IRSTI 34.31.11, 34.33.19 https://doi.org/10.26577/bb108320269

**A.A. Dauletova[1], K. Bolatkhan[1], A.A. Kakimova[1], G.A. Akhmetova[1], A. Askar[1], D. Ozcimen[2], B.K. Zayadan[1*]**

[1]Al-Farabi Kazakh National University, Almaty, Kazakhstan
[2] Yıldız Technical University, İstanbul, Turkey
*e-mail: zbolatkhan@gmail.com

# STUDY OF PHOTOTROPHIC MICROORGANISMS FROM OIL REFINERY WASTEWATER AND THEIR BIOREMEDIATION POTENTIAL

Wastewater from petroleum refining enterprises is characterized by a high content of toxic hydrocarbons that exert significant adverse effects on aquatic ecosystems.

The present study aimed to isolate and identify promising strains of microalgae and cyanobacteria from wastewater collected at the Atyrau Oil Refinery (five sampling sites) and technogenically contaminated areas of Caspi Bitum LLP (Aktau, samples M-13 and M-4) for their subsequent application in bioremediation processes.

A total of 25 cultures of phototrophic microorganisms were isolated from industrial samples. Based on their high growth rates and resistance to petroleum hydrocarbons, 10 of the most promising isolates were selected for further investigation. These included cyanobacteria (*Anabaena* sp., *Nostoc* sp., *Phormidium* sp., *Oscillatoria* sp., *Synechococcus* sp.), green microalgae (*Chlorella* sp., *Tetradesmus* sp., *Desmodesmus* sp., *Pediastrum* sp.), and diatoms *(Navicula* sp.).

During the preliminary screening, the optical density (OD) of the cultures increased from 0.15 to 0.95–1.85 within 14 days of cultivation. Experimental results showed that petroleum hydrocarbon removal efficiency varied from 31% to 88% after 10 days, depending on the wastewater concentration (25%, 50%, and 75%). The highest biodegradation efficiency was achieved at a wastewater concentration of 25%. Among the microalgae, *Chlorella* sp. and *Tetradesmus* sp. demonstrated the greatest potential, reducing petroleum hydrocarbon content by 88% and 84%, respectively. Among the cyanobacteria, *Nostoc* sp. exhibited the highest hydrocarbon degradation capacity, achieving a removal efficiency of 85%. High degradation efficiencies were also observed for *Anabaena* sp. and *Phormidium* sp., which removed 75% and 71% of petroleum hydrocarbons, respectively.

The obtained results indicate the high biotechnological potential of the isolated indigenous microalgal and cyanobacterial cultures for application in biological treatment systems for oil-contaminated industrial wastewater.

**Keywords:** bioremediation, oil-containing wastewater, microalgae, cyanobacteria, petroleum hydrocarbons, biodegradation.

А.А. Даулетова[1], К. Болатхан[1], А.А. Какимова[1], Г.А. Ахметова[1], А. Асқар[1], D. Ozcimen[2], Б.К. Заядан[1*]

[1]Әл-Фараби атындағы Қазақ ұлттық университеті, Алматы, Қазақстан
[2] Йылдыз техникалық университеті, Ыстамбұл, Түркия
*e-mail: zbolatkhan@gmail.com

## Мұнай өңдеу зауыттарының ағынды суларының фототрофты микроорганизмдері және олардың биоремедиациялық әлеуетін зерттеу

Мұнай өңдеу кәсіпорындарының ағынды сулары су экожүйелеріне айтарлықтай теріс әсер ететін улы көмірсутектердің жоғары мөлшерімен сипатталады.

Зерттеу Атырау мұнай өңдеу зауытының ағынды суларынан (5 сынама алу нүктесі) және «Caspi Bitum» ЖШС-нің техногендік ластанған аумақтарынан (Ақтау қ., М-13 және М-4 сынамалары) микробалдырлар мен цианобактериялардың перспективалы штамдарын бөліп алу және сәйкестендіру, сондай-ақ оларды биоремедиация үдерістерінде қолдану мақсатында жүргізілді.

Өндірістік үлгілерден фототрофты микроорганизмдердің 25 культурасы бөлініп алынды. Өсу жылдамдығының жоғары көрсеткіштері мен мұнай көмірсутектерінің әсеріне төзімділігі негізінде әрі қарай зерттеу үшін ең перспективалы 10 изолят таңдап алынды. Олардың қатарында

 © 2026 Al-Farabi Kazakh National University

цианобактериялар (*Anabaena* sp., *Nostoc* sp., *Phormidium* sp., *Oscillatoria* sp., *Synechococcus* sp.), жасыл микробалдырлар (*Chlorella* sp., *Tetradesmus* sp., *Desmodesmus* sp., *Pediastrum* sp.) және диатомды балдырлар (*Navicula* sp.) анықталды.

Алдын ала скрининг барысында дақылдардың оптикалық тығыздығы (OD) 14 тәулік ішінде 0,15-тен 0,95–1,85-ке дейін артты. Эксперимент нәтижелері бойынша мұнай көмірсутектерін жою тиімділігі ағынды су концентрациясына (25%, 50% және 75%) байланысты 10 тәуліктің соңында 31%-дан 88%-ға дейін өзгерді. Биодеградацияның ең жоғары тиімділігі ағынды судың 25% концентрациясында байқалды. Микробалдырлар арасында ең жоғары потенциалды *Chlorella* sp. және *Tetradesmus* sp. көрсетті, олар мұнай өнімдерінің мөлшерін тиісінше 88% және 84%-ға төмендетті. Цианобактериялар арасында мұнай көмірсутектерін ыдыратудың ең жоғары қабілеті *Nostoc* sp. штаммында анықталды, оның тазарту тиімділігі 85%-ды құрады. Сондай-ақ *Anabaena* sp. және *Phormidium* sp. штаммдары жоғары нәтижелер көрсетіп, мұнай көмірсутектерінің тиісінше 75% және 71%-ын жойды.

Алынған нәтижелер мұнаймен ластанған өндірістік ағынды суларды биологиялық тазарту жүйелерінде қолдану үшін бөлініп алынған жергілікті микробалдырлар мен цианобактериялардың жоғары биотехнологиялық әлеуетін көрсетеді.

**Түйін сөздер:** биоремедиация, мұнай құрамды ағынды сулар, микробалдырлар, цианобактериялар, мұнай көмірсутектері, биодеградация.

А.А. Даулетова[1], К. Болатхан[1], А.А. Какимова[1],
Г.А. Ахметова[1], А. Асқар[1], D. Ozcimen[2], Б.К. Заядан[1*]

[1]Казахский национальный университет имени аль-Фараби, Алматы, Казахстан
[2]Технический университет Йылдыз, Стамбул, Турция
*e-mail: zbolatkhan@gmail.com

## Изучение фототрофных микроорганизмов из сточных вод нефтеперерабатывающих заводов и их потенциала в биоремедиации

Сточные воды нефтеперерабатывающих предприятий характеризуются высоким содержанием токсичных углеводородов, оказывающих выраженное негативное воздействие на водные экосистемы.

Исследование было направлено на выделение и идентификацию перспективных штаммов микроводорослей и цианобактерий из сточных вод Атырауского нефтеперерабатывающего завода (5 точек отбора) и техногенно загрязнённых участков ТОО «Caspi Bitum» (г. Актау, пробы М-13 и М-4) для их последующего применения в процессах биоремедиации.

Из промышленных образцов было выделено 25 культур фототрофных микроорганизмов. На основании высоких показателей скорости роста и устойчивости к воздействию нефтяных углеводородов для дальнейшего исследования были отобраны 10 наиболее перспективных изолятов. Среди них идентифицированы цианобактерии (*Anabaena* sp., *Nostoc* sp., *Phormidium* sp., *Oscillatoria* sp., *Synechococcus* sp.), зелёные микроводоросли (*Chlorella* sp., *Tetradesmus* sp., *Desmodesmus* sp., *Pediastrum* sp.) и диатомовые водоросли (*Navicula* sp.).

В процессе предварительного скрининга оптическая плотность (OD) культур увеличилась с 0,15 до 0,95–1,85 в течение 14 суток культивирования. По результатам экспериментов эффективность удаления нефтяных углеводородов исследуемыми культурами к 10-м суткам варьировалась от 31% до 88% в зависимости от концентрации сточных вод (25%, 50% и 75%). Наибольшая эффективность биодеградации была достигнута при концентрации сточных вод 25%. Среди микроводорослей наиболее высокий потенциал продемонстрировали *Chlorella* sp. и *Tetradesmus* sp., обеспечившие снижение содержания нефтепродуктов на 88% и 84% соответственно. Среди цианобактерий наиболее высокой способностью к деградации нефтяных углеводородов характеризовался штамм *Nostoc* sp. с эффективностью очистки 85%. Высокие показатели также были отмечены для *Anabaena* sp. и *Phormidium* sp., обеспечивших удаление 75% и 71% нефтяных углеводородов соответственно.

Полученные результаты свидетельствуют о высоком биотехнологическом потенциале выделенных аборигенных культур микроводорослей и цианобактерий для применения в системах биологической очистки нефтезагрязнённых промышленных сточных вод.

