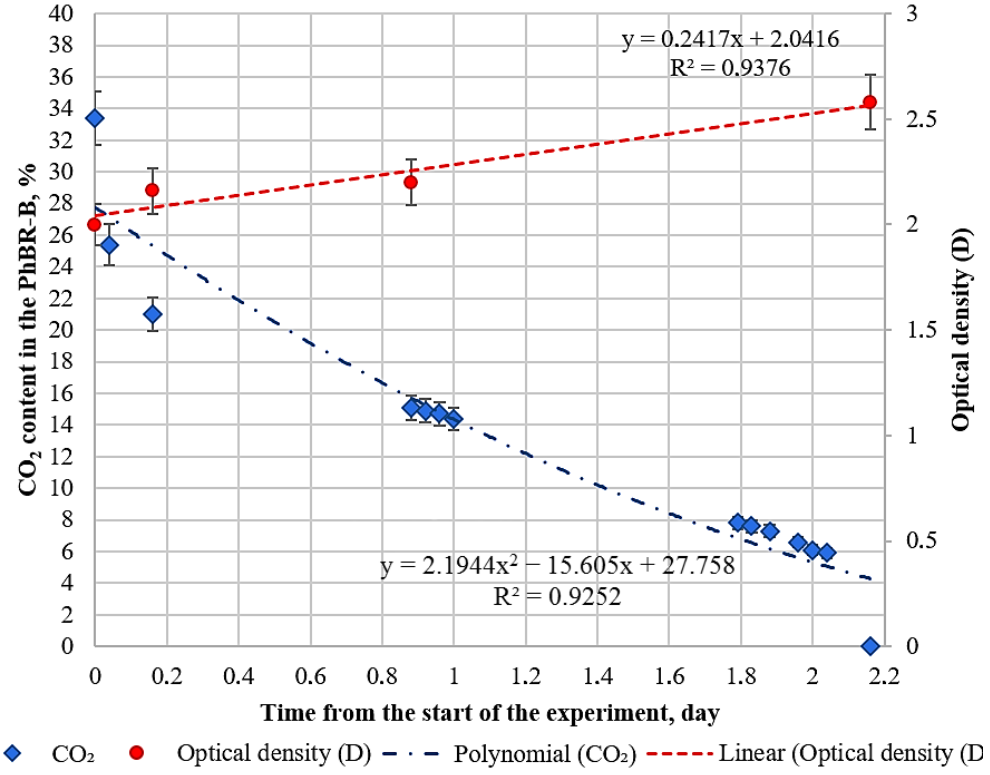

Figure 10. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. sorokiniana* microalgae suspension on cultivation time (2,24 days).

The dynamics of CO_2 uptake by a suspension of microalgae *C. sorokiniana* (initial optical density—2.2) for 9 h (the seventh day from the beginning of the experiment) are shown in Figure 11.

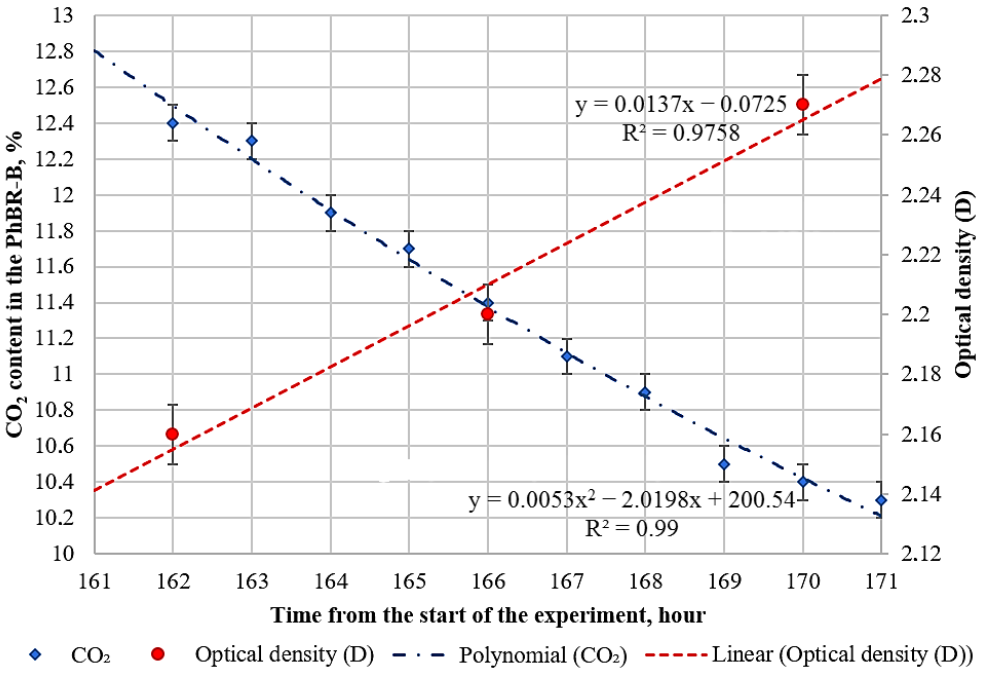

Figure 11. Dependence of CO_2 content in PhBR-B and optical density (D) of *C. sorokiniana* microalgae suspension on cultivation time (9 h).

