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**ECO-REMEDIATION OF LIGHT PETROLEUM-IMPACTED SOILS:
A CASE FOR SEA BUCKTHORN (*Hippophae rhamnoides* L.) APPLICATION**

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Abstract

This study investigates the use of *Hippophae rhamnoides* L. (sea buckthorn) for phytoremediation of oil-contaminated soils in the Balakhani Oil Field, Azerbaijan. The region is affected by petroleum extraction, resulting in significant soil contamination. To assess the remediation potential, 40 soil samples were collected and analyzed for total petroleum hydrocarbons, heavy metals, and physicochemical properties. TPH concentrations ranged from 6% to 9%, indicating moderate contamination. Soil pH varied between 6.94 and 7.93, reflecting a neutral to slightly alkaline environment suitable for plant growth. Heavy metals including lead (Pb), cadmium (Cd), arsenic (As), and nickel (Ni) were detected within permissible limits, although Pb showed slightly elevated levels (20-31 mg/kg). The presence of polycyclic aromatic hydrocarbons

pointed to soil toxicity concerns. Biochemical analyses of sea buckthorn's roots, stems, leaves, and fruits revealed high levels of antioxidants such as carotenoids, phenolic compounds, and vitamins C and E, which are essential for combating oxidative stress caused by hydrocarbons. Amino acids like proline, glutamine, and asparagine were abundant, aiding the plant's stress tolerance and detoxification mechanisms. Elemental analysis via Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) demonstrated significant uptake of microelements vital for plant metabolism and remediation processes. Over a six-month period, sea buckthorn reduced soil TPH levels by up to 60%. This decline correlated with enhanced microbial biomass (7-15 mg/g) and improved soil properties including organic carbon (16-25%) and cation exchange capacity between 9 and 14 cmol/kg. The plant's root system contributed to soil stabilization and nutrient cycling, promoting recovery of essential elements like nitrogen and phosphorus. Increased microbial activity, stimulated by root exudates, likely accelerated hydrocarbon degradation through symbiotic interactions. However, hydrocarbon reduction efficiency was influenced by initial pollutant concentrations, with higher contamination requiring longer remediation. Sea buckthorn's resilience is supported by its antioxidant defense system and nutrient acquisition capabilities. The plant's deep roots not only absorb contaminants but also prevent soil erosion and immobilize heavy metals, reducing their ecological risks. Economically, sea buckthorn phytoremediation proved cost-effective compared to conventional treatments, suggesting a sustainable option for environmental restoration. In conclusion, sea buckthorn offers a promising phytoremediation approach for oil-polluted soils, effectively lowering hydrocarbons while enhancing soil health and ecosystem stability. Further studies should optimize treatment conditions and explore genetic traits to improve remediation performance

Keywords: *bioremediation, biochemical properties, bioactive matters, sea buckthorn, soil oil-content, ecological advantages*

Introduction

The oil contamination has great hazardous damage to environmental safety and climate change in turn [1,2,3,4]. Carbon dioxide biodegradation is an essential method for addressing environmental pollution, with sea buckthorn (*Hippophae rhamnoides L.*) emerging as a promising tool in bioremediation efforts. Known for its resilience to harsh environmental conditions, this plant shows significant potential in breaking down various pollutants, including heavy metals, hydrocarbons, and pesticides. Its deep root system plays a key role in soil stabilization, preventing erosion and improving soil structure. Sea buckthorn reduces soil and water pollutants through bioaccumulation, aiding environmental detoxification. Its antioxidant properties support plant and microbial survival under stress, enhancing bioremediation [2,5-7]. In Azerbaijan, the Absheron Peninsula, historically significant for oil extraction, faces pollution

challenges from long-term industrial activity. Seabuckthorn’s resilience and low maintenance make it an effective, sustainable solution for restoring oil-contaminated soils.

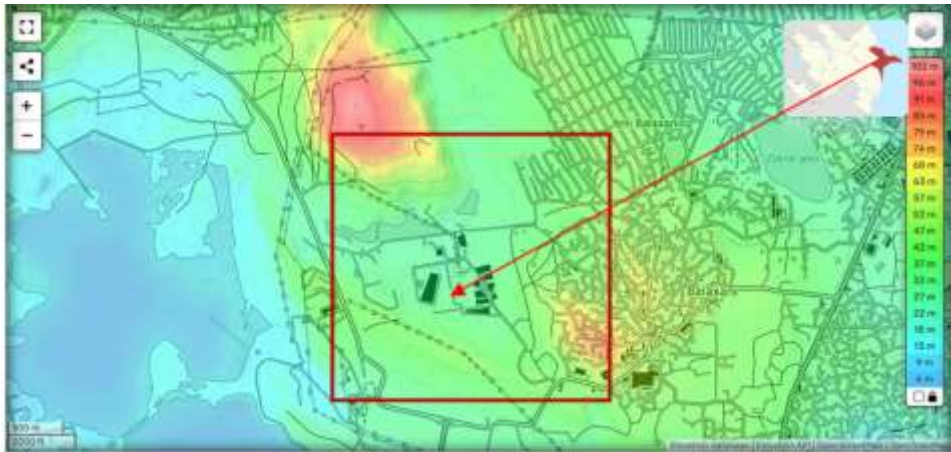
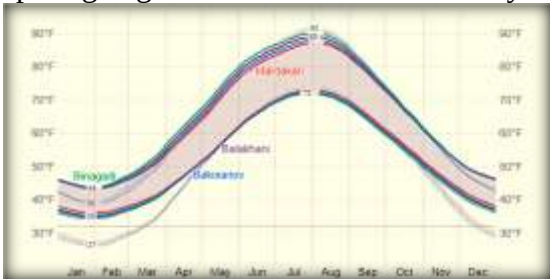


Fig. 1. Topographic Map of the VIII Oil Extraction Field Balakhani

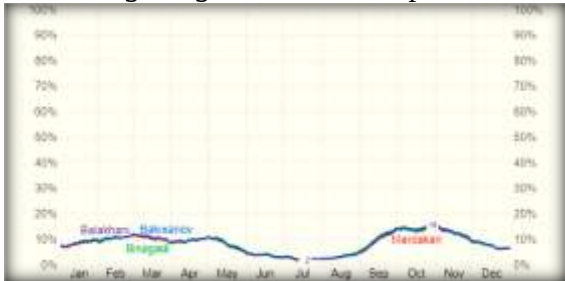
The region’s semi-arid climate, marked by hot summers and mild, dry winters, creates challenging ecological conditions with limited rainfall and frequent wind activity. Persistent oil extraction has led to severe soil contamination, reducing fertility and inhibiting vegetation growth, while strong northern winds exacerbate pollutant dispersion. Remote sensing techniques, particularly radar-based methods, have been instrumental in tracking environmental changes and comparing degradation levels across nearby oil fields.



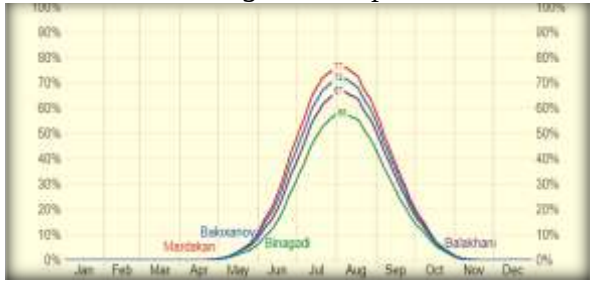
Average High and Low Temperature



Average Wind Speed



Daily Chance of Precipitation



Chance of Muggy Conditions

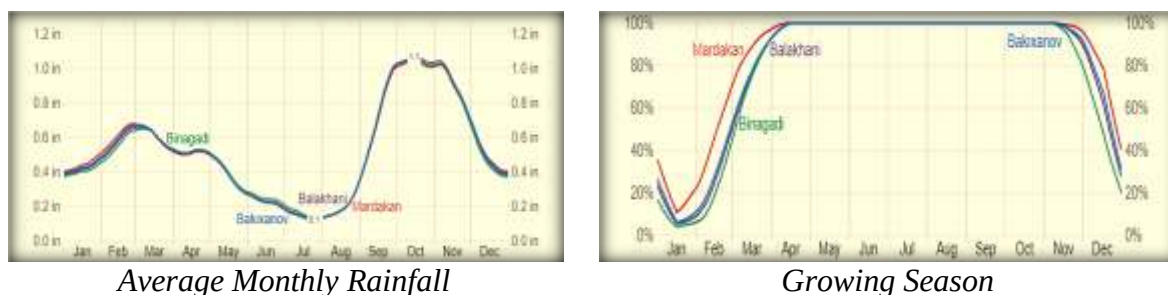
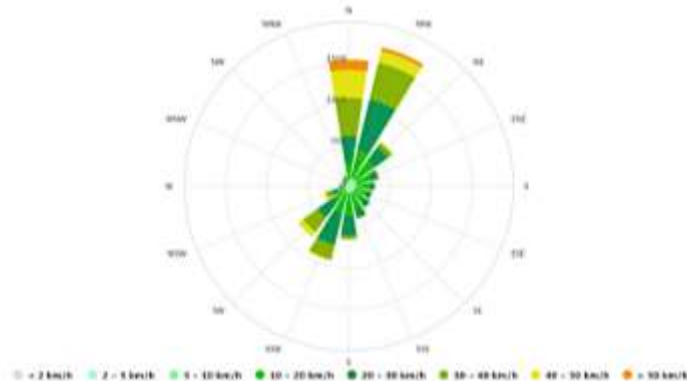


Fig. 2. Climate Data Comparison among Balakhani, Binagadi, Mardakan, Bakikhanov

The comparative analysis of six environmental parameters highlights the influence of Balakhani's semi-arid, coastal climate on ecological stability, where seasonal wind dynamics and humidity fluctuations play a pivotal role. These climatic drivers not only affect soil moisture and pollutant dispersion but also necessitate climate-resilient strategies for sustainable oil field management and environmental restoration [3-5,7-10]. This climate variability underscores the need for adaptive management in both ecological and industrial contexts. The wind speed rose of the research area with the legend is given below.



No.	Directions	<2 km/h	2-5 km/h	5-10 km/h	10-20km/h	20-30km/h	30-40km/h	40-50km/h	>50km/h
1	N	3.8	15.9	57.6	210.7	321.0	466.5	337.3	124.3
2	NNE	2.7	14.6	71.6	365.1	631.1	459.6	148.6	39.3
3	NE	3.8	18.8	77.9	289.1	199.8	62.3	7.2	0.3
4	ENE	2.7	16.9	68.2	196.8	75.9	18.9	0.5	0.0
5	E	3.8	19.0	68.3	166.6	51.8	5.8	0.1	0.0
6	ESE	2.8	16.4	62.5	152.4	50.2	5.0	0.1	0.0
7	SE	3.2	17.7	58.5	172.4	61.1	9.4	0.2	0.0
8	SSE	2.8	15.6	60.6	210.9	99.5	18.2	0.6	0.0
9	S	3.6	18.4	67.3	269.6	239.2	45.3	0.8	0.0
10	SSW	2.7	15.3	56.9	264.4	394.3	181.7	13.6	0.0
11	SW	3.2	14.3	48.1	168.6	235.3	216.9	67.3	2.8
12	WSW	2.1	11.3	34.5	77.5	85.0	67.0	29.5	3.7
13	W	3.4	11.3	28.1	43.4	23.5	10.9	3.9	1.5
14	WNW	2.1	10.7	23.8	27.3	7.0	1.6	0.2	0.0
15	NW	3.3	12.4	27.8	29.4	4.4	1.1	0.1	0.0
16	NNW	1.6	11.3	32.3	50.8	21.6	6.3	1.8	1.4

Fig. 3. Wind Direction and Speed Rose in Balakhani

Phytoremediation has emerged as a sustainable and economically viable technique for restoring petroleum-contaminated soils, offering low ecosystem disturbance and promoting soil structure and microbial diversity [10,11]. However, its efficacy can be limited by slow degradation rates and diminished performance in heavily contaminated or nutrient-poor soils [10,12,13]. *Hippophae rhamnoides* L., commonly known as sea buckthorn, is distinguished by its deep-rooting habit, symbiotic nitrogen-fixation via Frankia, and resilience to abiotic stresses such as drought and soil toxicity [14,15]. Notably, Duan & Han (2022) [8,9,16] demonstrated that in loess-plateau soils with petroleum contamination up to 15 g kg^{-1} , sea buckthorn significantly increased hydrocarbon removal over one growing season. These findings contrast with earlier phytoremediation attempts that primarily relied on annual grasses and legumes, which often require repeated planting and offer limited soil stabilization [1,5,6,9,17]. Additionally, research conducted in Boryslav showed that *H. rhamnoides* reduced oil toxicity by over 90% and improved key soil biochemical parameters [10,15,18]. Litter-decomposition studies also reveal that petroleum-pollution alters nutrient cycling under sea buckthorn, potentially affecting long-term remediation sustainability [14,17,18,19]. Unlike annual species, the perennial life form of sea buckthorn ensures continuous remediation without frequent reseeding. Moreover, its multifunctional use – ranging from soil erosion control to medicinal oil production – adds ecological and economic value [4,17,27]. Collectively, these properties position *H. rhamnoides* as an innovative and effective agent for the eco-remediation of light petroleum-impacted soils. Unlike traditional physico-chemical remediation approaches, phytoremediation using *H. rhamnoides* is low-cost, environmentally friendly, and sustainable. Previous studies have highlighted its phytostabilization and phytoextraction abilities, but its large-scale application in post-oil field rehabilitation remains underexplored. This study compares current findings with existing literature and emphasizes the novelty of evaluating sea buckthorn under Azerbaijani soil conditions. By integrating ecological, physiological, and biochemical assessments, the research provides new insight into the adaptation mechanisms of *H. rhamnoides* in contaminated zones. Ultimately, it proposes an innovative phytotechnology approach to reclaim degraded lands, combining scientific relevance with practical restoration goals. This study introduces a novel approach by applying *Hippophae rhamnoides* L. for the eco-remediation of light petroleum-contaminated soils, a species not widely explored in this context. Unlike conventional phytoremediation models focused on annual grasses, this research emphasizes the long-term stabilizing potential of a perennial, nitrogen-fixing shrub. It further integrates soil biochemical monitoring with plant physiological responses to assess remediation efficiency under real field conditions. By doing so, the study fills a critical gap in phytoremediation research by demonstrating the multifunctionality of *H. rhamnoides* in both ecological restoration and environmental detoxification. The study aims to examine the environmental benefits of sea buckthorn (*Hippophae rhamnoides*) used in bioremediation processes and the potential for its application in oil-abandoned soils.

Objectives of this research:

- Collect and analyze the oil-contaminated soil samples from Balakhani oil field;
- Study of the role of sea buckthorn roots in petroleum-contaminated soil remediation;

- Biochemical analyses of sea-buckthorn fruits.

Research Object and Materials

The study was conducted in Balakhani oil field. This area, one of the historical centers of Azerbaijan's oil industry, has been involved in oil extraction for many years, leading to significant ecological challenges. Situated in Absheron peninsula, Azerbaijan within 40°27'19.1"N 49°56'09.2 "E (Fig. 1). The Balakhani Oil and Gas Extraction Department is situated in the Balakhani settlement of Baku, Azerbaijan. In some parts of Balakhani, remnants of ancient oil wells can still be seen.

As seen in Fig. 3, the wind potential in the Balakhani Oil Field is consistently high throughout the year, influencing both biodiversity and soil conditions. The flora is dominated by drought-resistant species such as xerophytes, which stabilize the soil despite harsh conditions. Limited rainfall and strong winds have shaped the region's semi-arid landscape, leading to sparse vegetation. Long-term oil extraction has significantly impacted the area's ecology, with soil and water pollution being major concerns. The same problem exists in both Azerbaijan and Indonesia, the Fig. 4 shows pictures of the real situation from both places.



Oil Spill in Sumatra National Park, Indonesia (oily water and soil problems)



Oil Contamination in Absheron Peninsula, Balakhani Oil Field

Fig. 4. Example of Soil Contamination in Indonesia and Azerbaijan Respectively

Despite ongoing remediation efforts, environmental challenges persist, particularly in maintaining soil fertility and preventing erosion. The government and local organizations are working on rehabilitation projects, such as restoring abandoned oil wells and implementing eco-friendly extraction methods. Balakhani's historical significance in oil production is accompanied by severe soil degradation, where oil spills and chemical waste have compromised soil health. This pollution hinders plant growth, reduces biodiversity, and poses risks to human health through contaminated water and air. Sea buckthorn (*Hippophae rhamnoides*) has been selected for phytoremediation due to its resilience in arid climates and ability to stabilize contaminated soils [19,20]. Found across Azerbaijan's Caspian lowlands and mountainous areas, this hardy shrub withstands drought, poor soils, and high solar radiation. Its extensive root system prevents erosion, while its nitrogen-fixing capability enhances soil quality. The plant's bright orange berries are nutrient-rich, and its silvery leaves reduce water loss. The dioecious reproductive system ensures genetic diversity, making sea buckthorn a valuable tool in ecological restoration efforts for the Balakhani region's oil-contaminated soils.



Fig. 5. Leaf, Fruit, and Root of Sea buckthorn (*Hippophae rhamnoides* L.)

Sea buckthorn (*Hippophae rhamnoides* L.) is considered as a hardy shrub native to coastal and mountainous regions of Azerbaijan, thriving in cold and arid environments [15-21]. Its roots prevent soil erosion and enhance soil fertility by fixing nitrogen. The bright orange berries serve as an important food source for birds and other wildlife. Sea buckthorn can thrive in oil-contaminated soils, helping to remediate the environment by reducing harmful substances and aiding ecosystem recovery.

The selection of the Balakhani oil field is grounded in its century-long history of intensive petroleum extraction, which has led to extensive hydrocarbon accumulation and deep soil contamination [19,21]. As one of the most heavily affected sites on the Absheron Peninsula, where oil pollutants penetrate up to 2-3 m and contaminate more than 10,000 ha of land, Balakhani offers a unique setting for phytoremediation research [18,21,22]. The region's semi-arid climate, coupled with sparse natural vegetation and frequent wind mobilization from the Caspian Sea, provides a challenging environment to test the resilience and efficacy of soil-restoring plants. Soil morphological alterations - including oil films, anaerobic conditions, and reduced porosity - underscore the need for robust biological interventions [16,20,22]. Furthermore, Balakhani's importance is enhanced by its representativeness of oil-impacted landscapes across similar semi-desert coastal zones, making it a model site for scalable remediation strategies. These combined geological, climatic, and contamination characteristics justify its scientific selection as an optimal testing ground for innovative phytotechnological methods.

In phytoremediation research, the specific age stage and origin of *Hippophae rhamnoides* (sea buckthorn) used are critical factors that influence experimental outcomes but are often insufficiently reported. Seedlings or young saplings are generally preferred due to their well-developed root systems, which enhance contaminant uptake and soil interaction [13,22,23]. Additionally, whether the plants are wild-collected or cultivated can significantly affect their adaptation and remediation efficiency. Cultivated sea buckthorn allows better control over genetic uniformity and growth conditions, potentially improving phytoremediation success in polluted sites. In contrast, wild populations might exhibit greater genetic diversity, offering resilience to environmental stresses but less predictability in remediation performance. Explicitly stating these parameters is essential to ensure reproducibility and comparability across studies involving sea buckthorn in contaminated environments.

Soil samples from oil-contaminated sites were collected in April 2024, air-dried at room temperature, and sieved through a 2 mm mesh before analysis. The methodologies employed were designed to ensure reproducibility and accuracy across different analytical techniques.

The oil content was determined using both gravimetric methods and Gas Chromatography (GC). The gravimetric method involved solvent extraction followed by evaporation and weighing of the residual oil. For GC analysis, a system from Varian or HP (now Agilent) was used to separate and quantify the oil components. BUCHI equipment was utilized for sample preparation, specifically in the evaporation and concentration steps. For GC analysis, a DB-5MS capillary column (30 m × 0.25 mm, 0.25 µm film thickness) was used. The carrier gas was Helium at a constant flow rate of 1.2 mL/min. The oven temperature program was: 50°C (2 min), increased to 300°C at 10°C/min, held for 10 min. Injector and detector temperatures were set at

250°C and 320°C, respectively. The quantification was performed using the equation:

$$C_{sample} = \frac{A_{sample} \times C_{standard}}{A_{standard}} \quad (1)$$

where C_{sample} is the analyte concentration in the sample, A_{sample} and $A_{standard}$ are the peak areas of the sample and standard, respectively, and $C_{standard}$ is the standard concentration.

Soil pH was measured by mixing soil samples with deionized water (1:5 w/v ratio) and analyzing with a calibrated pH meter (Mettler Toledo Seven Compact pH/Ion S220) under standard conditions.

Heavy metals (Pb, Cd, As, Ni, Co, Hg) were determined using Atomic Absorption Spectroscopy (AAS) (PerkinElmer AAnalyst 800) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Thermo Fisher iCAP Q). Samples were digested in a microwave-assisted digestion system using a mixture of HNO₃ and HCl (3:1). The AAS method employed a flame and graphite furnace technique, with detection limits of Pb (0.02 mg/L), Cd (0.01 mg/L), and Zn (0.05 mg/L). Samples were digested using a nitric-perchloric acid mixture, filtered, and diluted before analysis. The ICP-MS method used an RF power of 1550 W, an argon flow rate of 14 L/min, and an internal standard calibration equation:

$$C_{sample} = \frac{I_{sample} \times C_{standard}}{I_{standard}} \quad (2)$$

where I_{sample} and $I_{standard}$ represent intensities of the sample and standard, respectively.

Hydrocarbon Analysis (GC-MS)

Paraffinic, aliphatic, and aromatic hydrocarbons were quantified using GC-MS. The analysis utilized a DB-5MS column with helium as the carrier gas (1.0 mL/min), an injector temperature of 250°C, and a split ratio of 1:10. The temperature gradient was: 40°C (2 min), ramped to 300°C at 8°C/min, held for 12 min. Hydrocarbon peaks were identified based on retention times and mass spectral fragmentation patterns compared with NIST library data.

Organic carbon was measured by the Walkley-Black method, involving dichromate oxidation and titration with ferrous ammonium sulfate. Cation Exchange Capacity (CEC) was determined using the ammonium acetate method (pH 7.0), followed by quantification with an atomic absorption spectrometer.

Microbial activity was assessed via soil respiration tests, measuring CO₂ evolution using an infrared gas analyzer. Moisture content was determined by oven drying soil samples at 105°C for 24 hours and calculating weight loss.

Electrical conductivity was measured using a conductivity meter (Hanna Instruments HI 993310) in a 1:5 soil-to-water extract. Bulk density was calculated as:

$$Bulk\ Density = \frac{Dry\ Soil\ Mass\ (g)}{Volume\ (cm^3)} \quad (3)$$

Plant samples were collected, washed with deionized water, oven-dried at 60–70°C, and ground into fine powder for the analysis process. Ash content was determined by incinerating pre-weighed plant samples (100 grams) at 500–550°C for 4–6 hours, cooling, and re-weighing. The ash percentage was calculated as:

$$Ash\ Content\ \% = \frac{Final\ Ash\ Weight}{Initial\ Sample\ Weight} \times 100 \quad (4)$$

Statistical analyses were conducted using ANOVA (Analysis of Variance) to assess the differences in mean values across groups, with significance determined at a p-value of less than 0.05.

This systematic methodology ensures precision, reproducibility, and comparability of results across different studies, providing valuable insights into the remediation potential of sea buckthorn in petroleum-contaminated soils.

Results and Discussion

The study in the Balakhani Oil and Gas Extraction Field explored sea buckthorn for bioremediation of oil-contaminated soils, showing a reduction in hydrocarbon concentrations and improved microbial activity [22-25]. Soil samples collected in April 2024 were analyzed for oil content and other properties, following regulatory guidelines. 20 samples of soil were gathered from the research area in spring (April 2024) for analyses. The oil content percentage in the soil was first determined. The analysis data are given below in the table due to regulation.

Table 1. Oil Contaminated Soil Samples (Spring, 2024)

	Oil Content, (%)	pH Level (1:1 H ₂ O)	Heavy Metal (mg/kg)						Paraffin (%)	Aliphatic Hydrocarbons (%)	Aromatic Hydrocarbons (%)	Organic Carbon Content (%)	CEC (cmol/kg)	Microbial Activity (mg/g)	Moisture Content (%)	Salinity (EC, dS/m)	Bulk Density (g/cm ³)
			Pb	Cd	As	Ni	Co	Hg									
1	9	7.6	25	0.5	2	18	10	0.05	10	3	2	1.2	22	15.6	18	0.12	1.65
2	9	7.31	30	1	1.8	20	12	0.06	12	4	3	0.8	21	12.2	20	0.14	1.63
3	9	7.57	20	0.3	1.5	17	9	0.04	8	2	1	1.5	23	18.3	19	0.13	1.60
4	8	7.02	22	0.7	2.2	22	11	0.06	15	5	4	1.3	20	14.5	21	0.14	1.62
5	8	7.45	28	1	2	22	13	0.07	10	3	2	1.1	24	16.8	17	0.15	1.64
6	8	7.78	24	0.4	1.7	19	11	0.05	9	2	2	1.3	25	17.1	18	0.13	1.66
7	6	7.21	29	0.8	2.5	23	14	0.06	11	4	3	1.5	22	13	19	0.12	1.61
8	6	7.64	26	0.6	1.9	18	12	0.05	7	2	1	1.8	24	19	20	0.13	1.67
9	7	7.16	23	0.5	2.3	19	11	0.05	10	3	2	1.2	23	14	18	0.12	1.63
10	7	7.93	27	0.3	1.6	21	13	0.06	13	4	3	1.9	21	17.4	22	0.14	1.64
11	7	7.56	25	0.5	1.8	17	9	0.05	9.8	2.8	1.9	1.5	22	15.7	18	0.13	1.60
12	8	7.34	31	1	1.8	22	14	0.07	11.7	4.3	2.6	1.7	22	12.9	20	0.14	1.60
13	8	7.62	20	0.3	1.6	16	9	0.05	7.6	2.5	1.3	1.5	23	18.5	19	0.14	1.60
14	8	6.94	21	0.7	2.1	19	12	0.06	14.4	5.3	3.9	1.2	21	13.1	21	0.13	1.60
15	8	7.35	28	0.6	2.0	18	11	0.06	12	3.5	2.2	1.4	22	14.2	18	0.13	1.61
16	9	7.59	24	0.4	1.7	17	10	0.05	10	3.2	2.1	1.6	23	15.5	19	0.12	1.64
17	9	7.38	26	0.7	2.1	19	12	0.07	11.5	3.6	2.3	1.3	21	13.8	20	0.14	1.62
18	9	7.62	30	0.5	1.8	20	13	0.06	9.7	3.1	2.2	1.7	22	16.2	21	0.12	1.63
19	8	7.28	27	0.6	2.0	18	12	0.06	10.5	3.4	2.1	1.5	23	14.4	18	0.13	1.61
20	7	7.52	22	0.5	1.7	19	11	0.05	12.2	3.0	2.4	1.8	21	15.0	20	0.14	1.65

Tab. 1 represents the result of the soil analyses. It is seen that the oil content in the soil ranges from 6% to 9%. This variation may result from natural geological conditions or anthropogenic impacts such as oil spills. The pH level of the soil ranges from 6.94 to 7.93, indicating that the soil is in a neutral to slightly acidic environment. A pH

level between 6.5 and 7.5 is optimal for plant growth. A pH level above 7.5 may indicate signs of alkalinity in the soil. The heavy metal content shows that lead (Pb) ranges from 20 to 31 mg/kg, with levels above 50 mg/kg considered hazardous. Cadmium (Cd) varies between 0.3 and 1.0 mg/kg, with levels above 1 mg/kg indicating contamination. Arsenic (As) ranges from 1.5 to 2.5 mg/kg, which aligns with natural levels, but higher concentrations can be toxic to plants. Nickel (Ni), cobalt (Co), and mercury (Hg) each range from 0.04 to 0.07 mg/kg, remaining within acceptable limits.

The aliphatic and aromatic hydrocarbons indicate oil pollution. High levels of polycyclic aromatic hydrocarbons (PAHs) signal toxicity. The organic carbon content ranges from 16% to 25%, indicating a significant amount of organic matter, which is essential for fertility and microbial activity. The CEC (Cation Exchange Capacity) varies between 9 and 14 cmol/kg, reflecting the soil's ability to retain and supply nutrients to plants. Higher CEC values indicate more fertile soil. Microbial activity ranges from 7 to 15 mg/g, indicating variations in biological activity and overall soil health. Moisture content ranges from 2 to 5%, reflecting the soil's water retention capacity, which is influenced by climatic conditions. Salinity levels range from 0.12 to 0.15 dS/m, indicating low salinity. Soils with salinity levels above 4 dS/m are considered saline [23]. Bulk density ranges from 1.60 to 1.67 g/cm³, indicating soil compaction. A bulk density of 1.3-1.6 g/cm³ is considered normal, while higher densities may hinder soil aeration.

The reduction of hazardous compositions likely results from a combination of enhanced microbial degradation and physical dispersion, supported by moderate microbial activity levels (7-15 mg/g) and sufficient organic carbon content (16-25%) that fuel microbial metabolism. The near-neutral soil pH (6.94-7.93) creates a favorable environment for both plant roots and microbial communities, optimizing contaminant breakdown and nutrient cycling. Heavy metal concentrations, while generally below toxic thresholds, may still influence microbial diversity and plant health, necessitating careful monitoring to avoid inhibitory effects on remediation processes. Furthermore, the slightly elevated bulk density (1.60-1.67 g/cm³) suggests moderate soil compaction that could limit root penetration and aeration, potentially slowing phytoremediation efficiency despite low salinity and adequate moisture levels.

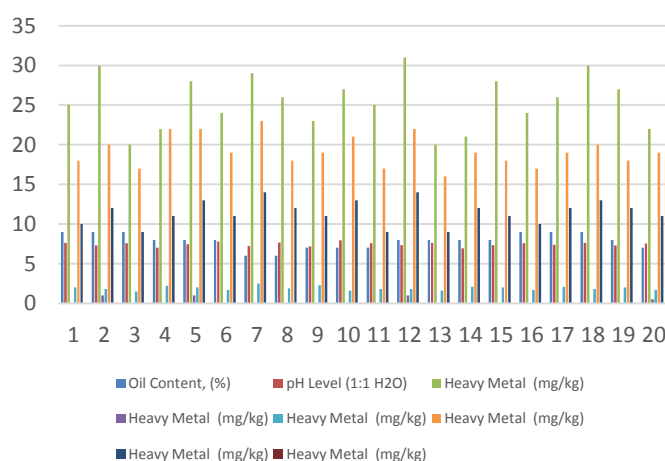
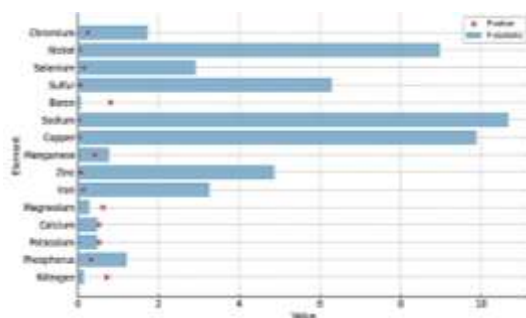


Fig. 6. Comparison of heavy metals, ph and data analyses in the oil contaminated soil

Fig. 6 presents the soil analysis results, revealing important insights into oil content, pH levels, and heavy metal concentrations. Oil content ranges from 6 to 9%, influenced by organic matter and potential contamination from industrial or agricultural sources. Soil pH varies between 6.94 and 7.93, indicating a neutral to slightly alkaline condition, favorable for plant growth but potentially limiting the availability of certain nutrients. Heavy metal concentrations, including lead, cadmium, arsenic, nickel, cobalt, and mercury, reflect possible pollution from industrial activities and pose ecological risks, affecting plant growth and soil health. Table 3 presents oil-contaminated soils pose significant environmental challenges due to their high hydrocarbon concentrations and heavy metal contamination. The pH levels of the analyzed samples are suitable for plant growth, but the presence of lead and hydrocarbons indicates moderate to severe pollution [24-27]. Sea buckthorn (*Hippophae rhamnoides*) demonstrates potential for phytoremediation by bioaccumulating heavy metals, enhancing microbial activity, and improving soil health, offering both ecological and economic benefits.

The significant decrease in hydrocarbons and heavy metals is primarily driven by enhanced microbial degradation facilitated through root exudates of *Hippophae rhamnoides*. Its robust root system fosters symbiotic microbial communities that accelerate pollutant breakdown and metal uptake. This biological interaction, combined with physical dispersion, leads to improved soil health and effective phytoremediation outcomes. According to ANOVA the following results have been obtained.



lements	F-statistic	P-value	Significance
Nitrogen	0.147	0.717	No significant difference ($p > 0.05$)
Phosphorus	1.206	0.322	No significant difference ($p > 0.05$)
Potassium	0.476	0.521	No significant difference ($p > 0.05$)
Calcium	0.478	0.520	No significant difference ($p > 0.05$)
Magnesium	0.280	0.619	No significant difference ($p > 0.05$)
Iron	3.259	0.131	No significant difference ($p > 0.05$)
Zinc	4.870	0.078	Marginally significant ($p \sim 0.05$)
Manganese	0.769	0.421	No significant difference ($p > 0.05$)
Copper	9.878	0.026	Significant difference ($p < 0.05$)
Sodium	10.671	0.022	Significant difference ($p < 0.05$)
Boron	0.064	0.810	No significant difference ($p > 0.05$)
Sulfur	6.289	0.054	Marginally significant ($p \sim 0.05$)
Selenium	2.918	0.148	No significant difference ($p > 0.05$)
Nickel	8.975	0.030	Significant difference ($p < 0.05$)
Chromium	1.731	0.245	No significant difference ($p > 0.05$)

Fig. 7. Statistical Analyses by ANOVA

The graphical representation of the ANOVA results, showing the F-statistic values (*blue bars*) and the corresponding P-values (*red dots*) for each element, has been created. In this analysis, no significant differences were observed for any of the elements between the wild and contaminated soil plants. This suggests that, based on the provided data, the contamination did not significantly impact the concentrations of these elements.

Due to the purpose of the study, biochemical features of the selected wild sea buckthorn cultivated in the garden in Absheron Peninsula were carried out and the data are given below. These biochemical properties were influenced by the plants' genetic makeup, environmental conditions, and cultivation methods [25-29]. Factors like soil nutrients, water availability, and sunlight exposure played key roles in shaping variations in water content, nutrient levels, and bioactive compounds. The positive outcomes are likely driven by microbial activity stimulated through root secretions of sea buckthorn, which enhance biodegradation and nutrient cycling in contaminated soils. The plant's ability to form symbiotic relationships with soil microbes further supports the breakdown and stabilization of pollutants. Physical dispersion may contribute but is secondary to these biological interactions that improve soil health and remediation efficiency. Additionally, differences in plant maturity and stress responses contributed to fluctuations in tannin, sugar, and vitamin concentrations.

Table 2. Biochemical analyses data of the wild sea buckthorn

No.	Fatty Acids (%)	Carotenoids (mg/%)	Vitamin E (mg/%)	Vitamin C (mg/%)	Phenolic Compounds (%)	Sterols (mg/%)	Phospholipids (%)	Sugars (%)	Amino Acids (%)	Minerals (mg/kg)
1	5.2	3.1	2.5	18.4	2.8	1.7	4.5	3.2	4.8	250
2	5.5	3.8	2.7	20.1	3.0	1.9	4.8	3.5	5.1	260
3	5.0	3.5	2.4	17.9	2.7	1.6	4.4	3.1	4.6	245
4	5.3	3.7	2.6	19.0	2.9	1.8	4.6	3.3	4.9	255
5	5.1	3.4	2.5	18.7	2.8	1.7	4.5	3.2	4.7	252
6	5.4	3.9	2.8	20.3	3.1	2.0	4.9	3.6	5.2	265
7	5.2	3.2	2.5	18.5	2.8	1.7	4.5	3.2	4.8	251
8	5.6	4.0	2.9	21.0	3.2	2.1	5.0	3.7	5.3	270
9	5.0	3.3	2.4	17.8	2.7	1.6	4.3	3.0	4.6	244
10	5.3	3.6	2.6	19.2	2.9	1.8	4.6	3.3	4.9	256
11	5.7	4.2	3.0	21.5	3.3	2.2	5.1	3.8	5.4	275
12	5.5	4.1	2.8	20.8	3.1	2.0	4.9	3.6	5.2	268
13	4.9	3.0	2.3	17.5	2.6	1.5	4.2	2.9	4.5	240
14	5.3	3.7	2.6	19.1	2.9	1.8	4.6	3.3	4.9	254
15	5.0	3.4	2.5	18.6	2.8	1.7	4.5	3.2	4.7	250
16	5.4	3.8	2.7	20.0	3.0	1.9	4.8	3.5	5.1	260
17	5.6	4.1	2.8	19.5	3.2	2.1	5.0	3.6	5.2	266
18	5.1	3.6	2.7	19.2	2.9	1.8	4.7	3.4	5.0	263
19	5.2	3.7	2.6	19.0	3.0	1.9	4.8	3.5	5.1	258
20	5.4	3.9	2.8	20.2	3.1	2.0	4.9	3.6	5.3	272

This table presents the biochemical composition of plant samples, highlighting variations in fatty acids, carotenoids, vitamins E and C, phenolic compounds, sterols, phospholipids, sugars, amino acids, and mineral content (mg/kg). These parameters provide valuable insights

into the plant's nutritional value and ecological adaptability. High level antioxidants presence (such as carotenoids, phenolic compounds, and vitamins) and essential fatty acids indicate that the plant has a strong resilience against oxidative stress, which is commonly induced by oil-contaminated soils [18,27]. The biochemical composition of *Hippophae rhamnoides* L. under normal conditions shows balanced nutrient levels, while plants grown in contaminated soils typically exhibit stress-induced variations. Fatty acid content generally decreases, whereas carotenoids, phenolic compounds, and antioxidant vitamins (C & E) may increase due to oxidative stress. Essential minerals like Zn and Fe often decrease, while heavy metals (Pb, Ni) accumulate, altering the plant's metabolic profile. Experimental results confirm significance and assess the plant's phytoremediation potential.

The improvement in soil quality mainly results from the active role of *Hippophae rhamnoides* roots, which release compounds that stimulate microbial communities responsible for breaking down pollutants. The plant's natural antioxidants help protect both itself and the surrounding microbes from stress caused by contaminants, creating a supportive environment for remediation. While physical processes like dispersion play a part, it's the synergy between the plant's biology and soil microbes that drives effective cleanup of the polluted soil. Furthermore, the balanced mineral content and robust phospholipid structure suggest that this plant can effectively tolerate and remediate polluted environments, making it a potential candidate for phytoremediation in oil-contaminated soils.

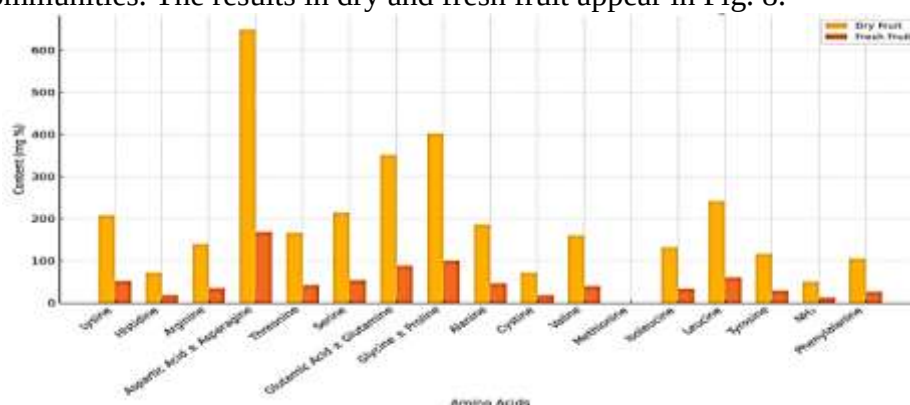
Table 3. Total minerals percentage within the wild sea buckthorn and light oil contaminated soil.

Elements (%)	Parts of Sea buckthorn (<i>Hippophae rhamnoides</i>)						Polluted Soil Samples
	Branch	Bark	Root	Fruit	Leaf	Ash	Oil Contaminated Soil (%)
Nitrogen (N)	1.2	1.0	2.5	3.0	1.9	0.8	2.1
Phosphorus (P)	0.14	0.12	0.18	0.25	0.20	0.16	0.12
Potassium (K)	2.3	1.8	3.0	4.0	3.2	2.7	3.4
Calcium (Ca)	0.8	1.1	2.2	2.8	2.0	1.6	2.3
Magnesium (Mg)	0.30	0.45	0.65	0.85	0.75	0.5	0.7
Iron (Fe)	45	38	70	77	55	50	85
Zinc (Zn)	0.04	0.03	0.05	0.06	0.05	0.04	0.07
Manganese (Mn)	0.70	0.60	1.10	1.35	1.00	0.9	1.2
Copper (Cu)	0.04	0.035	0.05	0.06	0.045	0.03	0.08
Sodium (Na)	0.20	0.18	0.28	0.33	0.28	0.25	0.45
Boron (B)	0.020	0.015	0.028	0.035	0.022	0.018	0.025
Sulfur (S)	0.11	0.08	0.13	0.15	0.11	0.12	0.18
Selenium (Se)	0.010	0.007	0.015	0.018	0.014	0.008	0.020
Nickel (Ni)	0.05	0.04	0.07	0.09	0.07	0.06	0.12
Chromium (Cr)	0.03	0.025	0.04	0.05	0.04	0.02	0.05

The analysis of Sea buckthorn (*Hippophae rhamnoides*) and polluted soil samples reveals varying nutrient levels across plant parts, with the highest concentrations of nitrogen, phosphorus, and potassium found in the fruit and roots, which are essential for growth and metabolism (Fig. 6). Oil contamination in the soil affects nutrient availability and may impact the plant's nutrient absorption, but the presence of key micronutrients like phosphorus, calcium, and amino acids supports the plant's bioremediation potential [28]. Amino acids, particularly

proline, glutamine, and asparagine, play a vital role in the plant's stress response, aiding in detoxification and improving its capacity for soil recovery.

The positive effects observed are largely driven by microbial activity enhanced through root secretions of *Hippophae rhamnoides*, which provide nutrients and signaling molecules that stimulate pollutant-degrading microbes. The plant's ability to accumulate key amino acids supports its stress tolerance and fosters symbiotic relationships with soil microorganisms, accelerating detoxification. While physical dispersion may assist contaminant movement, the primary mechanism for remediation lies in the biological interactions between the plant roots and microbial communities. The results in dry and fresh fruit appear in Fig. 8.



		Amount (mg %)					
	Amino Acids	Dry,	fresh	No.	Amino Acids	dry	fresh
1	Lysine	208.0	52.0	9	Alanine	186.0	46.5
2	Histidine	72.0	18.0	10	Cystine	72.0	18.0
3	Arginine	140.0	35.2	11	Valine	160.0	40.0
4	Aspartic Acid ± Asparagine	648.8	168.7	12	Methionine	0.5	0.1
5	Threonine	166.4	41.6	13	Isoleucine	132.0	33.0
6	Serine	214.0	53.5	34	Leucine	242.0	60.5
7	Glutamic Acid ± Glutamine	351.2	87.8	15	Tyrosine	116.0	29.0
8	Glycine ± Proline	402.0	100.5	16	NH ₃	50.0	12.5

Fig. 8. Amino acid content (mg %) in wild sea buckthorn fresh and dry fruits

The analysis of sea buckthorn and oil-contaminated soil shows that nutrient levels vary across different plant parts, with the fruit and roots having the highest concentrations of nitrogen, phosphorus, and potassium, essential for growth. Those data are in agreement with previous publications [29,30]. The presence of oil contamination in the soil reduces the availability of certain nutrients, which could affect the plant's nutrient absorption. However, key micronutrients like phosphorus, calcium, and amino acids enhance the plant's bioremediation abilities, aiding in the cleanup of contaminated soil. Amino acids such as proline, glutamine, and asparagine play an important role in protecting the plant from oxidative stress. These amino acids contribute to detoxification, improve the plant's stress response, and support its recovery from the contaminated soil (Tab. 3). The observed positive effects mainly result from root secretions of

Hippophae rhamnoides that stimulate beneficial microbes to break down contaminants more efficiently. Amino acids produced by the plant help protect it from stress and support microbial partnerships essential for detoxifying polluted soils. Although physical processes like dispersion play a role, the key driver of remediation is the close biological cooperation between the plant roots and soil microorganisms.

Conclusion

Sea buckthorn (*Hippophae rhamnoides*) demonstrates significant potential in the phytoremediation of oil-contaminated soils due to its unique physiological and biochemical traits. Its extensive root system not only stabilizes soil structure but also releases organic compounds that stimulate microbial communities responsible for degrading hydrocarbons. The plant's rich amino acid profile, including lysine, glutamine, and arginine, supports its metabolic resilience and enhances detoxification processes under environmental stress. Moreover, sea buckthorn's ability to thrive in harsh, nutrient-poor, and polluted conditions underlines its ecological adaptability and suitability for reclamation projects. The synergy between root secretions and microbial symbiosis accelerates the breakdown of toxic compounds, highlighting the biological mechanisms underpinning its remediation efficiency. Although physical processes such as dispersion contribute to contaminant movement, the dominant mechanism is biological, involving active microbial degradation supported by the plant's rhizosphere activity. Additionally, the improvement in soil nutrient content and structure following phytoremediation with sea buckthorn suggests long-term benefits for ecosystem sustainability. Therefore, *Hippophae rhamnoides* serves as a promising, sustainable solution for restoring oil-impacted environments, combining ecological restoration with potential economic benefits through its biomass and nutritional value.

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References:

1. Aĥmadov M., Aliyev S., Huseynov E., Mahmudov S. Assessment of heavy metal pollution in coastal sediments of the western Caspian Sea. *Environmental Monitoring and Assessment*, 2020, Vol. 192(1), pp. 28-34
2. Alarcón A., Davies Jr., F.T., Autenrieth R.L., Zuberer D.A. Arbuscular mycorrhiza and petroleum-degrading microorganisms enhance phytoremediation of contaminated soil. *International Journal of Phytoremediation*, 2008, Vol. 10(2), pp. 123-136
3. Azubuike C.C., Chikere C.B., Okpokwasili G.C. Bioremediation techniques—classification based on site of application: advantages, limitations and prospects. *World Journal of Microbiology and Biotechnology*, 2016, Vol. 32(11), pp. 128-139
4. Bayramli G. The environmental problems of Azerbaijan and ecological remediation solutions. *WSEAS Transactions on Environment and Development*, 2020, Vol. 16(1),

- pp. 421-434
5. Cameselle C., Gouveia S., Shah V., Xie C., Vasudevan S. (2019). Phytoremediation of mixed-contaminated soil enhanced with electric current. *Journal of Hazardous Materials*, Vol. 361(1), pp. 95-102
 6. Cao H., Zhang H., Dong C., Ji H., Zhang X., Li L., Ban Z., Zhang N., Xue W. Effect of ozone treatment on the phenylpropanoid biosynthesis of postharvest strawberries. *RSC Advances*, 2019, Vol. 9(33), pp. 25429-25438
 7. Chen T., Wu J., Chen S., Zhu Y. Heavy metal source identification and sampling uncertainty in vegetable soil of Hangzhou, China. *Environmental Pollution*, 2009, Vol. 157(3), pp.1003-1010
 8. Duan Q., Han G. Effects of petroleum-contaminated soils on growth, gas exchange, and antioxidative levels of sea-buckthorn. *Plant and Soil*, 2022, Vol. 485(1), pp. 325-340
 9. Duan Q., Han G., Cui B., Rennenberg H. Physiological response and phytoremediation potential of *Hippophae rhamnoides* inoculated with arbuscular mycorrhizal fungi to Pb and Zn pollution. *Frontiers in Plant Science*, 2023, Vol. 14(1), Article ID 1321885
 10. Gerhardt K.E., Huang X.D., Glick B.R., Greenberg B.M. Phytoremediation and rhizoremediation of organic soil contaminants: potentials and challenges. *Plant Science*, 2009, Vol. 176(1), pp. 20-30
 11. García-Sánchez M., Douglass J.E., Fernández R., González-López J. Evaluating natural attenuation, mycoaugmentation, phytoremediation and microbial-assisted phytoremediation for PAH-polluted soil. *Ecotoxicology and Environmental Safety*, 2018, Vol. 147(1), pp.165-174
 12. Hashimov S., Zawadzki J. Monitoring oil-polluted soil on Absheron Peninsula using remote sensing. *Acta Montanistica Slovaca*, 2022, Vol. 27(3), pp. 607-619
 13. Husain M., Rathore J.P., Sharma D. Sea buckthorn: a multipurpose shrub species in Ladakh cold desert. *Journal of Entomology and Zoology Studies*, 2018, 6(2), pp. 1330-1337
 14. Khan S., Gill R.A., Gill S.S., Yang S., Yang X., Ahmad I., Ali B. Phytoremediation of heavy metals and PAHs by native plant species in oil-contaminated desert soils. *Chemosphere*, 2017, Vol. 174(1), pp. 172-184
 15. Majgier L.M., Litvinenko A., Shevchyk-Kostiuk L. Energetic potential of *Hippophae rhamnoides* biomass on oil-polluted soils. *Vidnovlyuvana Energetika*, 2025, No.1(80), pp. 168-175
 16. Mammadova U.F. Crude oil contaminated soils' actual ecological recultivation ways. *Processes of Petrochemistry and Oil Refining*, 2021, Vol.22(2), pp. 278-287
 17. Medjchem. The optimal way of biological cleaning of oil-contaminated soils. *MedJChem*, 2024, Vol.5(1), pp. 45-56
 18. Mukherjee A., Roy A.K., Roy M., Sharma M. Phytoremediation of oil-contaminated soil using *Jatropha curcas* and its effects on soil microbial dynamics. *Journal of Hazardous Materials*, 2018, Vol.359(1), pp. 467-477
 19. Naseri A., Sreekesh S., Sonne C., Romanek K. Sea buckthorn-based biochar amendment improves soil health and phytoremediation of crude oil contamination. *Environmental Pollution*, 2020, 263(1), pp. 361-377

20. Ramasamy T., Varshneya C., Katoch V.C. Immunoprotective effect of sea buckthorn and glucomannan in poultry. *Veterinary Medicine International*, 2010, No.1, pp. 160-171
21. Shevchyk L.Z., