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Evaluation of the assimilation capacity and self-cleaning ability of biogeoecosystems along the Caspian Sea coastal zone

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✓ **Abstract.** The purpose of this study was to determine the level of ability of the Caspian coastal soils to neutralise anthropogenic load based on the assessment of their assimilation and self-purification characteristics. The research methodology was based on a comparative analysis of the soils of the Absheron-Khizi and Guba-Khachmaz regions of Azerbaijan, where samples were taken from the 0-20 cm horizon, after which different levels of oil load were reproduced under model conditions and microbiological, biochemical, and bioindicative parameters were assessed to determine the self-purification capacity of ecosystems. The greatest resistance was demonstrated by meadow-forest soils, which had a neutral reaction of the environment (pH 7.1-7.4), high humus reserves (70-240 t/ha) and increased biological activity, which was confirmed by the carbon dioxide content of 0.65%. Their ability to decompose hydrocarbons was 1.12 ± 0.08 mg per gram of soil per day, and the mineralisation factor reached 0.52 ± 0.03 . Meadow soils with humus of 35-60 t/ha and a share of oil-degrading microorganisms of 18-22% had lower biodegradation – 0.78 ± 0.05 mg/g×day with a mineralisation factor of 0.31 ± 0.02 . The most vulnerable soils were grey-brown soils with a minimum organic matter stock (24-38 t/ha) and a low proportion of destructors (8-12%); the assimilation capacity did not exceed 0.34 ± 0.04 mg/g×day with a mineralisation factor of 0.12 ± 0.01 . Bioindication tests showed a drop-in germination of watercress and alfalfa to 40-45% and a 50% reduction in biomass under conditions of 10% oil contamination. The results confirmed that meadow-forest soils were the most resistant, meadow soils were in an intermediate position, while grey-brown soils were the most vulnerable to oil pollution. The practical significance of the findings lies in their potential to be used by environmental services and agricultural research centres to monitor soil conditions and develop bioremediation strategies in the Caspian Sea regions

✓ **Keywords:** bioindication; oil products; toxic effects; biodegradation; sustainability; pollutant; microbial communities

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Introduction

The soils of the Caspian Sea coastal zone play a key role in maintaining biogeoecological balance, as they ensure the accumulation and transformation of organic matter, regulate the quality of surface and groundwater, and create conditions for biodiversity conservation. Their assimilation capacity and self-purification ability determine the resilience of ecosystems to external stress and form a natural barrier against anthropogenic pollution. At the same time, the long-term impact of hydrocarbon production and transportation, the development of industrial facilities, and urbanisation processes have led to the accumulation of oil products, heavy metals, and other xenobiotics in soils. This was accompanied by a change in their physical and chemical parameters, a decrease in the activity of microbial communities, and a slowdown in mineralisation processes. Such changes limit the natural potential of soils to maintain the stability of biogeoecosystems and counteract external anthropogenic pressure.

The study of the Caspian Sea coastal soils has gradually shifted from general descriptions to quantitative analysis of their properties. M.P. Babaev *et al.* (2020) proposed to determine the maximum permissible concentrations (MPC) of oil products using indicators of the soil assimilation potential. The researchers showed that this approach helped to adapt the standards to concrete soil types, but its universalisation proved impossible due to regional specifics. N. Ismailov *et al.* (2020) substantiated the concept of including assimilation capacity in soil and landscape passports, which helped to comprehensively consider physicochemical and microbiological indicators. Therewith, scientists noted the lack of unified field validation methods, which limited the practical application of this approach. The current state of the soil cover of the coastal strip was analysed by N.T. Aliyeva *et al.* (2023), who revealed the impact of a combination of climatic and anthropogenic factors on degradation processes. The greatest changes were recorded in areas with intensive economic use, where the ability of soils to recover decreased. M. Ahmadov *et al.* (2020) conducted a spatial analysis of the content of heavy metals in the coastal sediments of the western Caspian Sea. The results confirmed that background levels were exceeded even in areas remote from industrial centres, indicating a large-scale nature of the anthropogenic impact.

The study of biological mechanisms of soil restoration after oil pollution showed that microorganisms and associated plant communities play a leading role in stabilising degradation processes (Islamzade *et al.*, 2025). Q. Duan *et al.* (2023) proved that petroleum hydrocarbon pollution disrupted growth and gas exchange in sea buckthorn plants, while reducing the level of antioxidant defence. The researchers emphasised that such changes not only reduced bioproductivity but also limited the potential of plants to take part in natural soil self-purification. The analysis conducted by G. Yerulker *et al.* (2023) demonstrated differences in the structure of microbial communities in areas with different degrees of oil contamination. The researchers

demonstrated that under conditions of high hydrocarbon content, microbial communities lost their functional diversity, which complicated the degradation of organic matter. X. Sui *et al.* (2021) covered the prospects of microbial and combined bioremediation methods, studying the effectiveness of combining microbial consortia with phytotechnology. The results revealed that integrated approaches accelerated the decomposition of hydrocarbons and reduced the toxicity of the soil environment. The accumulated data were summarised by B. Mekonnen *et al.* (2024), who systematised the principles and mechanisms of microbial degradation of petroleum compounds. This review noted that the key factor in the effectiveness of bioremediation was the adaptability of microbial communities to specific environmental conditions.

The problems of the functioning of the Caspian coastal soils should be considered in the context of broader environmental challenges that determine the prospects for sustainable development of the region. S. Xenarios *et al.* (2025) conducted a comprehensive review of current threats, including oil hydrocarbon pollution, degradation of coastal ecosystems, and the effects of sea level fluctuations. The results showed that the integration of local soil research into the regional policy system is a prerequisite for the development of balanced scenarios for natural resource management. B. Iskakov *et al.* (2024) covered the practical aspect of environmental safety, assessing the sensitivity and vulnerability of the coast to oil spills. The study found that the consideration of the soil cover characteristics increased the accuracy of environmental risk assessment and enabled more informed planning of response measures.

Despite the existence of some regional and international studies, there are still no comprehensive studies that integrate physicochemical and biological criteria for assessing the resilience of Caspian coastal soils to anthropogenic stress. The purpose of the present study was to quantify the assimilation capacity and self-purification potential of the soils of the Caspian Sea coastal zone. For this, it was necessary to solve the following tasks: to analyse the composition and properties of soils in the area affected by anthropogenic factors; to assess the level of assimilation capacity and self-purification capacity; to compare the results between individual sections of the coast to identify spatial differences.

Materials and Methods

The area and period of the study

The study was conducted within the soil cover of two economically significant regions of Azerbaijan – Absheron-Khizi and Guba-Khachmaz. These areas were characterised by a prominent level of anthropogenic pressure due to the development of the Siazan oil fields, the proximity of industrial facilities in the Absheron Region, and the passage of the Northern Export Pipeline. The soil cover of the territories had a different structure: the Guba-Khachmaz Region was characterised by meadow-forest and partially meadow soils, while the Absheron-Khizin Region was

represented mainly by grey-brown soils with an admixture of meadow soils. Hydrocarbons were chosen as the key indicator of pollution, as their presence in the soil causes toxic effects on living organisms and leads to substantial changes in the biogeochemical cycle. Considering the absence of MPC standards for oil and oil products in Azerbaijani soils, their content was determined as a percentage of mass, considering the range of 0.5-10%. The study was conducted in 2023-2024, covering the spring (March-May) and autumn (September-November) periods, which ensured representative sampling under different moisture and microbial activity conditions.