It follows from Figure 10 that in 9 h (on the seventh day of the experiment), 50 L of *C. sorokiniana* microalgae suspension (initial optical density 2.2) absorbed 1.05 L of CO_2.

Thus, 1 L of *C. sorokiniana* microalgae suspension (initial optical density—2) is able to absorb an average of 0.0053 L of CO_2 in 1 h, and in 1 day, an average of 0.127 L of CO_2.

A total of 1 L of suspension of microalgae *C. sorokiniana* (initial optical density—2) absorbs 0.225 ± 0.001 g of CO_2 per day on average. In this case, the absorbing capacity increases as the number of biomass cells (optical density of the suspension) increases during the first nine days. In the future, even with an increase in optical density, the ability to absorb CO_2 decreases.

Dry biomass was obtained from the suspension of microalgae remaining after the experiment. Dry biomass is a raw material for obtaining valuable components.

The method of purification of emissions from carbon dioxide by *C.* microalgae with subsequent production of dry biomass is shown in Figure 12.

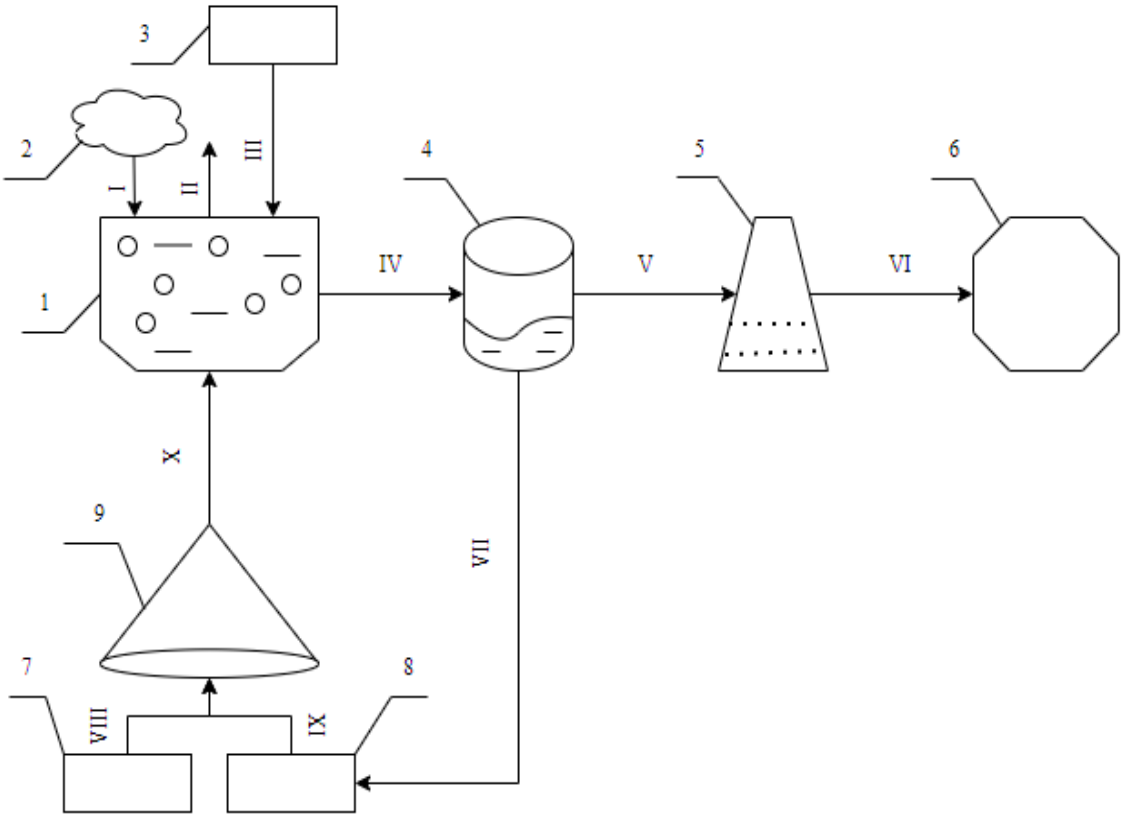

Figure 12. Block diagram of carbon dioxide emissions purification by microalgae C.: 1—PhBR-B, 2—a source of gases with a high content of CO_2, 3—a stock culture supply unit, 4—block for centrifugation of the resulting biomass, 5—block for hydrophilic drying, 6—a raw material for obtaining valuable components, 7—sewage supply unit, 8—nutrient medium supply unit, 9—mixing unit of nutrient medium, wastewater, and residual culture after centrifugation, I—CO_2, II—O_2, III—stock culture, IV—biomass, V—biomass after centrifugation, VI—biomass after drying, VII—residual culture after centrifugation, VIII—wastewater, IX—nutrient medium, X—mixture of nutrient medium, wastewater, and residual culture after centrifugation.