**Ключевые слова:** биоремедиация, нефтесодержащие сточные воды, микроводоросли, цианобактерии, нефтяные углеводороды, биодеградация.

## Introduction

The petroleum refining industry is a major contributor to the world economy, providing fuels, lubricants and the building blocks for the synthesis of petrochemicals. However, this industry is also one of the major sources of anthropogenic environmental pollution. Oil refinery wastewater contains a variety of noxious substances such as sulfur-containing compounds, dissolved solids, high hydrocarbon content, heavy metals and other pollutants which are detrimental to the aquatic ecosystem and human health (Kondaveeti et al., 2023).

Kazakhstan experiences substantial obstacles in managing industrial sewage as a primary oil producer and refiner in Central Asia. Large regional industries like Atyrau Oil Refinery and LLP "Caspi Bitum" in Aktau generate large amounts of extremely polluted wastewater that must be purified before flowing into the environment. The conventional physicochemical treatment methods are widely applied, including flotation, coagulation, adsorption and oxidation, but they have drawbacks such as high energy consumption, high operational costs, secondary pollution and incomplete destruction of complex organics (Bekzhigitov & Zhonova, 2022). Among the modern methods of bioremediation, the use of microalgae and cyanobacteria is remarkable. These microorganisms possess distinctive biochemical traits, notably the capacity to degrade organic xenobiotics and convert into valuable biomass. This biomass then can be served as a feedstock for third-generation biofuels, biofertilizers and feed additives, which lead to integration of wastewater treatment into a circular bioeconomy (Touliabah et al., 2022).

The efficacy of phototrophic bioremediation hinges on the deployment of robust, indigenous microalgae and cyanobacteria strains naturally adapted to site-specific conditions, which frequently outperform strains subjected to induced mutagenesis. At the same time, the native microflora of the arid technogenically stressed ecosystems of western Kazakhstan is poorly studied. The enzymatic capabilities, hydrocarbon tolerance and morphological adaptations of the autochthonous microalgae and cyanobacteria of these areas have been little explored, and comparative studies relating the structural changes of phototrophic bacteria with their functional resistance in the treatment of wastewater are lacking (Kazim et al., 2024; Radelyuk et al., 2019). Filling in these gaps in knowledge is essential to move forward the development of bioremediation technologies adapted to local conditions.

The present work is devoted to the study of phototrophic microbial communities in petroleum-contaminated environments of western Kazakhstan with the purpose of isolating and testing native microalgae and cyanobacteria for wastewater bioremediation. This study aimed to isolate promising microalgae and cyanobacterial cultures from petroleum-contaminated wastewater collected from the Atyrau Oil Refinery (five sampling sites) and technogenically polluted areas of LLP "Caspi Bitum" (Aktau, samples M-13 and M-4). These naturally adapted microalgal and cyanobacterial cultures present significant potential for the engineering of climate-resilient bioremediation systems. Furthermore, the resulting biomass can be valorized into biofuels, aligning industrial wastewater treatment with circular economy principles. The newly isolated axenic cultures were further investigated for their hydrocarbon tolerance and ability to rapidly accumulate biomass under contaminated conditions.

The use of phototrophic microorganisms for the bioremediation of oil-contaminated environments has been a major research area worldwide over the past few decades. Early foundational work by Oswald and Gotaas (1957) demonstrated that phototrophic microorganisms could absorb excess nutrients and stabilize organic loads in conventional sewage, thereby establishing the physiological principles of phycoremediation. Many studies further demonstrated the high potential of microalgae (*Chlorella, Scenedesmus* and *Chlamydomonas*) and cyanobacteria (*Anabaena, Nostoc, Oscillatoria* and *Phormidium*) represent an environmentally sustainable and economically viable approach for the remediation of oil contaminated wastewater (Hamouda et al., 2023; Madhubalaji et al., 2024; Radice et al., 2023; Romero-Lopez et al., 2012) and are currently being used in China, Japan and India (Abdel-Raouf et al., 2012; Pancha et al., 2019).

The microalgal phytoremediation is a sustainable process and reduces the cost of cultivation and produces valuable biofuels and bioproducts (Wang et al., 2024). *Ourococcus*, *Chlamydomonas*, *Scenedesmus*, and *Chlorella* have been reported to be effective in pollutant removal and lipid-rich biomass generation, further capable of producing biodiesel (Kadri et al., 2024). Specifically, *Chlorella vulgaris* serves as a platform for the removal of chemical contaminants from palm oil mill effluents, alongside extensive nitrogen and phosphorus assimilation from municipal wastewater (Khoufi et al., 2015). Photobioreactor systems using robust algal strains are capable of removing 85–90 % of chemical oxygen demand, total pe-

troleum hydrocarbons and hazardous volatile organic compounds from oily waste streams (Abdur Razzak et al., 2024). The polishing mechanism is equally effective in complex multi-stage configurations, where integrating a *Scenedesmus* sp. culture with anaerobic co-digestion and ultrafiltration systems yields highly purified water and extractable industrial biomass (Karray et al., 2022). Although modern phototrophic treatment systems remove 70–90 % of target hydrocarbons, scaling from laboratory to industrial operation is still challenged by the high cost of biomass harvesting and the practical difficulties of mechanical separation.

The current research trends in phycoremediation are mainly focused on the search for efficient phototropic microorganisms and the success of this approach substantially depends on the accurate determination of the physiological and morphological characteristics of cultures under stress conditions (Romero-López et al., 2012). Additionally, cyanobacteria directly isolated from refinery wastewater are able to perform hydrocarbon compounds degradation to survive in harsh environments (Akoijam et al., 2015; Haberle et al., 2020). They can also form consortia that are suspected to be effective against complex pollutants. Microalgal–cyanobacterial consortia are more efficient in degrading petroleum hydrocarbons than monocultures (Hamouda et al., 2023). This has been possible due to several synergistic mechanisms, including photosynthetic oxygenation, co-metabolism, biosurfactant-mediated hydrocarbon emulsification, and mutualistic nutrient exchange. Therefore, stable artificial consortia are considered promising, so screening for hydrocarbon-tolerant cultures requires detailed taxonomic and structural validation at multiple levels.

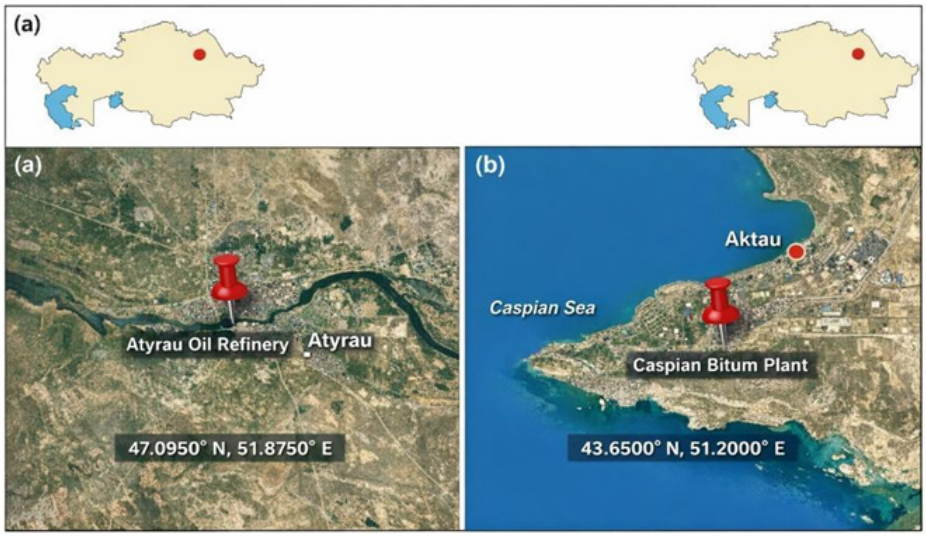
In Kazakhstan, significant advancements have been achieved by local investigators who have determined the ecotoxicological risks of heavy oil fractions on regional water bodies and analyzed multi-stage purification matrices to mitigate industrial hazards (Yernazarova et al., 2021). Microalgae and cyanobacteria in these areas have endured long-term natural selection, yet their enzymatic plasticity and adaptation remain underexplored. Furthermore, there is a lack of comparative data on the link between morphological changes in phototrophic microorganisms and their resistance in petroleum-contaminated wastewater treatment. The study focused on isolating and characterising novel axenic cultures of microalgae and cyanobacteria from petroleum-contaminated wastewater at the Atyrau Oil Refinery and LLP ‘’Caspi Bitum’’ aiming to evaluate their bioremediation potential.

## Materials and methods

### *2.1 Sampling collection*

The subjects of the study were newly isolated axenic cultures of microalgae and cyanobacteria obtained from the oil-polluted wastewater of two oil refineries in western Kazakhstan (fig.1):

**Figure 1**
*Location of the research sites in Kazakhstan*




*(a) Atyrau Oil Refinery (47.0950° N, 51.8750° E, Atyrau); (b) LLP «Caspian Bitum» (43.6500° N, 51.2000° E, Aktau)*

Atyrau Oil Refinery (AOR) (47.0950° N, 51.8750° E, Atyrau): Samples were collected from 5 units accumulating effluents from primary crude oil distillation (ELOU-AT, ELOU-AVT) and atmospheric-vacuum furnaces.