Ethical norms

Experimental studies using cultivated and wild plants, including the collection of plant material, were conducted following institutional, national, and international guidelines in the field of bioethics and nature protection. Particular attention was paid to ensuring that sampling did not harm natural populations or disturb the ecological balance in the study regions. The study followed the requirements of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973) and the Convention on Biological Diversity (1992), which guaranteed the legality and environmental safety of the experiments.

Soil sampling and preparation

Soil samples were taken at key points along the 0-20 cm horizons, which reflect the most active processes of pollutant transformation. The sampling scheme followed the principle of uniform coverage of the territory using a 200×200 m grid. The samples were collected using the “envelope” method, resulting in a total weight of 1 kg, which was placed in sterile bags and transported to the laboratory. There, they were distributed in plastic containers to which the required doses of a hydrocarbon pollutant, n-hexadecane (a saturated alkane with C16 (16 carbon atoms), were added, the choice of which as a model substrate ensured reproducibility and controllability of the experimental conditions. A total of 60 soil samples were collected, 30 from each site (Absheron-Khizin and Guba-Khachmaz). The sampling was performed in three replications, which minimised random errors and enabled the calculation of mean values and standard deviations for each indicator.

Physicochemical and biotic parameters

A comprehensive assessment of the assimilation capacity of soils included the determination of both physicochemical and biological characteristics. The acid reaction of the medium (pH) was measured in an aqueous soil-water suspension (1:2.5) using a Hanna Instruments HI 2211 pH meter (Italy). Soil moisture content was determined according to the gravimetric method after drying the samples to a constant weight at 105°C in a Memmert UF55 drying oven (Germany). Climatic parameters included both precipitation and temperature characteristics. Annual precipitation (mm/year) and air temperature data were obtained from

local meteorological stations equipped with automatic Vaisala MAWS201 systems (Finland). The sum of active temperatures above +10°C (°C×day/year) was calculated by summing mean daily air temperatures exceeding the +10°C threshold over the annual cycle. This indicator was used to characterise the thermal and energy potential of the soil-climate system and its influence on biological activity.

The adsorption capacity of soils with respect to organic pollutants was determined under laboratory conditions using a batch equilibrium method. Air-dried soil samples (10 g, sieved through a 2-mm mesh) were equilibrated with a model hydrocarbon solution based on n-hexadecane at a known initial concentration. The soil-solution suspensions were shaken for 24h at 20 ± 2°C to achieve adsorption equilibrium. After centrifugation, the residual hydrocarbon concentration in the supernatant was measured spectrophotometrically using a Shimadzu UV-VIS UV-1800 spectrophotometer (Japan). Adsorption of organic pollutants (%) was calculated as the proportion of hydrocarbons removed from the solution relative to the initial concentration. The biological component included determination of the number of microorganisms capable of assimilating petroleum hydrocarbons, performed using the method of limiting dilutions on selective media, with incubation in a Binder BD 56 thermostat (Germany). The combined analysis of physicochemical, climatic, and microbiological indicators enabled an integrated characterisation of soil assimilation capacity.

Microbiological and biochemical methods

The total number of soil microorganisms was determined according to the method of limiting dilutions of soil suspensions, which were sown on meat-peptone agar and incubated at 28-30°C for 5-7 days. Accounting was conducted at the beginning of the experiment, as well as on the Days 5 and 15 after the introduction of hydrocarbon pollutants. Untampered samples were considered control samples, the number of microorganisms in which was taken as 100%, while in experimental samples the result was expressed as a percentage of the control. The destructive potential of microorganisms was assessed by the photocolourimetric method: a suspension of *Bacillus* and *Pseudomonas* strains was introduced into M9 medium (a mineral minimal medium containing inorganic salts and used for cultivation of bacteria in the presence of a single carbon source) with the addition of 250 mg/l n-hexadecane, after which changes in the substrate concentration were recorded spectrophotometrically. For assessing biological activity, soil respiration was quantified as the rate of CO₂ release, which served as an integrated indicator of microbial metabolic intensity. CO₂ released during microbial respiration was absorbed by 0.1 n potassium hydroxide (KOH), after which the remaining alkali was titrated with HCl to determine the amount of CO₂ fixed in the alkaline solution. This method is considered reliable, as it enables a direct assessment of the intensity of microbial respiration as one of the key integrated indicators of soil biological activity.

Bioindication experiments

To evaluate the phytotoxicity of soils, the test plants watercress (*Lepidium sativum* L., variety Vita, seeds from Agrosel, Romania) and seed alfalfa (*Medicago sativa* L., variety Vega 87, seeds from Eurograss, Germany) were used. In model vessels with a soil weight of 1 kg, 30 seedlings were sown, maintaining humidity at 60% of the highest moisture capacity (HC) and a temperature of 22-24°C under natural light. Within 30 days, the key indicators of plant viability were considered in three replications: seed germination (%) and biomass accumulation (g per 30 seedlings), which were determined after drying in a Memmert UF55 drying oven (Germany). Background soils served as a control, while a decrease in germination or biomass relative to the control was interpreted as an indicator of phytotoxicity. The yield indicator (t/ha) represents an integral indicator of above-ground biomass productivity of natural and semi-natural vegetation typical of the studied soil types. These values were derived by extrapolating experimentally measured biomass data using standard conversion coefficients and validated against regional statistical reference data.

Calculation of the assimilation capacity and mineralisation factor

The assimilation capacity of soils was assessed by the level of bacterial biodegradation of hydrocarbons, which was determined according to the following formula:

$$B = N \times K, \quad (1)$$

where B is the level of hydrocarbon biodegradation; N is the number of oil-degrading bacteria (colony forming units (CFU) per 1 g of soil), and K is the amount of hydrocarbons oxidised by one cell per day (3.76×10^{-8} mg/cell/day). The calculations were performed in three replications, and the results were expressed in mg of hydrocarbons per gram of soil per day. Additionally, the mineralisation coefficient (K_m) was used, which was defined as the ratio of the intensity of CO_2 formation absorbed by a 0.1-normal KOH solution to the intensity of oxygen consumption (O_2) by soil microorganisms. The measurements were performed using a Shimadzu UV-VIS UV-1800 spectrophotometer (Japan) and a Testo 310 gas analyser (Germany), which helped to establish not only the ability of microbial communities to decompose hydrocarbons, but also the degree of completion of the process to complete mineralisation of the organic substrate.

Results

Spatial differences in the physical and chemical characteristics of coastal soils

The study of the soil cover of the Caspian Sea coastal areas showed substantial differences between the key soil types - meadow-forest, meadow, and grey-brown soils, which are widespread in the Absheron-Khizin and Guba-Khachmaz regions. For a comprehensive analysis, a series of key physical and chemical parameters were considered that determine the ability of soils to assimilate pollutants and maintain the stability of biogeocoenoses. The results are summarised in Table 1.

