



Biologically Active Substances and Sorption Capacity of the Diatom *Climaconeis scalaris* (Brebisson) E.J. Cox

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ARTICLE INFO

Article History:

Received: July 20, 2025

Accepted: Sep. 25, 2025

Online: Nov. 14, 2025

Keywords:

Diatoms,
Methylene blue,
Polyunsaturated fatty
acids,
Polysaccharides,
Sorption,
Heavy metals,
Ciprofloxacin,
Climaconeis scalaris

ABSTRACT

Diatoms are known as a valuable natural source of biologically active compounds with potential uses in medicine, pharmaceuticals, biotechnology, and environmental applications. Among these compounds, polyunsaturated fatty acids (PUFAs), which cannot be synthesized by the human body, are of particular importance. After the extraction of biologically active substances, the remaining algal biomass deserves attention, as it can be used as a sorbent for pollutants such as synthetic dyes, heavy metals, and antibiotics in wastewater. In this study, the processing of the Black Sea diatom *Climaconeis scalaris* was examined. Gas-liquid chromatography showed that the lipid complex of *C. scalaris* mainly consisted of myristic (14:0), palmitic (16:0), palmitoleic (16:1), and alpha-linolenic (18:3) fatty acids, the latter being an essential polyunsaturated fatty acid. FTIR spectroscopy confirmed the presence of polysaccharides in the dry biomass. After lipids and polysaccharides were extracted, the remaining biomass demonstrated a strong ability to accumulate pollutants. It absorbed ciprofloxacin up to 391mg/ dm³ within the first 60 minutes, slightly increasing to 404mg/ dm³ after 120 minutes, and methylene blue up to 473mg/ dm³ in 60 minutes. In addition, the biomass showed good potential for removing heavy metals from model solutions, achieving purification efficiencies of 80% for Cu, 64% for Pb, 70% for Cd, and 76% for Zn. These results suggest that *C. scalaris* could be effectively used in wastewater treatment. This research supports Sustainable Development Goal 6 (Clean Water and Sanitation) and promotes the sustainable use of aquatic resources.

INTRODUCTION

Diatoms are a unique group of photosynthetic eukaryotic microorganisms that play a vital role in sustaining life on Earth, contributing globally to the carbon, oxygen, and silicon cycles. Their cell wall, based on silicon dioxide with a vast variety of forms and microstructures, is a unique characteristic feature. However, the potential of diatoms

goes beyond their structural characteristics (**Mal *et al.*, 2022**). Diatoms are a valuable but still understudied natural source of biologically active substances (BAS). Due to the presence of such BAS as carotenoids, polyunsaturated fatty acids, fucoxanthin, macro- and microelements in their cells, diatom algae have high potential to be used in such areas as medicine, ecology, biotechnology, and pharmaceuticals (**Singh *et al.*, 2024**).

Special attention should be paid to essential fatty acids (EFAs), which are not synthesized by the human body, leading to the need for dietary supplements containing EFAs. Currently, various sources and methods for PUFAs concentrate production are being studied, and diatom algae are considered to be one of the potential sources of it (**Peltomaa *et al.*, 2019**). Regularly, after PUFAs and valuable components are extracted from microalgae, the biomass is discarded. To ensure a comprehensive microalgae processing process, the possibilities for the subsequent use of the residual biomass are being considered.

The stringent environmental standards around the world has led to the required monitoring of heavy metal concentrations in water sources near industrial areas. Metals such as Cu, Cd, Pb, Ni, Cr, Ag, Fe, Co, Hg, and As are considered heavy metals, with only a few serving as essential trace elements for human life. High concentrations of heavy metals can cause serious health problems and pose a threat to the environment. Heavy metal ions can interfere with metabolism and negatively affect the central nervous system, disrupt the gastrointestinal tract, and lead to serious consequences resulting from the damage to vital organs (**Demeke & Tassew, 2016**).

Antibiotics are widely used in aquaculture, agriculture, veterinary, and human medicine due to their important role in treating microbial infections. However, the mass production and consumption of antibiotics have led to their widespread presence in the environment, posing a global environmental problem (**Li *et al.*, 2024**). Ciprofloxacin (CF) is one of the most widely used broad-spectrum antibiotics in human and veterinary medicine for the treatment of serious diseases. CF belongs to the fluoroquinolone class and acts on both Gram-positive and Gram-negative bacteria. Fluoroquinolone antibiotics were widely used during the COVID-19 pandemic to suppress secondary bacterial infections (**Karampela & Dalamaga, 2020**). Global emissions of CF are mainly originated from surface and municipal wastewater (**Kelly & Brooks, 2018**). Microalgae have been recently actively researched as a raw material for the treatment of wastewater containing CF (**Zhou *et al.*, 2022; Li *et al.*, 2024**).