LLP «Caspi Bitum» (43.6500° N, 51.2000° E, Aktau): Material was obtained from technological points M-13 and M-4 within the heavy hydrocarbon contamination area.

Sampling was conducted in the autumn period. The water temperature at the monitoring points ranged from 20 to 25°C and was recorded using an immersion thermometer with a measurement accuracy of ±0.5°C. The pH was determined directly *in situ* using a digital pH meter (HM Digital PH-80, USA) pre-calibrated with standard buffer solutions (pH 4.01, 7.00, and 10.01). Transportation to the laboratory was carried out in thermally insulated containers with cooling packs (18 ± 1°C) for 6 hours.

*2.2 Enrichment and isolation of microalgae and cyanobacteria*

The initial microbiological processing of the samples began no later than 6 hours after collection, which allowed for the preservation of the native structure of the microbiocenosis and the viability of phototrophic microorganisms (Baird et al., 2017). To obtain accumulation cultures, 0.5 mL samples of wastewater were inoculated into sterile Erlenmeyer flasks (250 and 500 mL volumes) containing 100 mL of liquid BG-11 nutrient medium. To ensure optimal gas exchange and aeration, the medium-to-flask volume ratio was kept at 1:5 and 1:10.

Agarized media blocks were used to isolate axenic cultures via the streak-plate method. Individual colonies were identified and selected based on distinctive morphological diagnostic criteria such as colouration, geometry, and colony consistency. Pure cultures were maintained in a range of selective and universal media: BG-11, Tamiya, Gromova, BBM, F/2, and Zarrouk (Zayadan et al., 2013). Culture purity and axenicity were strictly verified by subculturing isolates onto meat-peptone agar (MPA). The total absence of heterotrophic bacterial or fungal growth following incubation at 30°C for 48–72 hours served as the verification metric for culture purity, supplemented by regular phase-contrast microscopic monitoring to confirm structural homogeneity.

*2.3 Characteristics of Isolated Microorganisms*

The experimental objects comprised 10 novel isolated cultures of cyanobacteria and microalgae. The cyanobacteria group was represented by the genera *Anabaena* sp., *Nostoc* sp., *Phormidium* sp., *Oscillatoria* sp., and *Synechococcus* sp. The green microalgae group (*Chlorophyta*) included *Chlorella* sp., *Tetradesmus* sp., *Desmodesmus* sp., and *Pediastrum* sp. Additionally, the isolates included diatoms represented by the genus *Navicula* sp.

*2.4 Cultivation and growth monitoring*

Cultivation was carried out in a KS-200 SPU luminescent chamber (Russia) at a temperature of 25±1°C, with a light intensity of 55 µmol photons·$m^{-2}$·$s^{-1}$ and a photoperiod of 12 h light:12 h dark (Zayadan et al., 2013). Primary growth was recorded after 7–10 days. Growth dynamics were assessed every 48 hours using UV-VIS-15 spectrophotometer. To ensure accurate biomass assessment and minimize interference from photosynthetic pigments, the optical density (OD) of green microalgae, diatoms, and cyanobacteria was measured at 750 nm.

*2.5 Bioremediation experiments*

Bioremediation experiments were conducted in triplicate using 250 mL Erlenmeyer flasks containing 100 mL of sterilized wastewater at different dilution levels (25%, 50%, 75%, and undiluted oil-contaminated wastewater). The operational volume was limited to 100 mL to ensure an adequate head space and optimal gas exchange. Each flask was inoculated with 10 mL of actively growing and pre-adapted microalgal or cyanobacterial culture prepared according to the procedure described in Section 2.4.

All experiments were performed in a controlled climate chamber under identical environmental conditions for 10 days. The cultures were maintained at a constant temperature of 25°C and a 16:8 h light:dark photoperiod, under a light intensity ranging from 40 to 55 µmol photons·$m^{-2}$·$s^{-1}$ with continuous agitation on an orbital shaker at 120 rpm. The bioremediation efficiency was evaluated by determining the degradation of petroleum hydrocarbons at the end of the cultivation period.

Following 14 days of incubation, to account for both bio-absorbed and dissolved fractions, residual petroleum hydrocarbons were extracted directly from the whole culture broth (including biomass). Hexane was used as the organic solvent at a solvent-to-sample volumetric ratio of 1:5 (22 mL of hexane per 110 mL of the total mixture). The mixture was vigorously shaken for 15 min to ensure efficient extraction of hydrocarbon compounds. Subsequently,

the phases were separated by centrifugation at 4,000 rpm for 15 min. The concentration of residual petroleum hydrocarbons in the resulting organic phase (hexane supernatant) was determined spectrophotometrically at a wavelength of 254 nm according to the method described by Lurie (1984).

The hydrocarbon degradation efficiency (HDE, %) was calculated using the following equation:

$$HDE\ (\%) = C_0 - C_{10}/C_0 x100$$

Where $C_0$ is the initial concentration of petroleum hydrocarbons in the wastewater (mg\ $L^{-1}$), and $C_{10}$ is the residual concentration of petroleum hydrocarbons after 10 days of bioremediation (mg\ $L^{-1}$).

*2.6 Statistical Analysis*

All tests were carried out in triplicate, and the results were reported with standard error of the mean (SEM). Data analysis and charting were performed using Microsoft Excel (MS 2016), and one-way analysis of variance (ANOVA) followed by Duncan's multiple range test at a significance level of $p \leq 0,05$ using SPSS software (version 16.0) (Minitab LLC, 2019).

## Results and discussion

*3.1 Screening, Isolation, and Taxonomic Diversity of Phototrophic Isolates*

Comprehensive screening of petroleum-contaminated wastewater samples collected from industrial facilities in Western Kazakhstan enabled the isolation and purification of 25 axenic cultures of phototrophic microorganisms. Of the total isolates, 16 pure cultures were obtained from five technological units of the Atyrau Oil Refinery (AOR), while the remaining 9 cultures were isolated from sites heavily contaminated with petroleum products (samples M-13 and M-4) at LLP "Caspi Bitum" in Aktau city. Taxonomic analysis of the isolated microorganisms revealed (fig 2) the predominance of microalgae and cyanobacteria in the investigated petroleum-contaminated wastewater samples (table 1).

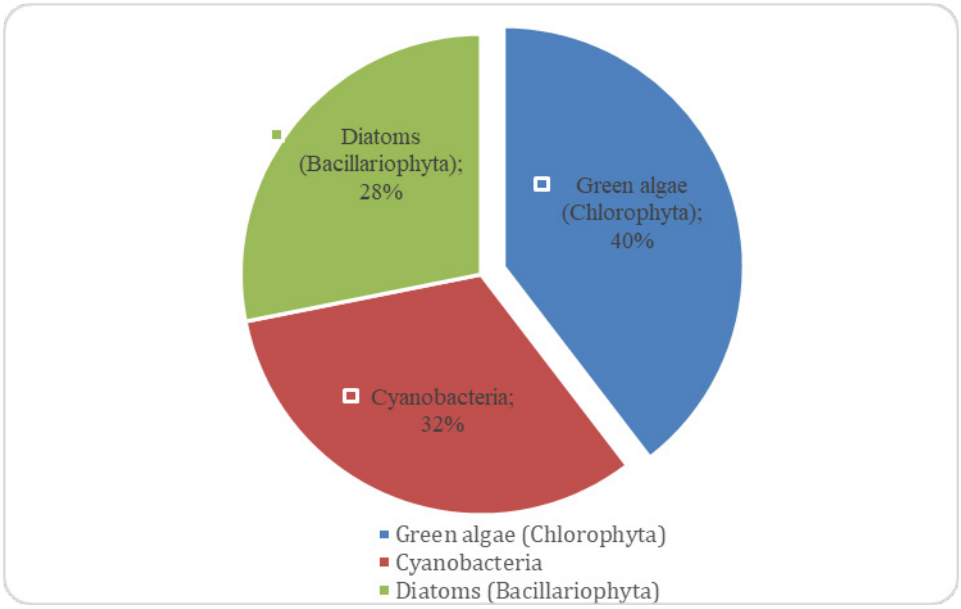
**Table 1**

*Sampling sites and composition of isolated microalgae and cyanobacterial cultures from oil-contaminated wastewater in Western Kazakhstan*

| № | Sampling Site | Coordinates | Sampling Month | Sample Type | Isolated Cultures |
|---|---|---|---|---|---|
| 1 | Atyrau Oil Refinery (AOR), Atyrau Region | 47.0950° N, 51.8750° E | October | Oil-contaminated wastewater | Cyanobacteria: *Anabaena* sp., *Nostoc* sp., *Oscillatoria* sp.; Green microalgae: *Chlorella* sp., *Tetradesmus* sp.; Diatoms: *Navicula* sp |
| 2 | LLP «Caspian Bitum» Mangystau Region (Aktau) | 43.6500° N, 51.2000° E | October | Oil-contaminated wastewater | Cyanobacteria: *Phormidium* sp., *Oscillatoria* sp., *Synechococcus* sp.; Green microalgae: *Desmodesmus* sp., *Pediastrum* sp., Diatoms: *Navicula* sp |