Table 1. Key physical and chemical properties of soils in the study area (average for the spring and autumn period of 2023-2024)

Soil type	pH	Humus reserves (t/ha)	Humus content (%)	Moisture coefficient	Water retention capacity (mg/cm ²)	Adsorption of organic pollutants (%)	Precipitation (mm/year)	Sum of active temperatures >10°C (°C·day/year)	Soil density (%)	Yield (t/ha)	CO ₂ content (%)
Meadow-forest	7.1-7.4	70-240	2.2-6.15	1.0-1.5	20-30	46.6	570-950	3,600-4,000	29-35	70-75	0.65
Meadow	7.7-8.0	35-60	1.5-2.3	0.4-1.25	20-25	37.6	232-300	3,900-4,600	16-20	60-70	0.18-0.22
Grey-brown	7.7-8.7	24-38	1.0-1.3	0.3-0.5	15.5	30.5	150-300	4,000-4,500	8-18	5-18	0.15-0.19

Note: the sum of active temperatures means the number of degree-days with an average daily temperature above +10°C per year, which determines the heat and energy potential of the soil and climate system

Source: compiled by the authors

The acidity level ranged within 7.1-8.7. The most favourable conditions were in meadow-forest soils with indicators of 7.1-7.4, which corresponded to an almost neutral environment. It is in this interval that most groups of soil microorganisms function optimally, and enzymatic reactions and hydrolysis of organic compounds are activated. In contrast, meadow and grey-brown soils were characterised by distinctly alkaline pH values (7.7-8.7). In an alkaline environment, the activity of acid-dependent enzymes was inhibited, the mineralisation of organic matter slowed

down, and, accordingly, the level of natural detoxification decreased. This explains why hydrocarbon degradation processes in grey-brown soils were much slower, while in meadow-forest soils, pollutants decomposed more intensively. Acidity was one of the basic parameters that determined the differences between the territories: neutral soils in the Guba-Khachmaz Region had an advantage over alkaline soils in the Absheron-Khizin Region.

The analysis of humus stocks showed a sharp differentiation between soil types. In meadow-forest soils, the

humus content was 2.2-6.15% (70-240 t/ha), indicating intensive accumulation of organic residues and a well-established cycle of matter. In meadow soils, this indicator was twice lower – 1.5-2.3% (35-60 t/ha), while in grey-brown soils it stayed at a minimum level – 1.0-1.3% (24-38 t/ha). Such dynamics directly influenced the pollution resistance: soils with a high humus content can bind pollutants, provide microbial communities with energy sources, and maintain their numbers. The degraded grey-brown soils with low humus content were virtually devoid of buffering properties, making them the most vulnerable to oil loading.

The moisture coefficient reflected the balance between the amount of precipitation and evaporation rate. In meadow-forest soils, it reached 1.0-1.5, reflecting relatively stable moisture conditions. In meadow soils, the indicators decreased to 0.4-1.25, and in grey-brown soils – to critical 0.3-0.5, which confirmed a constant moisture deficit. Analogous trends were observed in the water-holding capacity: from 20-30 mg/cm² in meadow-forest soils to only 15.5 mg/cm² in grey-brown soils. This meant that biodegradation processes in soils with low moisture content were much slower, as water is the medium for most biochemical reactions. Thus, the moisture deficit in the Absheron-Khizin Region created further barriers to the self-purification of soils from hydrocarbons (Guliyev et al., 2024).

The ability of soils to adsorb organic pollutants varied substantially: in meadow-forest soils it was 46.6%, in meadow soils – 37.6%, and in grey-brown soils – only 30.5%. This meant that in areas with grey-brown soils, oil hydrocarbons had increased mobility and could migrate more quickly to deeper horizons, entering aquifers. Due to their high sorption capacity, meadow-forest soils actually “localised” the pollution in the upper layers, where it became available for microbial degradation. The distribution of climatic indicators confirmed these differences. In the Guba-Khachmaz Region, the average annual precipitation was 570-950 mm, which created a relatively favourable water balance. In Absheron-Khizin, this figure did not exceed 150-300 mm against the background of evaporation of 1,000-1,200 mm. Another criterion was the total heat resource: in meadow-forest soils it ranged within 3,600-4,000°C×day/year, while in grey-brown soils it exceeded 4,000-4,500°C×day/year. Excessive heat in conditions of moisture deficit did not stimulate the activity of the microbiota, but only intensified degradation processes. This confirmed that it was the water regime, not

the temperature, which was the primary limiting factor for soil self-purification.

The soil CO₂ content as an integral indicator of microbial respiration showed a clear gradation: 0.65% in meadow-forest, 0.18-0.22% in meadow, and only 0.15-0.19% in grey-brown. This meant that the greatest intensity of biological processes was provided by soils with a high humus reserve and sufficient moisture. In grey-brown soils, where moisture and organic matter deficits were combined, the activity of microbial communities was almost minimal. Thus, even in the presence of potential oil-degrading bacteria, environmental conditions did not allow them to fulfil their metabolic potential. The physical structure of the soils confirmed the general pattern. The density of the meadow-forest soils was 29-35%, the density of the meadow soils was 16-20%, while the density of the grey-brown soils was only 8-18%. Low density combined with a lack of humus formed a loose structure that could not effectively retain moisture. At the same time, the yield as an integral indicator of environmental sustainability ranged within 70-75 t/ha in meadow-forest to 60-70 t/ha in meadow and only 5-18 t/ha in grey-brown. This once again confirmed that the degradation of physicochemical parameters was directly transformed into a loss of productivity.

Generalisation of all parameters allows forming a hierarchy of the assimilation capacity of the soils of the studied area: meadow-forest>meadow>grey-brown. Due to their neutral pH, high humus reserves, favourable water balance, and considerable bioactivity, meadow-forest soils showed the greatest resistance to oil pollution. Meadowlands occupied an intermediate position: their ability to self-purify was less stable due to a lack of moisture and lower organic content. The most vulnerable were grey-brown soils, where the combination of alkalinity, low organic reserves, and limited water-holding capacity contributed to the accumulation of hydrocarbons and slowed their mineralisation. The data obtained confirm that spatial differences in physicochemical and biological parameters directly determine the ability of soils to self-purify under conditions of anthropogenic load on the Caspian coast.

Biological reactions of soils to oil load

The obtained experimental data showed differences in the reactions of soil biota, which is reflected in the generalised indicators of the number and proportion of oil-degrading crops in Table 2.

Table 2. Dynamics of the number of microorganisms and the share of oil-degrading crops in soils (CFU×10⁶/g, %)

Soil type	Start of the experiment (0 days)	Day 5	Day 15	Share of oil-degradable crops (%)
Meadow-forest	2.1±0.12	2.8±0.15	3.4±0.18	30-35
Meadow	1.5±0.09	1.8±0.11	2.0±0.12	18-22
Grey-brown	0.9±0.07	0.8±0.06	0.6±0.05	8-12

Source: compiled by the authors

The number of heterotrophs in meadow-forest soils increased from 2.1×10⁶ CFU/g to 3.4×10⁶ CFU/g

(≈1.6-fold increase in 15 days), while the share of oil-degrading cultures reached 30-35%. This meant that the

microbial community not only stayed viable under the influence of the pollutant, but also structurally transformed towards consortia with a pronounced destructive potential. In meadow soils, the growth was more modest (1.5×10^6 CFU/g \rightarrow 2.0×10^6 CFU/g; \approx 1.3-fold), and the proportion of oil-degradable forms stabilised at 18-22%, i.e. adaptation occurred, but more slowly and less completely. In grey-brown soils, a consistent decrease in the total number was recorded (0.9×10^6 CFU/g \rightarrow 0.6×10^6 CFU/g), with a minimum proportion of destructors (8-12%), reflecting inhibition of microbial activity and low capacity for hydrocarbon mineralisation.

The synchronous analysis of time slices showed that already on Day 5, meadow-forest soils had a positive trend (2.8×10^6 CFU/g), while meadow soils were just beginning to recover (1.8×10^6 CFU/g), and grey-brown soils showed a decline (0.8×10^6 CFU/g). This discrepancy was consistent

with the previously identified physicochemical determinants: greater humus reserves, better moisture conditions, and closer to neutral pH in meadow-forest soils supported greater growth rates and catabolic activity of microbial consortia; while alkalinity, lack of organic matter, and moisture in grey-brown soils limited hydrolytic and oxidative processes. Accordingly, in meadow-forest soils, biodegradation managed to move to the mineralisation stage, while in grey-brown soils, intermediate (partially oxidised) products accumulated. The dynamics of the number of microorganisms in soils of different types revealed clear spatial and temporal differences. Within 15 days of observation, meadow-forest soils showed a stable increase in populations, while meadow soils showed a moderate increase, and grey-brown soils showed a gradual decrease (Fig. 1). This allows tracing the dependence of biological activity on the physical and chemical characteristics of the environment.