Synthetic dyes are a significant source of water pollution, often causing irreparable damage to aquatic ecosystems, leading to the death of organisms inhabiting water bodies and disrupting self-purification and photosynthesis processes (**Islam *et al.*, 2023**). Dyes can also affect the quality of drinking water, changing its organoleptic properties and making it unsafe for consumption. Due to their complex chemical composition and high solubility, dyes pose a serious problem for water purification (**Tkaczyk *et al.*, 2020**). Various treatment methods are used to remove dyes from wastewater, including adsorption,

coagulation, flocculation, precipitation, membrane filtration, and chemical oxidation (Shabir *et al.*, 2022). Among the methods listed, adsorption can be considered as one of the most promising methods due to its high efficiency, environmental friendliness, and low energy consumption (Wang & Seibert, 2017).

Diatom frustules, in addition to their unique physical and chemical characteristics, including chemical stability and mechanical strength, have several properties beneficial for sorbents. First, this is a large total sorption surface area due to the significant frustules' porosity (Rogato & De Tommasi, 2020). In addition, living diatom shells are covered with a thin organic layer with several functional groups (Sumper & Kröger, 2004; Bhat *et al.*, 2025). This indicates that diatom algae may be a promising alternative to currently used sorbents for the purification of wastewater from heavy metals, dyes, antibiotics, and other pollutants (Rashid *et al.*, 2021; Ojike *et al.*, 2025).

The objective of this study is to extract and evaluate the content of lipids and polysaccharides from *Climaconeis scalaris* (Brébisson) E.J.Cox marine diatom, and investigate the residual biomass sorption potential for heavy metal ions (Cu, Zn, Cd, Pb), the antibiotic ciprofloxacin, and the synthetic dye methylene blue. The data obtained are analyzed in terms of the waste-free production during the complex processing of the diatom biomass.

MATERIALS AND METHODS

1. Cultivation of *C. scalaris* biomass

The research object was a clonal culture (clone 9.0920-OC) of diatom algae from the genus *Climaconeis* Grunow, 1862, isolated from the Black Sea population in the waters of the Karadag Nature Reserve near Kuzmichev Rock, close to the Karadag Scientific Station (Davidovich *et al.*, 2019) (44°54'40" N, 35°12'46" E). Most species of the genus *Climaconeis* are tropical, and only three – *C. delicatula* (Cleve) E.J. Cox, *C. inflexa* (Brébisson ex Kützinger) E.J. Cox, and *C. scalaris* – are found in temperate latitudes.

Clonal cultures were obtained by micropipetting; a clone (clonal culture) is understood to be the offspring of a single cell formed as a result of mitotic division. The cultures were kept in Erlenmeyer flasks in a modified ESAW medium (Polyakova, Davidovich *et al.*, 2018) under natural lighting of 150-170 lux, a “day/night” lighting regime, and a constant temperature of 20±2°C. To obtain the required salinity, the initial medium (36‰) was diluted with distilled water, or sodium chloride was added to it. Salinity was measured using an RHS-10ATC refractometer (China). In order to accelerate biomass growth during cultivation, the nutrient medium was regularly (once every 5 days) renewed.

Subsequently, the samples were centrifuged on a CLM1-12 centrifuge (Russia) (1000 rpm) and dried at a temperature of 22 ± 2 °C until the residual moisture content in the samples was $6 \pm 1\%$.

2. Lipid extraction and determination of fatty acid composition in *C. scalaris*

To extract lipids from *C. scalaris* biomass, ultrasonic extraction was applied using a Scientz-IID disperser (Scientz Biotechnology, China). A 1:1 hexane:ethyl alcohol solvent system was used. Ultrasonic treatment was carried out with the following characteristics: power – 300W, time – 15min. After extraction completion, the extract was separated from the biomass, and the resulting lipid complex was dried on an EV311VAC rotary evaporator (LabTech, US) at a temperature of 32 ± 1 °C.