Green microalgae (*Chlorophyta*), namely *Chlorella* sp., *Tetradesmus* sp., *Desmodesmus* sp., and *Pediastrum* sp., made up 40% of the isolated cultures. Cyanobacteria accounted for 32% of isolates and were mainly represented by filamentous forms such as *Phormidium* sp., *Oscillatoria* sp., *Anabaena* sp., *Nostoc* sp., and unicellular *Synechococcus* sp., which were mainly found in samples from LLP "Caspi Bitum." Diatoms (*Bacillariophyta*) accounted for 28% of isolates and were mainly represented by *Navicula* sp. The results show that the species are highly tolerant to hydrocarbon pollution. The numerical dominance of filamentous cyanobacteria in wastewater containing bitumen is probably associated with the presence of a strong cell wall in these microorganisms and their ability to produce extracellular polymeric substances (EPS), which reduce the toxicity of petroleum products. In addition, the detection of *Chlorella* sp. The technological units of the Atyrau Oil Refinery demonstrate that these microalgae are adaptable and possess efficient enzymatic systems under the influence of petroleum hydrocarbons.

**Figure 2**
*Taxonomic structure and percentage distribution of phototrophic microorganism groups isolated from oil-contaminated wastewater of AOR and LLP "Caspi Bitum"*




*3.2 Validation of the Axenic Nature of Isolated Cultures and Morphological Features*

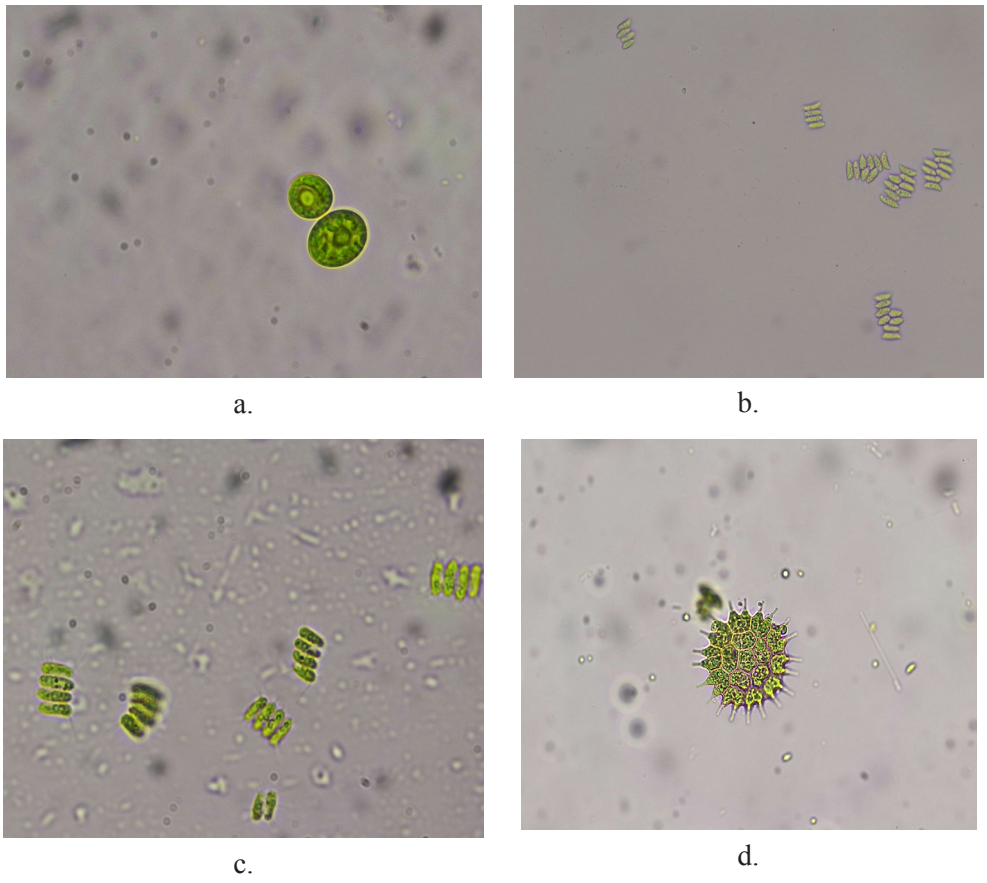
The purity of microalgae and cyanobacteria cultures was tested for all ten isolates by the meat-peptone agar (MPA) plating method. After incubation at 30°C for 48–72 h, no growth of foreign bacterial and fungal microflora was detected, confirming the axenicity of cultures. However, conventional plate tests have their limitations and more rigorous cultivation-independent methods are required for definitive verification of axenicity. Microscopic examination confirmed the uniformity of cells within the studied monocultures (Prescott, 1973).

Microalgal and cyanobacterial cultures were identified morphologically by means of an optical light microscope (MicroOptix MX 300T, Austria) with a digital camera for visualization. Morphological analysis is a conventional first step in the identification of microalgae and focuses on size, shape and cellular structures. These observations contributed to the description of cytological features of the isolates and showed adaptive changes due to prolonged exposure to petroleum hydrocarbons. Microalgae have shown tolerance to oil contamination through physiological acclimatization, where exposure to petroleum derivatives can induce cell wall thickening and accumulation of protective compounds, thereby forming a barrier against the oil toxicity. Moreover, stress conditions have been linked to changes in cell shape and organelle structure during acclimation, as well as the dynamic accumulation of lipid bodies as a stress response.

In the isolates obtained from the wastewater of an oil refinery, *Chlorella* sp. cells preserved their spherical or broadly ellipsoidal morphology, with the average cell diameter increasing by 15 to 20% (from 4,5 to 7,0 μm). It was observed in fig 3.a that cell walls were thickened and lipid inclusions formed in the cytoplasm, which perform a protective function in relation to petroleum products. The chloroplasts maintained a uniform bright green colour during the process (Guiry & Guiry, 2026).

As seen in fig 3.b and 3.c, the cells had a typical spindle-shaped or slightly curved form with pointed ends and formed coenobia of 4–8 cells being a distinct feature of *Tetradesmus* sp. and *Desmodesmus* sp. microalgae. Under oil stress conditions, there was an intense accumulation of lipid inclusions; however, the overall structure of the colonies wasn't show any visible deformations. Under the influence of petroleum hydrocarbons, there is no visible colony deformations observed in the fig 3.d; however, a moderate increase in cell size and the accumulation of lipid inclusions in the cytoplasm were noted, which indicates the culture's adaptation to stressful environmental conditions (Jacinto et al., 2023) *Pediastrum* sp. cultures formed characteristic flat star-shaped coenobia with a dense arrangement of cells.

**Figure 3**
*Microphotography of axenic culture of green microalgae*



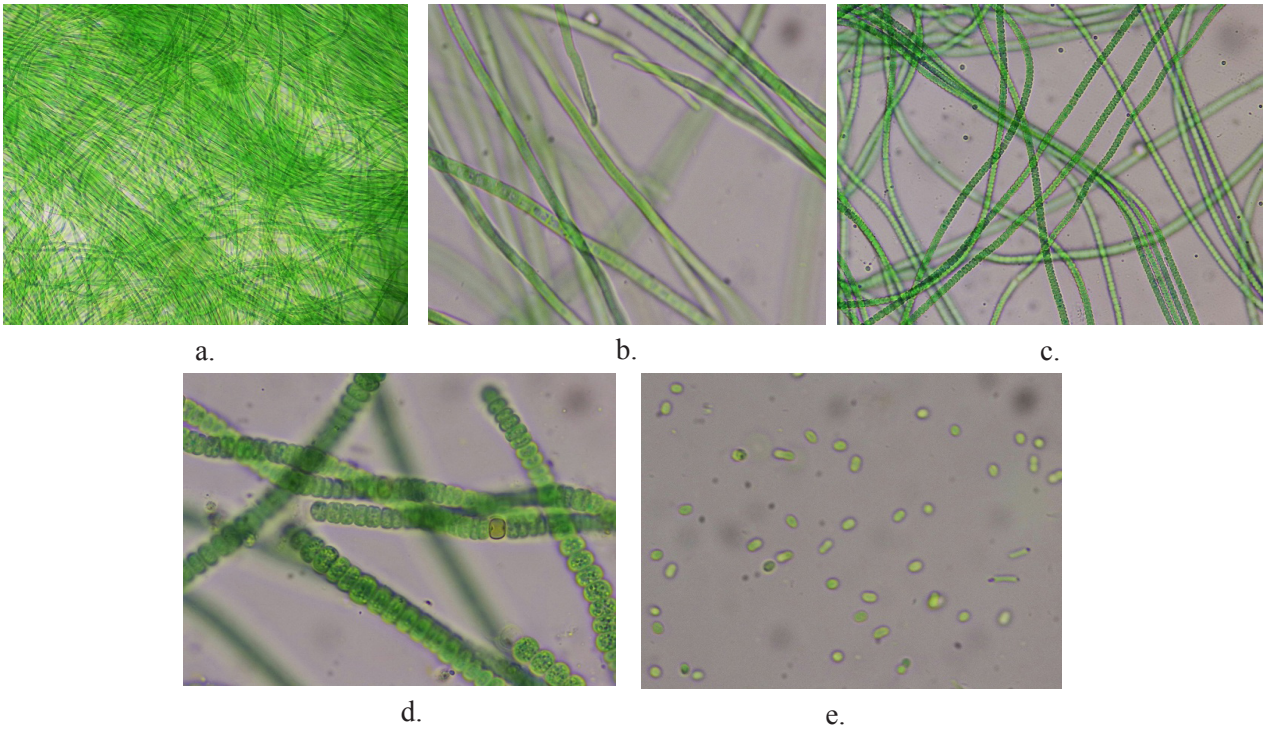

*A – Chlorella sp.; B – Tetradesmus sp; C – Desmodesmus sp.; D – Pediastrum sp.; under x100 magnification*