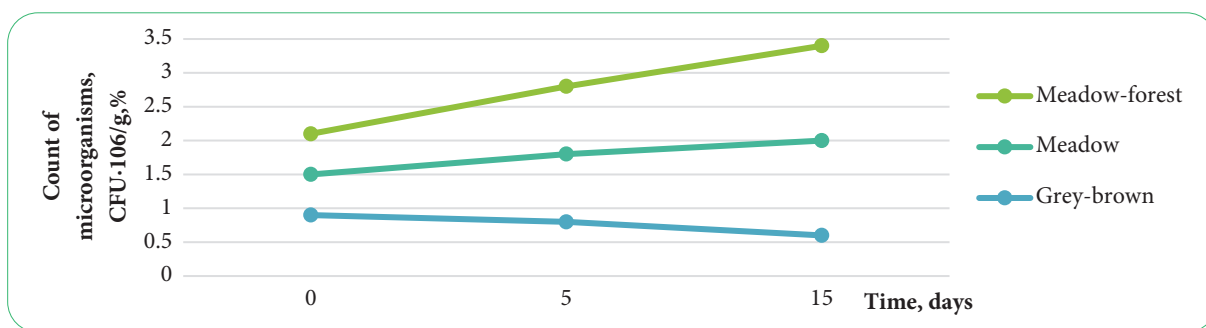


Figure 1. Dynamics of the number of microorganisms in the soil

Source: compiled by the authors

The greatest biotic potential was preserved in meadow-forest soils, where the number of microorganisms increased from 2.1×10^6 CFU/g to 3.4×10^6 CFU/g. The meadow soils had a more restrained dynamics, reaching only 2.0×10^6 CFU/g on Day 15, reflecting a limited ability to self-purification. In grey-brown soils, the number of bacteria decreased from 0.9×10^6 CFU/g to 0.6×10^6 CFU/g, which showed their extremely low resistance to oil pollution. This distribution confirmed the key role of organic matter and moisture regime in the development of assimilation capacity (Kozyatnyk *et al.*, 2015; 2017).

The bioindication experiments showed a clear dependence of the growth parameters of watercress and alfalfa on the concentration of oil pollutants in the soil. In the control samples, plants maintained high germination and biomass rates, while a gradual suppression of these characteristics was observed with increasing pollution levels. Particularly pronounced changes were recorded at a concentration of 5-10%, when the viability and productivity of both species were markedly reduced. Comparison of the two crops showed that watercress was somewhat more resistant to the toxic load, while alfalfa showed a faster biomass decline (Table 3).

Table 3. Results of bioindication experiments with test plants

Concentration, %	Germination rate of watercress (%)	Watercress biomass (g/30 seedlings)	Alfalfa germination rate (%)	Alfalfa biomass (g/30 seedlings)
0 (control)	95 ± 2	12.5 ± 0.6	93 ± 3	15.2 ± 0.7
0.5	90 ± 2	11.8 ± 0.5	89 ± 2	14.6 ± 0.6
5.0	70 ± 3	8.9 ± 0.4	65 ± 3	10.2 ± 0.5
10.0	45 ± 4	6.1 ± 0.3	40 ± 4	7.8 ± 0.3

Source: compiled by the authors

Bioindication tests showed that the impact of oil load on plants was clearly dose-dependent. Already at a minimum concentration of 0.5%, a slight inhibition of seed germination of both crops was observed (a decrease of 5-7

percentage points), while the weight of seedlings stayed almost unchanged. This indicated a certain resistance of the initial growth processes to a mild toxic effect, probably due to the buffering properties of the soil and compensatory

mechanisms of the seeds. At a concentration of 5%, substantial deviations from the control values were already detected. For watercress, germination decreased by a quarter (from 95% to 70%) and biomass by almost a third (from 12.5 g to 8.9 g), indicating inhibition of both germination and further growth. For alfalfa, the effect was even more pronounced: a 28 percentage point drop in germination (from 93% to 65%) and a one-third decrease in biomass (15.2 g→10.2 g). These results emphasise that alfalfa is a more sensitive crop to the toxicity of petroleum products, which can be explained by the specifics of its root system and the need for a greater amount of available nutrients. The maximum load (10%) had a sharply inhibitory effect on both crops. In watercress, germination was more than halved (from 95% to 45%), and biomass decreased by 51% (12.5 g→6.1 g). In alfalfa, the decline was even more critical: germination dropped to 40% (57% below the control), and biomass decreased by 48.7% (15.2 g→7.8 g). These dynamics indicated that under conditions of high oil pollution, the soil had lost its ability to ensure normal plant development even in the short term (De Carolis *et al.*, 2013). Comparison between the crops showed that watercress demonstrated relatively higher resistance: at 10%, it maintained greater germination and biomass than alfalfa. At the same time, alfalfa proved to be more indicative of toxicity, as its response to medium doses (5%) was more acute. This allows recommending the combined use of both crops in bioindication tests: watercress as a more tolerant species, reflecting the overall stability of the system, and alfalfa as a sensitive bioindicator of early negative changes (Peruzzo *et al.*, 2018; Fedoniuk *et al.*, 2022).

Comparison of the data in Table 1 and Table 2 showed that the level of phytotoxicity was closely related to the proportion of oil-degrading microorganisms: in meadow-forest soils with high microbial activity, the negative effects were much weaker, while in grey-brown soils with a low proportion of degraders, even moderate concentrations caused a sharp decrease in germination and biomass. This confirmed the key role of microbial communities as the principal regulator of soil assimilation capacity and a

determining factor of ecological resistance to oil load (Armenio *et al.*, 2019).

The regional context complemented the interpretation: the spatial contrasts established earlier (meadow-forest soils typical of the wetter Guba-Khachmaz sector were contrasted with the aridised grey-brown soils of the Absheron-Khizin area) explained why the same oil concentrations had different biotic responses. In the first case, the microbiota operated under better moisture and substrate conditions, and therefore the restructuring in favour of oil-degrading consortia was faster, and phytotoxicity was recorded at a lower level. In the second case, alkalinity, moisture deficit, and low humus stock limited both bacterial and plant subsystems, which increased the toxic effect. Thus, meadow-forest soils had a complete increase in the total number of microorganisms and a high proportion of destructors, which correlated with a milder phytoreaction; meadow soils had intermediate values for both blocks; grey-brown soils had a degradation trend in the microbiota and maximum inhibition of test cultures. From a practical standpoint, this meant that in the planning of bioremediation measures, microbial indicators (CFU dynamics and the proportion of destructors), together with phytoindicators, should be used as early and valid criteria for operational monitoring of effectiveness.

Integral indicators of assimilation capacity and self-cleaning ability

The integral characteristics of soils were essential for determining their ability to counteract oil pollution. While the previous parameters (pH, moisture, humus content, number of microorganisms) helped to characterise individual properties of the soil system, the integral coefficients reflected the generalised response of the soil to the complex impact of pollutants. In the present study, the key criteria were the level of bacterial biodegradation of hydrocarbons and the mineralisation coefficient, which helped to quantify the intensity of microbial decomposition and the degree to which the process was brought to complete mineralisation of organic substrates (Table 4).

Table 4. Integral indicators of soil assimilation capacity and mineralisation (mean values ± SD)

Soil type	Assimilation capacity (mg of hydrocarbons/g×day)	Mineralisation coefficient (K_m)
Forest-meadow	1.12 ± 0.08	0.52 ± 0.03
Meadow	0.78 ± 0.05	0.31 ± 0.02
Grey-brown	0.34 ± 0.04	0.12 ± 0.01

Source: compiled by the authors

The results showed that the assimilation capacity varied substantially depending on the soil type. The greatest values were recorded in meadow-forest soils (1.12 mg/g×day), which corresponded to their favourable structure, high humus content, and neutral acidity. This provided microbial communities with sufficient energy and nutrient substrates for active hydrocarbon oxidation. In meadow soils, the integrated index was almost one and a half times lower (0.78 mg/g×day), which was consistent with the data

on lower humus reserves and moisture deficit. The lowest level of assimilative capacity was demonstrated by grey-brown soils (0.34 mg/g×day), where a combination of alkaline environment, low organic saturation, and unfavourable hydrothermal conditions limited the catabolic potential of microbial communities.

Comparison of mineralisation coefficients (K_m) confirmed the general trend but helped to draw additional conclusions. In the meadow-forest soils, the K_m was 0.52, which

indicated the ability of microbial communities not only to decompose petroleum hydrocarbons but also to bring the process to the formation of the final mineralisation products – CO₂ and H₂O (water). In meadow soils, this coefficient was twice as low (0.31), reflecting incomplete mineralisation: some hydrocarbons accumulated in the form of intermediate metabolites that can have a toxic effect on soil biota and vegetation. In the grey-brown soils, the K_m was only 0.12, which actually meant inhibition of microbial processes and retention of the bulk of pollutants in the soil matrix without substantial biochemical decomposition.

The analysis of integral indicators revealed spatial differences between the study areas. In the Guba-Khachmaz Region, where climatic conditions provided a relatively better balance between precipitation and evaporation, the B and K_m values were consistently greater, especially in meadow-forest soils. Here, hydrocarbon biodegradation reached 1.15 mg/g×day, and the mineralisation coefficient exceeded 0.5, reflecting effective self-purification of ecosystems. In contrast, in the Absheron-Khizinsky district, due to moisture deficit and high levels of anthropogenic load, a decrease in both integral indicators was observed: the assimilation capacity ranged within 0.28-0.92 mg/g×day, and the K_m did not exceed 0.3. This confirmed the greater vulnerability of this region to oil pollution and the limited possibilities for natural soil recovery.

A comparison of the results with previous analyses showed their internal logic. Where high humus reserves, favourable water regime, and activity of microbial communities were previously recorded (meadow-forest soils of the Guba-Khachmaz district), the integral coefficients confirmed maximum resistance to anthropogenic load. In contrast, in the grey-brown soils of the Absheron-Khizin district, which were characterised by a deficit of organic matter, high alkalinity, and low moisture, the values of B and K_m were minimal, which was consistent with their inability to effectively self-purify. The mineralisation coefficient reflected not only the overall intensity of hydrocarbon destruction, but also the quality of this process. In soils with a low K_m , decomposition occurred mainly to intermediate organic products that could accumulate and reduce environmental safety. On the contrary, at high K_m values, mineralisation was reduced to final stable compounds, which reduced the risk of secondary pollution. Thus, the integral indicators helped not only to quantify the level of self-cleaning, but also to draw conclusions about its effectiveness and completeness.

The total interpretation helped to build a hierarchy of soil stability based on integral parameters: Meadow-forest>Meadow>Grey-brown. This gradation confirmed the previous data and demonstrated that it was the combination of physical, chemical, and biotic properties that determined the ability of soils to withstand oil load. In terms of practical environmental conclusions, this meant that additional bioremediation measures were needed in the Absheron-Khizin Region, while in the Guba-Khachmaz Region the natural potential of the soils was still relatively high.

Discussion

The results showed that the assimilation capacity of soils varied substantially between regions. Bioindication experiments confirmed a concentration-dependent drop in germination and biomass of test plants. The comprehensive assessment showed that meadow-forest soils had the greatest assimilation capacity due to their neutral pH (7.1-7.4), high humus reserves (70-240 t/ha), and increased biological activity (biogenicity) (CO₂ 0.65%). Grey-brown soils, on the other hand, were characterised by alkalinity (pH 7.7-8.7), minimal humus (24-38 t/ha), and a low proportion of oil-degrading microorganisms (8-12%), which substantially reduced their ability to self-purify. Analogous spatial contrasts were discussed by K. Pachikin *et al.* (2021), who showed that soil degradation on the northern Caspian coast was accompanied by loss of humus, profile compaction, and a decrease in buffering capacity.

Meadow soils occupied an intermediate position between meadow-forest and grey-brown soils in terms of assimilation capacity. With an alkaline reaction (pH 7.7-8.0) and average humus reserves (35-60 t/ha), they showed a share of oil-degrading microorganisms of only 18-22%, which ensured a relative ability to self-purification, but under conditions of moisture deficit (coefficient 0.4-1.25), their biological activity was limited. Such sensitivity of soil systems to fluctuations in the water regime shows that even an average level of organic buffering did not guarantee stable microbial functioning. A. Mamataeva *et al.* (2024) showed that the accumulation of oil products in medium-buffered environments contributed to the formation of toxic metabolites that reduced the overall assimilation capacity of ecosystems. Meadow soils have only a partial potential for self-purification: their effectiveness was determined by the balance between average humus levels and limited bioactivity in conditions of moisture deficit.

Thus, the results obtained confirm that the combination of abiotic and biotic characteristics is a key factor in the formation of the assimilation potential of soils under anthropogenic stress. Bioindicator tests showed that even 0.5% oil caused the first signs of inhibition, while at 5-10%, there was a sharp drop in germination and biomass of both crops: germination dropped to 70% and 45% for watercress and 65% and 40% for alfalfa, while biomass was almost halved. These differences reflected a clear concentration-dependent dynamic of phytotoxicity. The obtained patterns are consistent with the data of X. Zhang *et al.* (2025), who showed that hydrocarbon pollution caused a decrease in the activity of soil enzymes and a restructuring of microbial communities, which indirectly limited crop growth in phytoremediation systems. A.A. Akinsemolu & H.N. Onyeaka (2025) found analogous effects, focusing on the inhibition of the growth of sensitive plant species in coastal ecosystems with high organic load. M. Butu *et al.* (2021) noted a drop-in biomass on degraded soils with long-term anthropogenic impact, emphasising the direct link between chronic pollution and the productivity of phytoremediation. The findings of the study confirm the conclusions

of P. Baltrėnas & E. Baltrėnaitė (2020), who proved the species-specificity of the reactions: different crops reacted differently to analogous concentrations of hydrocarbons, which explains the sharper decrease in germination of alfalfa compared to watercress. The phytotoxic effect was not only dependent on the concentration of the pollutant, but also on the biological characteristics of the test crops, which is key to predicting the environmental consequences of oil loading (Hussain *et al.*, 2022).

The assimilation capacity was 1.12 ± 0.08 mg of hydrocarbons/g \times day in meadow-forest soils, 0.78 ± 0.05 mg/g \times day in meadow soils, and only 0.34 ± 0.04 mg/g \times day in grey-brown soils, while the mineralisation coefficient ranged from 0.52 ± 0.03 to 0.12 ± 0.01 . The data obtained revealed a clear gradation of ecosystems' resistance to oil loading. A comparison with the literature showed analogous patterns. The high efficiency of biodegradation under conditions of balanced pH and sufficient humus fund was confirmed by V. Ghisman *et al.* (2025), emphasising that it is the combination of physicochemical and biotic factors that ensures maximum resistance to anthropogenic impact. The findings of W. Jin *et al.* (2025) showed that in coastal industrial areas, hydrocarbon risks were reduced precisely where the rate of microbial mineralisation was higher, which is consistent with the maximum values of K_m in meadow-forest soils. E. Chapman *et al.* (2020) emphasised the vulnerability of ecosystems functioning on the edge of climatic and anthropogenic stresses and pointed to the increased effects of degradation with a decrease in microbial activity – an analogous situation was observed in grey-brown soils. Quantitative models by K. Fennel *et al.* (2022) proved that mineralisation parameters can be considered as key predictors of environmental stability, which confirms the value of the K_m coefficient in this study. Additionally, D.A. Hutchins & D.G. Capone (2022) emphasised the role of the nitrogen cycle as a limiting factor in bioremediation, which partially explains the reduced efficiency in grey-brown soils, where the biogenic potential was minimal.

In the Guba-Khachmaz Region, the level of self-purification processes was the greatest, as evidenced by the biodegradation of hydrocarbons in meadow-forest soils at 1.15 mg/g \times day and a mineralisation coefficient of more than 0.5. In contrast, in the Absheron-Khizin district, the assimilation capacity was only 0.28-0.92 mg/g \times day with a K_m below 0.3, reflecting a high vulnerability of these soils to oil loading. The obtained results were consistent with the findings of A. Vaksmaa *et al.* (2023), who proved that microbial communities demonstrate markedly greater degradation activity in wet ecosystems, while in dry conditions, the decomposition efficiency was sharply reduced. The risk analysis conducted by P.O. Iniaġhe & E.D. Kpomah (2023) showed that a low mineralisation factor was directly related to elevated levels of polycyclic aromatic hydrocarbons in soils, which confirmed the value of the data obtained for hazard assessment. M. Dehghani Darmian *et al.* (2020) demonstrated an analogous approach, considering the assimilative capacity as a key

criterion in controlling pollution in aquatic ecosystems. The use of spatial geographic information system technologies, as described by Y. Wang (2023), helped to reasonably map risks and identify the most vulnerable areas, which is especially significant for areas with moisture deficit. Finally, the generalisation by Y.M. Youssef *et al.* (2021) emphasised that the combination of natural and anthropogenic factors always determines the scale of degradation processes in coastal regions, which was fully reflected in the comparison of the two study areas.

A generalisation of the results showed that the soils differed substantially in terms of their assimilation capacity and resistance to oil load. The most favourable characteristics were recorded in meadow-forest soils with a high humus reserve, sufficient moisture, and considerable biological activity. The meadow soils had an intermediate level of self-cleaning, but their efficiency was limited by moisture deficit. The grey soils were the most vulnerable, as low humus and alkalinity contributed to the accumulation of pollutants. Spatial differences between the Guba-Khachmaz and Absheron-Khizin districts confirmed the decisive influence of climatic and anthropogenic factors.

✓ Conclusions

The analysis of physicochemical characteristics showed that meadow-forest soils had the greatest level of environmental sustainability. The neutral pH of 7.1-7.4, high humus reserves of 70-240 t/ha, moisture content of 1.0-1.5, and CO₂ content of 0.65% ensured active mineralisation and recovery processes. In meadow soils, the conditions were mediocre: pH 7.7-8.0, humus 35-60 t/ha, moisture content 0.4-1.25, CO₂ 0.18-0.22%, which limited the assimilation capacity in case of moisture deficit. The worst parameters were found in grey-brown soils: pH 7.7-8.7, humus 24-38 t/ha, moisture coefficient 0.3-0.5, CO₂ 0.15-0.19%. This indicated a low level of self-cleaning due to a lack of organic matter and moisture. Microbiological observations confirmed these differences. In the meadow-forest soils, the number of microorganisms increased from 2.1×10^6 CFU/g to 3.4×10^6 CFU/g in 15 days, and the share of oil-degrading crops was 30-35%, which reflected a high potential for destruction. In meadow soils, the growth was more modest – from 1.5×10^6 CFU/g to 2.0×10^6 CFU/g with a share of 18-22%. Grey-brown soils showed a regression: the number decreased from 0.9×10^6 CFU/g to 0.6×10^6 CFU/g, and the proportion of destructors did not exceed 8-12%. This confirmed that even in the presence of bacteria, the potential of their functioning depends on the organic matter reserves and water regime.

The results of bioindication tests showed a high sensitivity of plants to oil load. At a concentration of 5%, germination of watercress decreased from 95% to 70%, and alfalfa – from 93% to 65%, biomass decreased from 12.5 g to 8.9 g and from 15.2 g to 10.2 g, respectively. At 10% oil, germination dropped to 45% in watercress and 40% in alfalfa, and biomass almost halved to 6.1 g and 7.8 g. This demonstrated that even relatively resistant plant species are unable

to withstand elevated levels of pollution, making natural recovery impossible without additional interventions. Integral indicators confirmed the general trend. The assimilation capacity in meadow-forest soils was 1.12 ± 0.08 mg/g \times -day with a mineralisation coefficient of 0.52 ± 0.03 , which indicated that the process had reached stable end products. In meadow soils, the corresponding values were 0.78 ± 0.05 and 0.31 ± 0.02 , and in grey-brown soils – only 0.34 ± 0.04 and 0.12 ± 0.01 . This proved that soils with a neutral pH and high humus content provide the most effective self-purification, while alkaline soils with a lack of organic matter stay the most vulnerable.

A limitation of this study is not only the lack of long-term observations, which restricts assessment of the long-term dynamics of soil self-purification, but also the simplified experimental model of oil contamination. Laboratory experiments used n-hexadecane as a model saturated alkane, which ensured reproducibility but did not fully

reflect the complexity and toxicity of real crude oil containing surfactants, resins, asphaltenes, and other persistent components. Therefore, the obtained assimilation and biodegradation indicators should be interpreted as responses to a simplified hydrocarbon load rather than to actual oil pollution. Future studies should incorporate complex petroleum mixtures and long-term field monitoring to more accurately evaluate the self-purification potential of Caspian coastal soils under realistic contamination conditions.