The yield of the lipid fraction was determined using the formula:

$$M = m_{\text{total}} \times 100 / m, \quad (1)$$

Where, M — percentage mass of extracted lipids, %; m_{total} — mass of lipid extract, g; m — amount of *C. scalaris* dry biomass, g.

To determine the fatty acid composition of the extracts, gas chromatography was performed on a Chromatek Kristall-5000 gas chromatograph (Chromatek, Russia) with a flame ionization detector by analyzing methyl esters of fatty acids.

3. Polysaccharides extraction from *C. scalaris* biomass

A complex of polysaccharides was extracted from the biomass in a water bath at a temperature of 80 ± 1 °C for 120min and centrifuged on a CLM1-12 centrifuge (Russia) for 10 min at 1000 rpm. Further steps were performed according to the method of Sukhikh et al. (2023). The yield of polysaccharides was determined using the formula:

$$Y = \frac{m_1}{m_2} \cdot 100\%, \quad (2)$$

Where, m_1 – amount of polysaccharides obtained, g; m_2 – amount of *C. scalaris* dry biomass after lipid extraction, g.

Polysaccharides were determined using Fourier transform infrared spectroscopy. A sample of 0.01 mg of dry material was mixed with 0.391 mg of KBr and analyzed using the FSM 2201 device (InfraSpec, Russia). A KBr sample was used as a background.

4. Sorption of heavy metals Cu, Zn, Cd, Pb by *C. scalaris* biomass

To experiment on heavy metals sorption by *C. scalaris* biomass, after the extraction of lipids and polysaccharides, a model solution of pollutants was prepared. It contained copper, zinc, lead, and cadmium ions at a concentration of 2.5 mg/dm^3 . After

extracting lipids and polysaccharides, 0.15g of dry *C. scalaris* biomass (clone 9.0920-OC) was placed in 10ml of the model solution. The residual concentration of metals was determined after 30, 60, and 90 minutes using a TA-Lab voltammetric analyzer (Tomanalit LLC, Russia) according to the PND F 14.1:2:4.222-06 method (Methods for mass concentration measuring of zinc, cadmium, lead, and copper in drinking, natural, and waste waters)

The sorption efficiency, %, was calculated using the formula:

$$E = \frac{C_1 - C_2}{C_1} \cdot 100\% \quad (3)$$

Where, C_1 – initial concentration of heavy metals, mg/dm³; C_2 – final concentration of heavy metals in solution, mg/dm³.

5. Sorption of ciprofloxacin and methylene blue by *C. scalaris* biomass

To study the sorption of antibiotics and dyes by *C. scalaris* biomass after the extraction of lipids and polysaccharides, the following reagents were used: ciprofloxacin C17H18FN3O3 (1 tablet containing 500 mg of ciprofloxacin, Dr. Reddy's Laboratories, India), methylene blue C16H18N3SCl (Vekton CJSC, Russia).

To prepare a working solution of ciprofloxacin (CF), the crushed tablet was transferred to a 100 ml flask and brought to the mark with deionized water, obtaining a suspension containing some sediment in the form of starch and other additives, which was further separated by centrifugation. The initial concentration of the methylene blue (MB) solution was prepared by the weight method. The concentration was calculated using the formula:

$$C_0 = (1000 \cdot q) / V \quad (4)$$

Where, q – the dye weight, g, V – volume of the solution (deionized water), dm³.

To construct the adsorption graph, 0.0005±0.0002g of residual *C. scalaris* biomass after extraction of lipids and polysaccharides was dispersed in an aqueous solution of ciprofloxacin/methylene blue with a volume of 5ml at various concentrations (0.05– 0.5g/ dm³). The experiments were carried out in closed 50ml glass beakers with constant stirring and different contact times (from 0.08 to 24 hours) to find the adsorption equilibrium. After the specified time had elapsed, the samples were centrifuged for 15 minutes at 5500 rpm on a CLM1-12 centrifuge (Russia). The adsorption kinetics of ciprofloxacin/methylene blue were studied in a solution with a concentration of 0.5g/dm³. To construct the adsorption graphs for ciprofloxacin/methylene blue, the experiments were carried out similarly with a contact time of two hours, which, according to the kinetic data, corresponded to the adsorption equilibrium time.