*Phormidium* sp. and *Oscillatoria* sp. have filamentous forms consisting of cylindrical cells united into long unbranched trichomes with a diameter of 3,5–6,0 µm. Isolates from Caspi Bitum LLP exhibited active formation of mucous sheaths due to the secretion of exopolysaccharides (Zutshi & Fatma, 2015) . The fig 4.c showed that the *Anabaena* sp has filamentous forms (trichomes) consisting of chains of rounded and barrel-shaped vegetative cells. The filaments' structure consist of well-defined heterocyst – specialized cells responsible for atmospheric nitrogen fixation. The ability to fix nitrogen provides high competitiveness and stable growth in the wastewater of oil refineries, which are often characterized by an imbalance and deficiency of available biogenic elements (Zutshi & Fatma, 2015).

The *Nostoc* sp. culture is characterized macroscopically and microscopically by the formation of chain structures of rounded cells, among which intercalary heterocyst are regularly localized. Under hydrocarbon stress conditions, a key feature observed in this isolates is the formation of an abundant extracellular mucus sheath. The dense exopolysaccharide coat acts as a protective biobarrier: it is effectively localised. and binds oil components at the periphery, preventing their direct toxic impact on cell membranes. It is the presence of a developed mucous matrix that determines the high tolerance of the culture and its ability to selectively degrade complex, high-molecular-weight hydrocarbon fractions (Rippka et al., 1979).

The *Synechococcus* sp. cells had a rod-shaped or oval form measuring 2.0–4.5 µm. Under the influence of heavy bitumen fractions, a slight increase in size and local bending of the cells was observed; however, the ability to actively divide was maintained.

**Figure 4**
*Microphotography of axenic culture of cyanobacteria*




*A –Phormidium sp; B – Oscillatoria sp.; C – Anabaena sp; D – Nostoc sp.; E – Synechococcus sp; under x100 magnification*

The cells in fig 4.f were solitary, with a typical symmetrical boat-shaped form. The well-defined siliceous shell in *Navicula* sp served a protective function, limiting the impact of toxic oil components. The internal structure of the cells and the distribution of pigments remained unchanged (Round et al., 1990).

**Figure 5**
*Microphotography of axenic culture of diatom*



*Note: Navicula sp under x100 magnification*

The isolated cultures ability to change their properties and appearance demonstrates their exceptional adaptation to harsh living conditions. These phototrophic microorganisms are a promising raw material for biotechnology due to their high resilience. They can be effectively used for the synthesis of beneficial substances, the production of biofuels and the treatment of oil-contaminated wastewater.

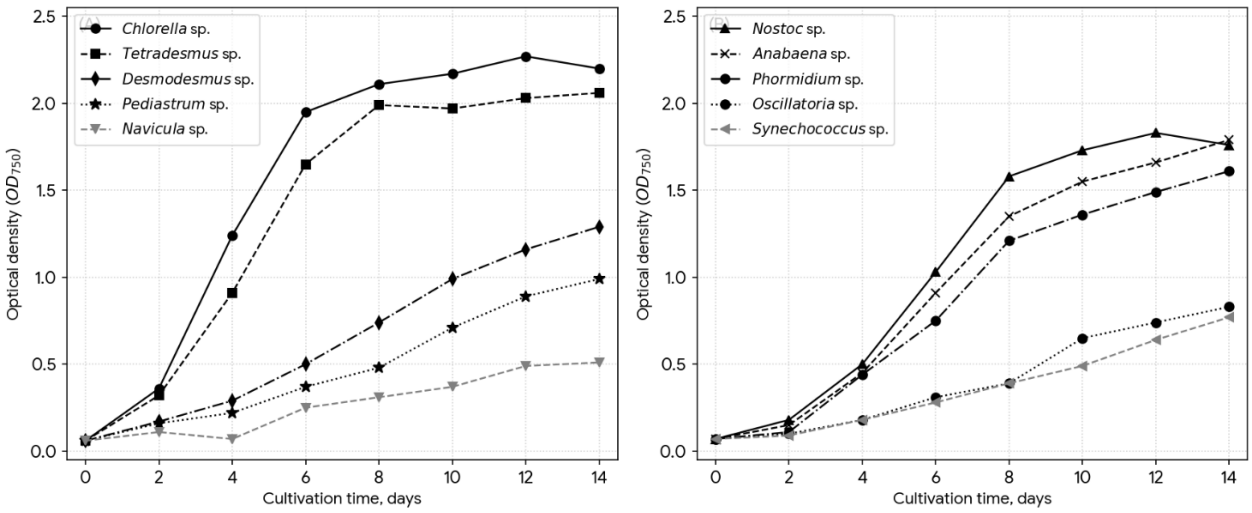
*3.3 Screening of Isolated Pure Cultures of Microalgae and Cyanobacteria*

For screening the most productive isolates for the treatment of oil-contaminated wastewater, the growth dynamics of isolated microalgae and cyanobacteria cultures were studied. The growth of microalgae and cyanobacteria was evaluated by the change in optical density at a wavelength of 750 nm over a 14-day cultivation period.

During the laboratory experiment, the highest growth rate and intense biomass accumulation were demonstrated by the green microalgae cultures *Chlorella* sp. and *Tetradesmus* sp., which reached maximum optical density values ($OD_{750}$>2.0) by 12-14 days. Notably, *Nostoc* sp., *Anabaena* sp., and *Phormidium* sp. displayed stable growth profiles, en-

tering the stationary phase by the end of the experiment with elevated optical density values ($OD_{750}$ = 1,6–1,8). In contrast, cultures of *Desmodesmus* sp., *Pediastrum* sp., and *Navicula* sp. ($OD_{750}$), alongside the cyanobacteria *Oscillatoria* sp. and *Synechococcus* sp. ($OD_{750}$), exhibited moderate growth dynamics, with final optical density values stabilizing within a narrow range of 0,5 to 1,3.

**Figure 6**
*The growth dynamics of microalgae and cyanobacteria isolates from oil refinery wastewater*




*Note: On the x-axis – 0, 2, 4, 6, 8, 10, 12, 14 – days of cultivation; on the y-axis – optical density (OD). a – microalgae genera monitored by ($OD_{750}$); b – cyanobacteria genera monitored by ($OD_{750}$).*

*3.4 Degradation efficiency of pure cultures of microalgae and cyanobacteria in oil-contaminated wastewater*