Centrifugation followed by drying is recommended for biomass dehydration. It is possible to use freeze-, IR-, or natural drying, depending on the component of production from a given biomass.

The results of the studies showed a high potential for CO_2 fixation (content in PhBR-B from 30% to 40% by free volume) by microalgae of all species of the genus *C.* (*C. vulgaris*, *C. kessleri*, and *C. sorokiniana*). This potential can be used to absorb CO_2 from TTP. Emissions from combined heat and power plants contain, on average, about 39% CO_2. The maximum

absorption of CO_2 occurs during the exponential growth phase (7–21 days) in all studied species of microalgae C. All studied species of microalgae C. are able to absorb gases with a high content of CO_2 (up to 39%).

Table 3 shows the results of studying the ability to absorb CO_2 by various types of microalgae of the genus *C.*

Table 3. The results of the study of the absorption capacity of microalgae of the genus C. in relation to CO_2.

Factors	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5	Sample No. 6
The volume of supplied CO_2, L/%	15.5/31	15.5/31	15.5/31	19.5/39	19.5/39	19.5/39
CO_2 utilization time, days	2.8	2	3	5	2.4	4
Volume of CO_2 utilized in 1 day by microalgae suspension, L *	5.500	7.500	5.100	3.900	8.125	4.875
CO_2 uptake rate, $g \cdot L^{-1} \cdot day^{-1}$	0.195	0.225	0.225	0.154	0.412	0.192
Optical density on the 1st day, D **	0.481	0.449	0.720	0.481	0.449	0.720
Optical density on the 27th day, D **	5.580	4.631	5.340	5.061	4.369	5.011

* With the addition of 15.5 ± 0.5 L of CO_2 on the 7th day from the start of the experiment; ** volume of microalgae suspension is 50 L.

For 648 h (27 days), the optical density of *C. kessleri* biomass increased to 5.580, and *C. vulgaris* up to 4.631 at a temperature of 25 °C, and at a maximum temperature of 30 °C, the optical density increased in the following ratios: *C. kessleri* up to 5.061, *C. vulgaris* up to 4.36, and. *C. sorokiniana* up to 5.011.

The maximum rate of absorption of CO_2 = 0.412 g/L·day and the maximum volume of CO_2 utilized in 1 day = 8.125 L are observed in a suspension of microalgae *C. vulgaris* at T = 30 °C, O = 3000 Lx, and V CO_2 = 19.5 L (39%).

4. Conclusions

Comparison of the dynamics of CO_2 uptake by different species of microalgae of the genus *C.* shows that the maximum rate of uptake of CO_2 = 0.412 g/L·day and the maximum amount of CO_2 utilized in 1 day = 8.125 L belong to the suspension of *C. vulgaris* microalgae.

Carbon biological sequestration may be one of the most promising methods for the reduction of CO_2 emissions in the energy sector, both from the cost and environmental points of view [65]. The optimal CO_2 demand for maximum microalgal growth can only be realized when a CO_2-rich gas is provided to the culture [38,66].

The problem of reducing the carbon footprint is a global problem for mankind. The introduction of biofilters based on microalgae will help reduce the negative impact of carbon dioxide on the environment. First of all, this is due to the ability of microalgae to absorb carbon dioxide from the emissions of thermal power plants, which will reduce the amount of carbon dioxide released into the atmosphere. In addition, when using biofilters based on microalgae, the spent absorbent is the biomass of microalgae, which can be used to create biofuel based on microalgae or as a co-substrate for the digestion of organic waste in order to increase biogas emissions [67,68]. This fact makes the development not only environmentally expedient but also economically profitable.

However, at this stage of development, the introduction of biofilters based on microalgae is associated with a few serious problems. First, this is because microalgae were used only in laboratory conditions and have not yet been tested on real thermal emissions. To a greater extent, this is due to the high initial costs of installing such technology for production and the company's justified risks in this regard. To conduct real field studies, it is necessary to design and install a whole complex for the purification of industrial emissions using a biofilter from microalgae. That is why it is necessary to continue studying the mechanism of CO_2 fixation by microalgae, not only for field studies but also for the imple-

mentation of the principles of sustainable development in various industries. These studies open a new step in promoting the principles of the circular economy and implementing these principles in real life. The study and development of new technologies to improve the environment and reduce the negative impact of production on the environment is an important element of scientific development since only through such modeling presented in this article is it possible to implement technologies in the future that can improve the life of every person.

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