The concentration of ciprofloxacin/methylene blue was determined using UV spectroscopy on a LEKI SS2109UV spectrophotometer (LOIP, Russia) based on the optical density at a wavelength of 275nm (for ciprofloxacin) and 246nm (for methylene blue). The sorbent capacity, mg/dm³ (amount of adsorbed substance), was determined using the formula:

$$X = \frac{(C_0 - C_1) \cdot V}{m} \quad (5)$$

Where, C_0 is the initial concentration of the antibiotic/dye solution, g/dm³; C_1 is the final concentration after sorption, g/dm³; V is the volume of the antibiotic/dye solution, dm³; m is the mass of the sorbent sample, g.

RESULTS & DISCUSSION

1. Fatty acid composition of dry *C. scalaris*

Ultrasound method with a 1:1 ratio of polar (ethyl alcohol) and nonpolar (hexane) solvents yielded a lipid fraction of 24.3% of the total *C. scalaris* dry weight.

The interpretation of *C. scalaris* fatty acid chromatogram showed (Table 1) that the predominant fatty acids in the lipid complex are myristic acid 14:0, palmitic acid 16:0, palmitoleic acid 16:1, and alpha-linolenic acid 18:3, which is an essential polyunsaturated acid, not synthesized in the human body.

According to the data on diatoms' fatty acid composition (Table 1), it can be concluded that a high content of palmitic 16:0 and palmitoleic 16:1 acids is characteristic for many species of diatoms. In contrast, a high content of alpha-linolenic acid is not a characteristic feature. Compared to other diatom species, *C. scalaris* stands out for its significantly higher content of alpha-linolenic acid. Diatoms such as *Porosira glacialis*, *Attheya longicornis*, and *Craticula cuspidata* have a high content of eicosapentaenoic acid C20:5, while the content of this acid in *C. scalaris* fatty acid complex is relatively low. The low content of eicosapentaenoic acid, which maintains membrane flexibility at low temperatures (important for cold-water organisms), may be explained by the fact that representatives of the genus *Climaconeis* live mainly in warm seas (Reid & Williams, 2002).

Table 1. Diatoms fatty acid composition

Diatom	C14:0	C16:0	C16:1	C18:0	C18:1	C18:3	C20:3	C20:5	C22:6	Reference
<i>Porosira glacialis</i>	4.17	12.35	18.95	3.51	1.68	4.39	-	23.66	5.75	Artamonova et al., 2017
<i>Attheya longicornis</i>	8.63	9.37	23.96	3.59	3.90	2.84	-	20.98	4.62	Artamonova et al., 2017
<i>Navicula</i> sp.	3.60	30.10	19.20	12.30	-	7.10	-	17.20	-	Li et al., 2017
<i>Cyclotella</i> sp.	1.50	19.70	31.20	19.20	-	0.00	-	19.20	-	Li et al., 2017
<i>Synedra</i> sp.	3.20	29.90	12.50	19.20	-	6.90	-	13.40	-	Li et al., 2017
<i>Sellaphora pupula</i>	9.25	33.20	39.50	-	2.15	5.04	-	0.13	-	Elfituri, 2025

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<i>Nitzschia palea</i>	6.72	26.20	34.20	7.14	2.42	1.23	-	11.60	0.81	
<i>Craticula cuspidata</i>	7.79	15.60	32.30	3.34	1.83	1.94	-	25.50	0.47	
<i>Nitzschia sigma</i>	12.20	29.20	29.90	1.19	5.40	3.66	-	12.60	0.62	
<i>Nitzschia</i> sp.	3.49	27.90	30.40	-	2.02	8.66	-	15.70	1.28	
<i>Chaetoceros calcitrans</i>	13.20	33.70	31.00	-	1.19	2.20	1.95	7.62	1.6	
<i>Climaconeis scalaris</i> 9.0920-OC	9.90	22.70	11.20	3.81	6.70	21.35	8.70	0.56	4.4	This study

2. Fourier transform infrared spectroscopy (FTIR)

Hot water extraction resulted in a polysaccharide yield of 3.2%. The IR profile of polysaccharides illustrates the characteristic of the functional chemical groups (Fig. 1).

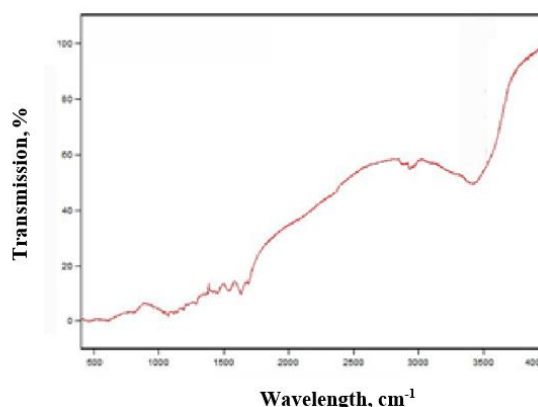


Fig. 1. IR spectrum of polysaccharides from dry *C. scalaris* after lipid extraction

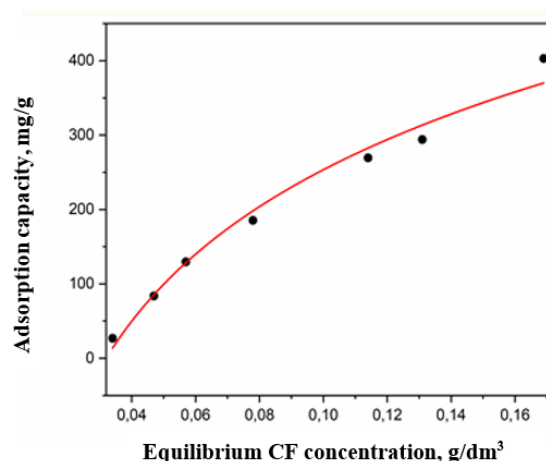
The O–H stretching vibration appears at 3274cm^{-1} , belonging to the group of hydroxyl compounds and water. The adsorption at 2927cm^{-1} corresponds to the asymmetric vibration of the C–H group. The adsorption at 1639cm^{-1} corresponds to the C=O group. The spectrum also shows adsorption at 1226 cm^{-1} , which corresponds to S=O stretching. The adsorption at 1039cm^{-1} may be associated with C–O–H stretching (Yang *et al.*, 2019). Sulfate groups have a wide range of biological and physiological effects (Na *et al.*, 2010). The range associated with sulfate groups found in this study is similar to the results of a study of polysaccharides from the diatom *Didymosphenia geminata*, which exhibited antioxidant and anti-inflammatory effects, and diatoms of the genus *Navicula* (Fimbres-Olivarría *et al.*, 2016; Figueroa *et al.*, 2020).

3. Sorption of ciprofloxacin (CF)

After valuable components extraction, *C. scalaris* residual biomass showed relatively high sorption capacity with respect to CF (Fig. 2 & Table 2).

Table 2. *C. scalaris* sorption capacity for CF

Initial CF concentration, g/dm ³	Equilibrium CF concentration, g/dm ³	<i>C. scalaris</i> sorption capacity, mg/g	Effectiveness, %
0.061	0.034	27	44
0.133	0.047	86	65
0.189	0.057	132	70
0.263	0.078	185	70
0.381	0.114	267	70
0.425	0.131	294	69
0.56	0.169	391	70

**Fig. 2.** Ciprofloxacin (CF) concentration and *C. scalaris* sorption capacity

The results (Table 2) indicate an increase in the sorption capacity of *C. scalaris* biomass proportional to the increase in ciprofloxacin concentration. According to Fig. (2), it can be seen that with an increase in CF initial concentration from 0.06 to 0.56g/dm³, *C. scalaris* adsorption capacity increased from 27 to 391mg/g. Similar data were obtained in the study of **Salah *et al.* (2024)**, who explained that CF concentration increase in the working solution leads to an increase in the difference between CF concentration in the solution and CF concentration on microalgae surface, which in turn leads to an increase in the driving force of mass transfer, contributing to the adsorption process at higher CF concentrations.

For a qualitative analysis of isotherms, the Brunauer classification of isotherms (or the Brunauer–Deming–Deming–Teller classification) was used, which is based on the relationship between the shape of the isotherm and the adsorption mechanism. According to this classification, the graph's initial section of CF adsorption by *C. scalaris* corresponds more to isotherm I, or the “Langmuir type”. In contrast, the rest of the graph resembles isotherms IV and V, which are characteristic of capillary reactions on mesoporous materials.

CF adsorption kinetics shows (Fig. 3) that *C. scalaris*, after extraction of valuable components, reaches a high sorption capacity of 290mg/ g in the first 5 minutes of the experiment, increasing to 389mg/ g in 15 minutes and then tends to increase slightly to 404mg/ g in 120 minutes. This maximum absorption remains within small fluctuations of ± 2 mg/ g for 24 hours. It can be concluded that the saturation limit of *C. scalaris* with CF is reached in 120 minutes.

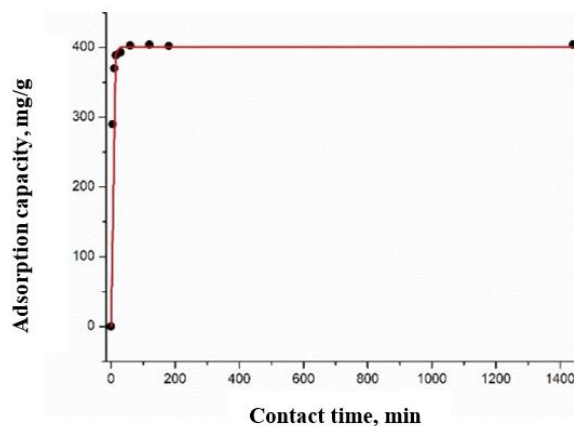


Fig. 3. CF adsorption kinetics

According to previously published studies (Al-Mashhadani *et al.*, 2023; Salah *et al.*, 2024), CF ions can attach to microalgae as a result of a complex process involving ion exchange, surface precipitation, electrostatic attraction, and surface complexation.

4. Sorption of methylene blue (MB)

Sorption of methylene blue by *C. scalaris* after the removal of lipids and polysaccharides showed a relatively high sorption capacity with respect to methylene blue (Table 3 & Fig. 4).

Table 3. *C. scalaris* sorption capacity for MB

Initial MB concentration, g/ dm ³	Equilibrium MB concentration, g/ dm ³	<i>C. scalaris</i> sorption capacity, mg/g	Effectiveness, %
0.054	0.013	41	76
0.115	0.014	101	88
0.182	0.015	167	92
0.24	0.015	225	94
0.365	0.016	349	96
0.493	0.02	473	96

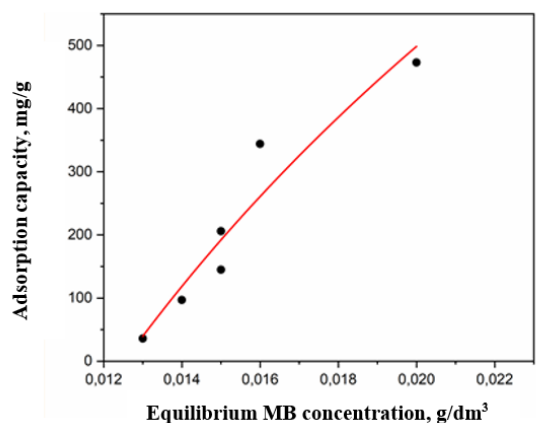


Fig. 4. Methylene blue (MB) concentration and *C. scalaris* sorption capacity

The results (Table 3) indicate an increase in *C. scalaris* sorption capacity proportional to the MB concentration increase. According to Fig. (4), it can be seen that with an increase in MB initial concentration from 0.054 to 0.493g/ dm³, *C. scalaris* adsorption capacity increased from 41 to 473mg/ g. Studies on the adsorption of dyes by diatoms indicate that the efficiency of synthetic dye adsorption depends on the presence of functional groups on the surface of silica shells and the organic component of diatom cells (Aragaw & Bogale, 2021; Dubey et al., 2024).

According to the Brunauer–Deming–Deming–Teller classification, the graph initial section of MB adsorption by *C. scalaris* is similar to isotherms I and II. The graph acquires the characteristics of isotherm IV, which indicates the occurrence of a capillary reaction on mesoporous materials.

The adsorption kinetic curve of MB (Fig. 5) shows that a reasonably high rate characterizes the sorption process. The study demonstrates an increase in MB adsorption amount by *C. scalaris* with time, with a sharp adsorption increase in the first 15 minutes, reaching 342mg/ g, followed by a slight adsorption increase up to 473mg/ g in 60 minutes. This maximum adsorption remains within a small range of ± 4 mg/ g for 24 hours. It can be concluded that the *C. scalaris* saturation limit with MB is reached in 60 minutes.