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✔ References

- [1] Ahmadov, M., Humbatov, F., Mammadzada, S., Balayev, V., Ibadov, N., & Ibrahimov, Q. (2020). Assessment of heavy metal pollution in coastal sediments of the western Caspian Sea. *Environmental Monitoring and Assessment*, 192, article number 500. doi: [10.1007/s10661-020-08401-3](https://doi.org/10.1007/s10661-020-08401-3).
- [2] Akinsemolu, A.A., & Onyeaka, H.N. (2025). Harnessing biotechnology for the remediation of organic pollutants in coastal marine ecosystems. *Applied Sciences*, 15(12), article number 6921. doi: [10.3390/app15126921](https://doi.org/10.3390/app15126921).
- [3] Aliyeva, N.T., Mammadova, R.I., Ibadova, S.Y., Abdullayeva, K.S., & Huseynova, M.A. (2023). The study of the state of soil cover of the coastal zones of the Caspian Sea, subject to the influence of climatic and anthropogenic factors. *IOP Conference Series: Earth and Environmental Science*, 1212, article number 012009. doi: [10.1088/1755-1315/1212/1/012009](https://doi.org/10.1088/1755-1315/1212/1/012009).
- [4] Armenio, E., De Serio, F., Mossa, M., & Petrillo, A.F. (2019). Coastline evolution based on statistical analysis and modeling. *Natural Hazards and Earth System Sciences*, 19, 1937-1953. doi: [10.5194/nhess-19-1937-2019](https://doi.org/10.5194/nhess-19-1937-2019).
- [5] Babaev, M.P., Ismailov, N.M., Nadzhafova, S.I., Keiserukhsaya, F.S., & Orudzheva, N.I. (2020). Approaches to determining maximum permissible concentrations of oil and oil products for different soil types on the basis of the assimilation potential (by the example of Azerbaijan soils). *Eurasian Soil Science*, 53, 1629-1634. doi: [10.1134/S1064229320110046](https://doi.org/10.1134/S1064229320110046).
- [6] Baltrėnas, P., & Baltrėnaitė, E. (2020). The importance of technogenesis and sustainable environmental protection technologies. In *Sustainable environmental protection technologies: Contaminant biofiltration, adsorption and stabilization* (pp. 1-38). Cham: Springer International Publishing. doi: [10.1007/978-3-030-47725-7_1](https://doi.org/10.1007/978-3-030-47725-7_1).
- [7] Butu, M., Sarac, I., Corneanu, M., & Butnariu, M. (2021). Advanced technologies for ecological reconstruction and bioremediation of degraded land. In R. Prasad (Ed.), *Environmental pollution and remediation* (pp. 81-130). Singapore: Springer Singapore. doi: [10.1007/978-981-15-5499-5_4](https://doi.org/10.1007/978-981-15-5499-5_4).
- [8] Chapman, E.J., Byron, C.J., Lasley-Rasher, R., Lipsky, C., Stevens, J.R., & Peters, R. (2020). Effects of climate change on coastal ecosystem food webs: Implications for aquaculture. *Marine Environmental Research*, 162, article number 105103. doi: [10.1016/j.marenvres.2020.105103](https://doi.org/10.1016/j.marenvres.2020.105103).
- [9] Convention on Biological Diversity. (1992, May). Retrieved from <https://www.cbd.int/doc/legal/cbd-en.pdf>.
- [10] Convention on International Trade in Endangered Species of Wild Fauna and Flora. (1973, March). Retrieved from <https://cites.org/eng/disc/text.php>.
- [11] De Carolis, G., Adamo, M., Pasquariello, G., De Padova, D., & Mossa, M. (2013). Quantitative characterization of marine oil slick by satellite near-infrared imagery and oil drift modelling: The Fun Shai Hai case study. *International Journal of Remote Sensing*, 34(5), 1838-1854. doi: [10.1080/01431161.2012.727494](https://doi.org/10.1080/01431161.2012.727494).
- [12] Dehghani Darmian, M., Khodabandeh, F., Azizyan, G., Giesy, J.P., & Hashemi Monfared, S.A. (2020). Analysis of assimilation capacity for conservation of water quality: Controllable discharges of pollutants. *Arabian Journal of Geosciences*, 13, article number 888. doi: [10.1007/s12517-020-05907-5](https://doi.org/10.1007/s12517-020-05907-5).
- [13] Duan, Q., Han, G., Cui, B., & Rennenberg, H. (2023). The effects of petroleum contaminated soils on the growth, gas exchange and antioxidative level of sea-buckthorn. *Plant and Soil*, 486, 535-550. doi: [10.1007/s11104-023-05888-w](https://doi.org/10.1007/s11104-023-05888-w).
- [14] Fedoniuk, T., Bog, M., Orlov, O., & Appenroth, K.J. (2022). *Lemna aequinoctialis* migrates further into temperate continental Europe – a new alien aquatic plant for Ukraine. *Feddes Repertorium*, 133, 305-312. doi: [10.1002/fedr.202200001](https://doi.org/10.1002/fedr.202200001).

- [15] Fennel, K., Mattern, J.P., Doney, S.C., Bopp, L., Moore, A.M., Wang, B., & Yu, L. (2022). Ocean biogeochemical modelling. *Nature Reviews Methods Primers*, 2, article number 76. [doi: 10.1038/s43586-022-00154-2](https://doi.org/10.1038/s43586-022-00154-2).
- [16] Ghisman, V., Muresan, A.C., Bogatu, N.L., Herbei, E.E., & Buruiana, D.L. (2025). Recent advances in the remediation of degraded and contaminated soils: A review of sustainable and applied strategies. *Agronomy*, 15(8), article number 1920. [doi: 10.3390/agronomy15081920](https://doi.org/10.3390/agronomy15081920).
- [17] Guliyev, A., Islamzade, R., Suleymanova, P., Babayeva, T., Aliyeva, A., & Hacıyeva, X. (2024). Impact of petroleum contamination on soil properties in Absheron Peninsula, Azerbaijan. *Eurasian Journal of Soil Science*, 13(4), 358-365. [doi: 10.18393/ejss.1531959](https://doi.org/10.18393/ejss.1531959).
- [18] Hussain, T., Ahmed, S.R., Lahori, A.H., Mierzwa-Hersztek, M., Vambol, V., Khan, A.A., Rafique, L., Wasia, S., Shahid, M.F., & Zengqiang, Z. (2022). In-situ stabilization of potentially toxic elements in two industrial polluted soils ameliorated with rock phosphate-modified biochars. *Environmental Pollution*, 309, article number 119733. [doi: 10.1016/j.envpol.2022.119733](https://doi.org/10.1016/j.envpol.2022.119733).
- [19] Hutchins, D.A., & Capone, D.G. (2022). The marine nitrogen cycle: New developments and global change. *Nature Reviews Microbiology*, 20, 401-414. [doi: 10.1038/s41579-022-00687-z](https://doi.org/10.1038/s41579-022-00687-z).
- [20] Iniaghe, P.O., & Kpomah, E.D. (2023). A comparative analysis on the concentration and potential risk of polycyclic aromatic hydrocarbons in surface water, sediment and soil from a non-crude oil and a crude oil explosion site in the Niger Delta, Nigeria. *Chemistry Africa*, 6, 1633-1653. [doi: 10.1007/s42250-023-00596-5](https://doi.org/10.1007/s42250-023-00596-5).
- [21] Iskakov, B., Nurakynov, S., Dabas, J., Zhantayev, Z., Balakay, L., Dedova, T., Yelisseeva, A., & Sydyk, N. (2024). Enhancing environmental sensitivity and vulnerability assessments for oil spill responses in the Caspian Sea. *Sustainability*, 16(21), article number 9566. [doi: 10.3390/su16219566](https://doi.org/10.3390/su16219566).
- [22] Islamzade, T., İslamzade, R., Azizov, R., Babayeva, T., Aliyeva, A., Hacıyeva, X., & Ashurova, N. (2025). Impact of Cadmium-contaminated water and irrigation levels on microbiological properties of soils with different textures. *Eurasian Journal of Soil Science*, 14(2), 107-115. [doi: 10.18393/ejss.1618797](https://doi.org/10.18393/ejss.1618797).
- [23] Ismailov, N.M., Nadzhafova, S.I., Keyseruchskaya, F., & Gasymova, A.S. (2020). Soil-assimilation potential as a component of the soil passport and the assimilation potential of landscapes. *Arid Ecosystems*, 10, 58-62. [doi: 10.1134/S2079096120010072](https://doi.org/10.1134/S2079096120010072).
- [24] Jin, W., Song, K., Zhai, C., Wang, S., Zheng, M., & Feng, Z. (2025). Low ecological risks for heavy metals and total petroleum hydrocarbons on typical coastal petrochemical sewage discharge waters: Monitoring and evaluation under One Health framework. *Marine Pollution Bulletin*, 218, article number 118163. [doi: 10.1016/j.marpolbul.2025.118163](https://doi.org/10.1016/j.marpolbul.2025.118163).
- [25] Kozyatnyk, I., Lövgren, L., & Haglund, P. (2015). On the leaching of mercury by brackish seawater from permeable barriers materials and soil. *Journal of Environmental Chemical Engineering*, 3(2), 1200-1206. [doi: 10.1016/j.jece.2015.04.017](https://doi.org/10.1016/j.jece.2015.04.017).
- [26] Kozyatnyk, I., Lövgren, L., Tysklind, M., & Haglund, P. (2017). Multivariate assessment of barriers materials for treatment of complex groundwater rich in dissolved organic matter and organic and inorganic contaminants. *Journal of Environmental Chemical Engineering*, 5(4), 3075-3082. [doi: 10.1016/j.jece.2017.06.011](https://doi.org/10.1016/j.jece.2017.06.011).
- [27] Mamataeva, A., et al. (2024). Biochemical analysis of the Caspian Sea sediments: Implications for environmental pollution and bioremediation. *Caspian Journal of Environmental Sciences*, 22(5), 1021-1032. [doi: 10.22124/cjes.2024.8217](https://doi.org/10.22124/cjes.2024.8217).
- [28] Mekonnen, B.A., Aragaw, T.A., & Genet, M.B. (2024). Bioremediation of petroleum hydrocarbon contaminated soil: A review on principles, degradation mechanisms, and advancements. *Frontiers in Environmental Science*, 12, article number 1354422. [doi: 10.3389/fenvs.2024.1354422](https://doi.org/10.3389/fenvs.2024.1354422).
- [29] Pachikin, K., Erohina, O., Adamin, G., Yershibulov, A., & Songulov, Y. (2022). Mapping the Caspian Sea's North coast soils: Transformation and degradation. In E. Saljnikov, L. Mueller, A. Lavrishchev & F. Eulenstein (Eds.), *Advances in understanding soil degradation* (pp. 717-736). Cham: Springer International Publishing. [doi: 10.1007/978-3-030-85682-3_33](https://doi.org/10.1007/978-3-030-85682-3_33).
- [30] Peruzzo, P., de Serio, F., Defina, A., & Mossa, M. (2018). Wave height attenuation and flow resistance due to emergent or near-emergent vegetation. *Water*, 10(4), article number 402. [doi: 10.3390/w10040402](https://doi.org/10.3390/w10040402).
- [31] Sui, X., Wang, X., Li, Y., & Ji, H. (2021). Remediation of petroleum-contaminated soils with microbial and microbial combined methods: Advances, mechanisms, and challenges. *Sustainability*, 13(16), article number 9267. [doi: 10.3390/su13169267](https://doi.org/10.3390/su13169267).
- [32] Vaksmaa, A., Polerecky, L., Dombrowski, N., Kienhuis, M.V.M., Posthuma, I., Gerritse, J., Boekhout, T., & Niemann, H. (2023). Polyethylene degradation and assimilation by the marine yeast *Rhodotorula mucilaginosa*. *ISME Communications*, 3(1), article number 68. [doi: 10.1038/s43705-023-00267-z](https://doi.org/10.1038/s43705-023-00267-z).
- [33] Wang, Y. (2023). Ecological risk identification and assessment of land remediation project based on GIS technology. *Environmental Science and Pollution Research*, 30, 70493-70505. [doi: 10.1007/s11356-023-27158-z](https://doi.org/10.1007/s11356-023-27158-z).
- [34] Xenarios, S., Orazgaliyev, S., Torabi Haghghi, A., & Kløve, B. (2025). A perspective on sustainability and environmental challenges in the Caspian Sea. *International Journal of Water Resources Development*, 41(1), 1-8. [doi: 10.1080/07900627.2025.2441052](https://doi.org/10.1080/07900627.2025.2441052).

- [35] Yerulker, G., et al. (2023). Comparative assessment of soil microbial community in crude oil contaminated sites. *Environmental Pollution*, 328, article number 121578. doi: 10.1016/j.envpol.2023.121578.
- [36] Youssef, Y.M., Gemail, K.S., Sugita, M., AlBarqawy, M., Teama, M.A., Koch, M., & Saada, S.A. (2021). Natural and anthropogenic coastal environmental hazards: An integrated remote sensing, GIS, and geophysical-based approach. *Surveys in Geophysics*, 42, 1109-1141. doi: 10.1007/s10712-021-09660-6.
- [37] Zhang, X., Yaxi, D.E.N.G., Goujian, C.H.I., Hong, L.Ü., & Hongxia, Z.H.A.O. (2025). Removal of petroleum hydrocarbons from contaminated soils: Analyses of soil enzymes and microbial community evolution during phytoremediation using *Suaeda salsa*. *Pedosphere*, 35(3), 591-601. doi: 10.1016/j.pedsph.2024.04.001.

Оцінка асиміляційної здатності та самоочисної спроможності біогеоекосистем прибережної зони Каспійського моря

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✔ **Анотація.** Метою цього дослідження було визначення рівня здатності прибережних ґрунтів Каспійського моря нейтралізувати антропогенне навантаження на основі оцінки їхніх асиміляційних і самоочисних характеристик. Методологія дослідження ґрунтувалася на порівняльному аналізі ґрунтів Апшерон-Хизинського та Губа-Хачмазького регіонів Азербайджану, де відбір зразків здійснювали з горизонту 0-20 см, після чого в модельних умовах відтворювали різні рівні нафтового навантаження та оцінювали мікробіологічні, біохімічні й біоіндикативні показники з метою визначення самоочисної здатності екосистем. Найвищу стійкість продемонстрували лучно-лісові ґрунти, які характеризувалися нейтральною реакцією середовища (рН 7,1-7,4), високими запасами гумусу (70-240 т/га) та підвищеною біологічною активністю, що підтверджувалося вмістом вуглекислого газу на рівні 0,65 %. Їхня здатність до розкладання вуглеводнів становила $1,12 \pm 0,08$ мг на грам ґрунту за добу, а коефіцієнт мінералізації досягав $0,52 \pm 0,03$. Лучні ґрунти з вмістом гумусу 35-60 т/га та часткою нафторуйнівних мікроорганізмів 18-22 % характеризувалися нижчим рівнем біодеградації – $0,78 \pm 0,05$ мг/г×добу при коефіцієнті мінералізації $0,31 \pm 0,02$. Найбільш уразливими виявилися сіроземно-бурі ґрунти з мінімальним запасом органічної речовини (24-38 т/га) та низькою часткою деструкторів (8-12 %); у цих ґрунтах асиміляційна здатність не перевищувала $0,34 \pm 0,04$ мг/г×добу при коефіцієнті мінералізації $0,12 \pm 0,01$. Біоіндикативні тести засвідчили зниження схожості насіння крес-салату та люцерни до 40-45 % і зменшення біомаси на 50 % за умов 10 % нафтового забруднення. Отримані результати підтвердили, що лучно-лісові ґрунти є найбільш стійкими, лучні ґрунти займають проміжне положення, тоді як сіроземно-бурі ґрунти є найбільш уразливими до нафтового забруднення. Практична значущість результатів полягає в можливості їх використання екологічними службами та аграрними науково-дослідними центрами для моніторингу стану ґрунтів і розроблення стратегій біоремедіації в регіонах Каспійського моря

✔ **Ключові слова:** біоіндикація; нафтопродукти; токсичний вплив; біодеградація; стійкість; забруднювач; мікробні угруповання