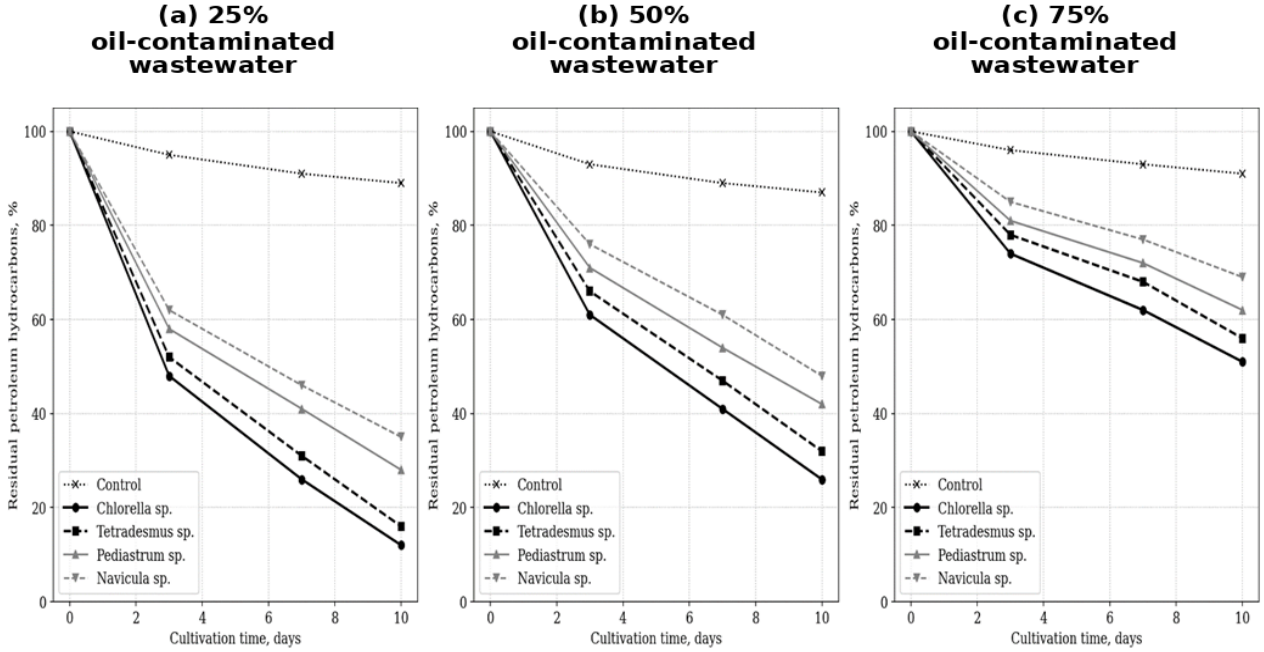
The degradation efficiency toward petroleum hydrocarbons by pure cultures of microalgae (*Pediastrum* sp., *Navicula* sp., *Chlorella* sp., *Tetradesmus* sp.) and cyanobacteria (*Oscillatoria* sp., *Synechococcus* sp., *Nostoc* sp., *Anabaena* sp., *Phormidium* sp.) was evaluated spectrophotometrically (Fig. 7, 8).

The dynamics of petroleum hydrocarbon removal during the cultivation of the microalgal strains *Chlorella* sp., *Tetradesmus* sp., *Pediastrum* sp., and *Navicula* sp. were investigated over a 10-day period (Figure 7). The obtained results demonstrated that the treatment efficiency depended both on the microalgal species and the degree of wastewater dilution.

At a wastewater concentration of 25%, all studied cultures exhibited the highest petroleum hydrocarbon degradation efficiency (Figure 7a). The most intensive reduction in pollutant concentration occurred during the first three days of cultivation, after which the purification process proceeded more gradually. *Chlorella* sp. showed the highest efficiency, reducing the residual petroleum hydrocarbon content to 12% by the end of the experiment, corresponding to a removal efficiency of 88%. Similar results were obtained for *Tetradesmus* sp., which achieved an 84% removal efficiency with a residual hydrocarbon content of 16%. *Pediastrum* sp. and *Navicula* sp. were less effective, leaving residual pollutant levels of 28% and 35%, corresponding to removal efficiencies of 72% and 65%, respectively.

Increasing the wastewater concentration to 50% resulted in a decline in treatment efficiency due to the enhanced toxic effects of pollutants on microalgal cells (Figure 7b). Nevertheless, *Chlorella* sp. and *Tetradesmus* sp. maintained high degradative activity. *Chlorella* sp. achieved a petroleum hydrocarbon removal efficiency of 74%, leaving a residual concentration of 26%. *Tetradesmus* sp. provided 68% degradation, with 32% of the initial hydrocarbon content remaining in the medium. In contrast, *Pediastrum* sp. and *Navicula* sp. exhibited noticeable inhibition of growth and metabolic activity, resulting in residual petroleum hydrocarbon levels of 42% and 48%, respectively.

**Figure 7**
*The effect of wastewater dilution on residual petroleum product content (%) during treatment with microalgae*




*Note: x-axis – cultivation time, days; y-axis – residual petroleum hydrocarbons, %. Wastewater dilution: (a) 25%; (b) 50%; (c) 75%. Control – untreated wastewater from an oil refinery corresponding to the dilution (without culture)*

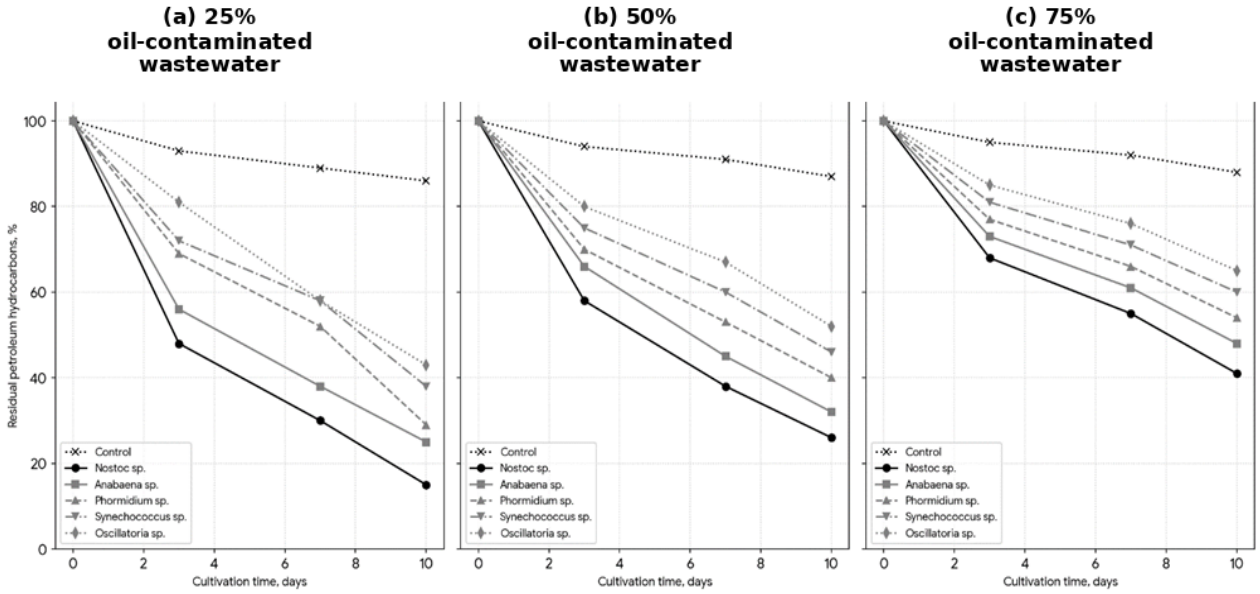
At the highest wastewater concentration (75%), the inhibitory effect of pollutants became significantly stronger, leading to a further decline in treatment efficiency across all experimental variants (Figure 7c). *Chlorella* sp. proved to be the most resistant strain, achieving 49% petroleum hydrocarbon degradation and leaving a residual concentration of 51%. *Tetradesmus* sp. demonstrated a removal efficiency of 44%. *Pediastrum* sp. and *Navicula* sp. were the most sensitive to pollutant toxicity, exhibiting degradation efficiencies of only 38% and 31%, respectively. As a result, more than 60% of the initial pollutant load remained in the medium by the end of the experiment.

In the control variants (wastewater without the addition of microalgae), no significant reduction in petroleum hydrocarbon content was observed during the 10-day period. The natural loss of petroleum products, mainly due to evaporation and abiotic transformation processes, amounted to only 9–13%, while the residual pollutant content remained within the range of 87–91%. These results indicate that the introduced microalgal cultures played the principal role in petroleum hydrocarbon degradation in the experimental systems.

The dynamics of residual petroleum hydrocarbon content during the cultivation of the cyanobacterial strains *Nostoc* sp., *Anabaena* sp., *Phormidium* sp., *Synechococcus* sp., and *Oscillatoria* sp. under different wastewater concentrations (25%, 50%, and 75%) over a 10-day period are presented in Figure 8.

At a wastewater concentration of 25%, the most intensive petroleum hydrocarbon biodegradation was observed (Figure 8a). *Nostoc* sp. exhibited the highest treatment efficiency among all tested strains. By the 10th day of cultivation, the residual petroleum hydrocarbon content had decreased to only 15%, corresponding to a removal efficiency of 85%. High degradative activity was also demonstrated by *Anabaena* sp., which reduced the hydrocarbon content by 75%, leaving a residual concentration of 25%. The removal efficiencies of *Phormidium* sp. and *Synechococcus* sp. reached 71% and 62%, respectively. The lowest degradation efficiency was recorded for *Oscillatoria* sp., which achieved a removal efficiency of 57%, leaving 43% of the hydrocarbons undegraded. In the control variant, the reduction in petroleum hydrocarbon concentration did not exceed 14%, and the residual pollutant content remained at 86%.

**Figure 8**
*The effect of wastewater dilution on residual petroleum product content (%) during treatment with cyanobacteria*




*Note: x-axis – cultivation time, days; y-axis – residual petroleum hydrocarbons, %. Wastewater dilution: (a) 25%; (b) 50%; (c) 75%. Control – untreated wastewater from an oil refinery corresponding to the dilution (without culture)*

When the wastewater concentration was increased to 50%, biodegradation efficiency declined due to the increased toxic load; however, *Nostoc* sp. and *Anabaena* sp. maintained their leading positions (Figure 8b). *Nostoc* sp. reduced the petroleum hydrocarbon concentration by 74%, leaving only 26% of the initial pollutant load in the medium. *Anabaena* sp. demonstrated a removal efficiency of 68%, with a residual hydrocarbon content of 32%. The treatment efficiencies of *Phormidium* sp. and *Synechococcus* sp. were 54% and 60%, respectively. The lowest efficiency was again observed for *Oscillatoria* sp., which degraded 48% of the petroleum hydrocarbons, leaving 52% of the pollutants in the medium.