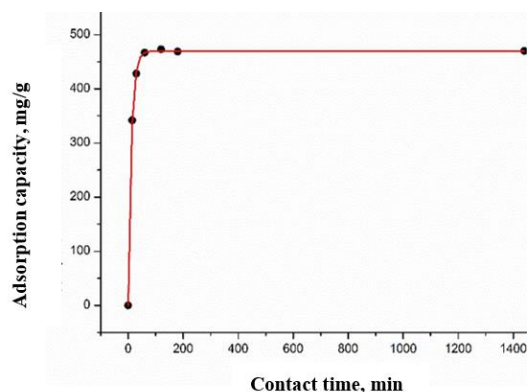


Fig. 5. MB adsorption kinetics

5. Sorption of heavy metals Cu, Zn, Cd, Pb

C. scalaris sorption capacity after the extraction of lipids and polysaccharides showed a relatively high ability of the biomass to bioaccumulate such heavy metal ions as Cu, Zn, Cd, and Pb (Table 4). The sorption process of heavy metals by *C. scalaris* residual biomass showed an uneven sorption/desorption process for copper, zinc, cadmium, and lead. The accumulation of zinc, cadmium, and lead reaches its maximum in 90 minutes, while the accumulation of copper ions reaches 80% in the first 30 minutes, followed by a desorption process. At the same time, the sorption of copper and zinc in the first 30 minutes is more effective than the sorption of cadmium and lead. The results obtained correlate with the data of a prior study (Sbihi *et al.*, 2014), where the sorption of copper and zinc by the diatom *Planothidium lanceolatum* is more effective than the sorption of cadmium.

Table 4. Heavy metals sorption by *C.scalaris* residual biomass. Initial concentration of heavy metals is 2.5mg/ g.

Metal	Time of experiment, h					
	0.5		1.0		1.5	
	Final concentration, mg/ dm ³	Effectiveness, %	Final concentration, mg/ dm ³	Effectiveness, %	Final concentration, mg/ dm ³	Effectiveness, %
Cu	0.05±0.13	80	0.65±0.16	74	0.85±0.21	66
Zn	0.70±0.18	72	0.68±0.17	73	0.60±0.15	76
Cd	1.00±0.24	60	0.93±0.22	63	0.75±0.18	70
Pb	1.05±0.26	58	0.98±0.24	61	0.90±0.23	64

Schmitt *et al.* (2001) studied heavy metals sorption by the diatoms *Cyclotella cryptica* and *Phaeodactylum tricornutum*. They showed the complex process of biosorption and bioaccumulation in their study. Special attention should be paid to the dependence of heavy metal sorption by diatom algae on metal-binding centers on the

surface of diatom cells. **Da Costa Santos (2010)** demonstrates the binding of Cd ions to proteins on the surface of *Nitzschia palea* frustules. **Qi et al. (2017)** noted the selective binding of active centers of purified diatom frustules with Pb ions in the presence of other heavy metals. The efficiency of Cd ion sorption by *P. tricornutum* shells was proven in the study of **Ma et al. (2020)**. It is important to emphasize that the metalloproteome of diatoms is a significant part of their proteome, which is also one of the key factors in heavy metal bioaccumulation (**Chasapis et al., 2022**).

CONCLUSION

The present study demonstrates the feasibility of *C. scalaris* diatom complex processing. The significant amount of alpha-linolenic acid with three double bonds (omega-3; 18:3ω3) in *C. scalaris* fatty acid complex indicates the possibility of using this diatom as a source of PUFAs for humans and animals. The ciprofloxacin sorption results by residual (after extraction of lipids and polysaccharides) *C. scalaris* allow it to be used as a sorbent for additional purification of wastewater containing antibiotics. The high sorption rate of methylene blue characterizes *C. scalaris* biomass as a potential sorbent for synthetic dyes under static conditions. The sorption of zinc, copper, cadmium, and lead by *C. scalaris* biomass allows us to consider its application for the additional treatment of wastewater containing heavy metals. Thus, the complex processing of *C. scalaris* diatom is a practical approach to ensuring a waste-free production cycle.

Acknowledgement

The studied diatom strain was isolated, introduced, and maintained in culture thanks to project No. 124030100100-0 “Study of the fundamental characteristics of marine hydrobionts that ensure their functioning in ecosystems and serve as the basis for their rational use and conservation,” funded by the Ministry of Science and Higher Education of the Russian Federation and the Shared Use Center of the Karadag Scientific Station “Diatom Algae of the World Ocean”.

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