At the highest wastewater concentration (75%), pronounced inhibition of cyanobacterial metabolic activity was observed, resulting in a further decline in treatment efficiency (Figure 8c). *Nostoc* sp. remained the most resistant strain to toxic stress, achieving 59% petroleum hydrocarbon degradation and leaving a residual pollutant content of 41%. *Anabaena* sp. demonstrated a removal efficiency of 52%, leaving 48% of the initial hydrocarbon content in the medium. For *Phormidium* sp., *Synechococcus* sp., and *Oscillatoria* sp., the removal efficiencies were 46%, 40%, and 35%, respectively. Consequently, the residual petroleum hydrocarbon content in these variants ranged from 54% to 65%. In the control variant, the reduction in petroleum hydrocarbon concentration amounted to only 12%, indicating the negligible contribution of natural self-purification processes to hydrocarbon removal.

## Conclusion

In this study, 25 cultures of phototrophic microorganisms were isolated from oil-contaminated wastewater collected from industrial enterprises of Western Kazakhstan (Atyrau Oil Refinery and Caspi Bitum LLP). Based on their high growth rates and resistance to petroleum hydrocarbons, 10 of the most promising isolates representing green microalgae, cyanobacteria, and diatoms were selected for further investigation. Microscopic analysis revealed several morphological adaptations of the studied strains to petroleum contamination, including cell wall thickening, accumulation of lipid inclusions, and the formation of protective exopolysaccharide structures. During the preliminary screening, the optical density (OD) of the cultures increased from an initial value of 0.15 to 0.95–1.85, depending on the strain.

Bioremediation experiments demonstrated that the highest petroleum hydrocarbon removal efficiency was achieved at a wastewater concentration

of 25%. The greatest degradation efficiencies over the 10-day cultivation period were exhibited by the green microalgae *Chlorella* sp. and *Tetradesmus* sp., with removal efficiencies of 88% and 84%, respectively, as well as by the cyanobacteria *Nostoc* sp. and *Anabaena* sp., which removed 85% and 75% of petroleum hydrocarbons, respectively. These findings indicate the high biotechnological potential of the isolated indigenous phototrophic strains for the bioremediation of oil-contaminated wastewater. In the future, these cultures may serve as the basis for developing stable algal–cyanobacterial consortia for environmentally friendly industrial wastewater treatment systems, with the additional benefit of producing biomass suitable for conversion into biofuels and other valuable bioproducts.

**Acknowledgments**

This work was supported by grant AP23485836, «Development of technology for bioremediation of petroleum-contaminated wastewater based on an algal-cyanobacterial consortium for potential biofuel production» (2024-2026), funded by the Ministry of Higher Education and Science of the Republic of Kazakhstan.

**Funding**

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan within the framework of project AP23485836.

***Author contribution***

*A.A. Dauletova: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing; K. Bolatkhan: Project administration, Funding acquisition, Validation; A.A. Kakimova: Language editing, Writing – review & editing; G.A. Akhmetova: ORCID registration, Software; A. Askar: Software, Language editing, Writing – review & editing; D. Ozcimen: Methodology, Scientific supervision; B.K. Zayadan: Conceptualization, Scientific supervision, Funding acquisition, Writing – review & editing.*

**References**

Abdel-Raouf, N., Al-Homaidan, A. A., & Ibraheem, I. B. M. (2012). Microalgae and wastewater treatment. *Saudi Journal of Biological Sciences*, *19*(3), 257–275. https://doi.org/10.1016/j.sjbs.2012.04.005

Abdur Razzak, S., Bahar, K., Islam, K. O., Haniffa, A. K., Faruque, M. O., Hossain, S. Z., & Hossain, M. M. (2024). Microalgae cultivation in photobioreactors: Sustainable solutions for a greener future. *Green Chemical Engineering*, *5(4)*, 418–439. https://doi.org/10.1016/j.gce.2023.10.004

Akoijam, C., Langpoklakpam, J. S., Chettri, B., & Singh, A. K. (2015). Cyanobacterial diversity in hydrocarbon-polluted sediments and their possible role in bioremediation. *International Biodeterioration & Biodegradation*, *103*, 97–104. https://doi.org/10.1016/j.ibiod.2015.03.035

Al-Jabri, H., Das, P., Khan, S., Thaher, M., & AbdulQuadir, M. (2020). Treatment of wastewaters by microalgae and the potential applications of the produced biomass–A review. *Water*, *13*(1), 27. https://doi.org/10.3390/w13010027

Baird, R. B., Eaton, A. D., & Rice, E. W. (Eds.). (2017). Standard methods for the examination of water and wastewater (23rd ed.). American Public Health Association.

Bekzhigitov, E. T., & Zhonova, Sh. E. (2022). Work experience of the LLP "JV" CASPI BITUM" in prevention of environmental risks. *Hydrometeorology and Ecology*, *106*(3), 49–55.

Griffiths, M. J., Garcin, C., van Hille, R. P., & Harrison, S. T. L. (2011). Interference by pigment in the estimation of microalgal biomass concentration by optical density. *Journal of Microbiological Methods*, *85*(2), 119–123. https://doi.org/10.1016/j.mimet.2011.02.005

Guiry, M. D., & Guiry, G. M. (2026). *AlgaeBase*. https://www.algaebase.org

Haberle, I., Hrustić, E., Petrić, I., Pritišanac, E., Šilović, T., Magić, L., Geček, S., Budiša, A., & Blažina, M. (2020). Adriatic cyanobacteria potential for cogeneration biofuel production with oil refinery wastewater remediation. *Algal Research*, *50*, 101978. https://doi.org/10.1016/j.algal.2020.101978

Hamouda, A. A., Alhumairi, A. M., & Saddiq, A. A. (2023). Simultaneous bioremediation of petroleum hydrocarbons and production of biofuels by the micro-green alga, cyanobacteria, and its consortium. *Heliyon*, *9*(6), e16656. https://doi.org/10.1016/j.heliyon.2023.e16656

Jacinto, G. S. S., Cruz, G., Cabral, A. A., Bezerra, G. V. P., Peña Garcia, R. R., Magalhães, U. N., & Gomes, W. C. (2023). Biotechnological investigation of *Pediastrum boryanum* and *Desmodesmus subspicatus* microalgae species for a potential application in bioenergy. *Algal Research*, *75*, 103266. https://doi.org/10.1016/j.algal.2023.103266

Kadri, M. S., Nayana, K., Fassi Fihri, R., Abdi, G., Sukumar, C., & Kulanthaiyesu, A. (2024). Greening the oil industry: Microalgae biorefinery for sustainable oil-produced water treatment and resource recovery. *Journal of Water Process Engineering*, *60*, 105259. https://doi.org/10.1016/j.jwpe.2024.105259

Karray, R., Elloumi, W., Ben Ali, R., Loukil, S., Chamkha, M., Karray, F., & Sayadi, S. (2022). A novel bioprocess combining anaerobic co-digestion followed by ultra-filtration and microalgae culture for optimal olive mill wastewater treatment. *Journal of Environmental Management*, *303*, 114188. https://doi.org/10.1016/j.jenvman.2021.114188

Kazim, M., Dauletova, A., Sandybayeva, S., Bukharbayeva, Z., & Zayadan, B. (2024). Isolation and study of cyanobacterial cultures from oil refinery wastewaters. *BIO Web of Conferences*, *100*, 02019. https://doi.org/10.1051/bioconf/202410002019

Khoufi, S., Louhichi, A., & Sayadi, S. (2015). Optimization of anaerobic co-digestion of olive mill wastewater and liquid poultry manure in batch condition and semi-continuous jet-loop reactor. *Bioresource Technology*, *182*, 67–74. https://doi.org/10.1016/j.biortech.2015.01.092

Kondaveeti, S., Govindarajan, D., Mohanakrishna, G., Thatikayala, D., Abu-Reesh, I. M., Min, B., Nambi, I. M., Al-Raoush, R. I., & Aminabhavi, T. M. (2023). Sustainable bioelectrochemical systems for bioenergy generation via waste treatment from petroleum industries. *Fuel*, *331*, 125632. https://doi.org/10.1016/j.fuel.2022.125632

Lurie, Yu. Yu. (1984). *Analiticheskaya khimiya promyshlennykh stochnykh vod* [Analytical chemistry of industrial wastewater]. Khimiya. (In Russian)

Madhubalaji, C. K., Reddy, M. M. S., Chauhan, V. S., & Sarada, R. (2024). Petrochemical wastewater remediation by microalgae. In G. A. Ravishankar, A. R. Rao, S. K. Kim (Eds.), *Algae mediated bioremediation: Industrial prospectives* (pp. 439–456). Wiley.

Minitab LLC (2019). *Minitab Statistical Software* (Version 19). https://www.minitab.com

Oswald, W. J., & Gotaas, H. B. (1957). Photosynthesis in sewage treatment. Transactions of the American Society of Civil Engineers, 122(1), 73-97.

Pal, S., Banat, F., Almansoori, A., & Abu Haija, M. (2016). Review of technologies for biotreatment of refinery wastewaters: progress, challenges and future opportunities. *Environmental Technology Reviews*, *5*(1), 12–38. https://doi.org/10.1080/21622515.2016.1164252

Pancha, I., Chokshi, K., & Mishra, S. (2019). Industrial wastewater-based microalgal biorefinery: A dual strategy to remediate waste and produce microalgal bioproducts. In S. K. Gupta & F. Bux (Eds.), *Application of microalgae in wastewater treatment: Volume 2. Biorefinery approaches of wastewater treatment* (pp. 173–193). Springer. https://doi.org/10.1007/978-3-030-13909-4_8

Radelyuk, I., Tussupova, K., Zhapargazinova, K., Yelubay, M., & Persson, M. (2019). Pitfalls of wastewater treatment in oil refinery enterprises in Kazakhstan–A system approach. *Sustainability*, *11*(6), 1618. https://doi.org/10.3390/su11061618

Radice, R. P., De Fabrizio, V., Donadoni, A., Scopa, A., & Martelli, G. (2023). Crude oil bioremediation: From bacteria to microalgae. *Processes*, *11*(2), 442. https://doi.org/10.3390/pr11020442

Rippka, R., Stanier, R. Y., Deruelles, J., Herdman, M., & Waterbury, J. B. (1979). Generic assignments, strain histories and properties of pure cultures of cyanobacteria. *Microbiology*, *111*(1), 1–61. https://doi.org/10.1099/00221287-111-1-1

Romero-Lopez, J., Lopez-Rodas, V., & Costas, E. (2012). Estimating the capability of microalgae to physiological acclimatization and genetic adaptation to petroleum and diesel oil contamination. *Aquatic Toxicology*, *124–125*, 227–237. https://doi.org/10.1016/j.aquatox.2012.08.001

Round, F. E., Crawford, R. M., & Mann, D. G. (1990). *The diatoms: Biology and morphology of the genera*. Cambridge University Press.

Touliabah, H. E. S., El-Sheekh, M. M., Ismail, M. M., & El-Kassas, H. (2022). A review of microalgae- and cyanobacteria-based biodegradation of organic pollutants. *Molecules*, *27*(3), 1141. https://doi.org/10.3390/molecules27031141

Wang, R., Zhu, W., Sun, J., Zhang, C., Dai, H., & Qu, T. (2024). Novel three-stage microalgal cultivation system for lipid production utilizing nutrients derived from refinery waste. *Bioresource Technology*, *414*, 131623. https://doi.org/10.1016/j.biortech.2024.131623

Yernazarova, G. I., Bukharbayeva, Zh. M., Zayadan, B. K., Turasheva, S. K., & Omarova, G. K. (2021). Development of technology for biological treatment of oily wastewater with a consortium of microorganisms, microalgae and aquatic plants. *Bulletin of the Karaganda University "Biology medicine geography Series"*, *102*(2), 30–36. https://doi.org/10.31489/2021bmg2/30-36

Zayadan, B. K., Akmukhanova, N. R., & Sadvakasova, A. K. (2013). *Kollektsiya mikrovodorosley i metody ikh kul'tivirovaniya* [Collection of microalgae and methods for their cultivation]. Liter. (In Russian)

Zutshi, S., & Fatma, T. (2015). Cyanobacteria. In D. Sahoo & J. Seckbach (Eds.), *The Algae World* (pp. 57–89). Springer. https://doi.org/10.1007/978-94-017-7321-8_3

***Information about the authors:***

*Dauletova Aliyam – PhD student in the Department of biotechnology of the Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: dauletova.aliyam13@gmail.com).*

*Bolatkhan Kenzhegul – PhD, associate professor in the Department of biotechnology of the Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: bkenzhegul23@gmail.com).*

*Kakimova Ardak – PhD, Senior Lecturer in the Department of biotechnology of Al-Farabi Kazakh National University, Associate Professor at the Kazakh National Research Technical University named after K. I. Satbayev (Almaty, Kazakhstan, e-mail: ardakkakimova1@gmail.com).*

*Akhmetova Gulnaz – PhD student, Senior Lecturer in the Department of biotechnology of the Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: gulnaz_akhmetova92@mail.ru).*

*Askar Aidana – Master student in in the Department of biotechnology of the Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: aydana.askr.04@mail.ru).*

*Didem Ozcimen – Professor in Bioengineering department, Chemical and Metallurgical Engineering Faculty, Yıldız Technical University (Turkey, İstanbul, e-mail: didem.ozcimen@gmail.com)*

*Zayadan Bolatkhan (Corresponding author) – Doctor of Biological Sciences, academician of the National Academy of Sciences of the Republic of Kazakhstan, professor of Biotechnology Department, director of the International Research Center "AlgaBioTech"in Al-Farabi Kazakh National University (Almaty, Kazakhstan, e-mail: zbolatkhan@gmail.com).*

***Авторлар туралы мәлімет:***

*Даулетова Алиям Абликимовна – әл-Фараби атындағы Қазақ ұлттық университетінің биотехнология кафедрасының докторанты (Алматы, Қазақстан, e-mail:dauletova.aliyam13@gmail.com).*

*Болатхан Кенжегүл – PhD, әл-Фараби атындағы Қазақ ұлттық университетінің биотехнология кафедрасының ассоциирленген профессоры (Алматы, Қазақстан, e-mail: bkenzhegul23@gmail.com).*

*Какимова Ардақ Болатовна – PhD, әл-Фараби атындағы Қазақ ұлттық университетінің биотехнология кафедрасының аға оқытушысы, Қ.И. Сәтбаев атындағы Қазақ ұлттық техникалық зерттеу университеті қауымдастырылған профессоры (Алматы, Қазақстан, e-mail: ardakkakimova1@gmail.com).*

*Ахметова Гүлнәз Асқарқызы – PhD-докторанты, әл-Фараби атындағы Қазақ ұлттық университетінің биотехнология кафедрасының аға оқытушысы (Алматы, Қазақстан, e-mail: gulnaz_akhmetova92@mail.ru).*

*Асқар Айдана – әл-Фараби атындағы ҚазҰУ-дың биология және биотехнология факультетінің биотехнология кафедрасының магистранты (Алматы, Қазақстан, e-mail: aydana.askr.04@mail.ru).*

*Дидем Озчимен – Йылдыз техникалық университетінің химия және металлургия инженериясы факультетінің биоинженерия кафедрасының профессоры (Ыстамбул, Түркия, e-mail: didem.ozcimen@gmail.com).*

*Заядан Болатхан Казыханұлы (корреспонденттік автор) – биология ғылымдарының докторы, ҮҒА-ң Академигі, биотехнология кафедрасының профессоры, әл-Фараби атындағы Қазақ ұлттық университетінің «AlgaBioTech» халықаралық ғылыми-зерттеу орталығының директоры (Алматы, Қазақстан, e-mail: zbolatkhan@gmail.com).*

***Сведения об авторах:***

*Даулетова Алиям Абликимовна – PhD-докторант кафедры биотехнологии факультета биологии и биотехнологии КазНУ им. аль-Фараби (Алматы, Казахстан, e-mail: dauletova.aliyam13@gmail.com).*

*Болатхан Кенжегүл – PhD, и. о. профессора кафедры биотехнологии КазНУ им. аль-Фараби (Алматы, Казахстан, e-mail: bkenzhegul23@gmail.com).*

*Какимова Ардак Болатовна – PhD, старший преподаватель кафедры биотехнологии КазНУ им. аль-Фараби, ассоциированный профессор КазНИТУ им. К. Сатпаева (Алматы, Казахстан, e-mail: ardakkakimova1@gmail.com).*

*Ахметова Гулназ Асқарқызы – PhD-докторант, старший преподаватель кафедры биотехнологии факультета биологии и биотехнологии КазНУ им. аль-Фараби (Алматы, Казахстан, e-mail: gulnaz_akhmetova92@mail.ru).*

*Аскар Айдана – магистрант кафедры биотехнологии факультета биологии и биотехнологии КазНУ им. аль-Фараби (Алматы, Казахстан, e-mail: aydana.askr.04@mail.ru).*

*Дидем Озчимен – профессор кафедры биоинженерии факультета химической и металлургической инженерии Технического университета Йылдыз (Стамбул, Турция, e-mail: didem.ozcimen@gmail.com).*

*Заядан Болатхан Казыханулы (автор-корреспондент) – доктор биологических наук, академик НАН РК, профессор кафедры биотехнологии, директор международного научно-исследовательского центра «AlgaBioTech» при Казахском национальном университете имени аль-Фараби (Алматы, Казахстан, e-mail: zbolatkhan@gmail.com).*

*Received January 10, 2025*
*Re-uploaded May 7, 2026*
*Accepted September 15, 2026*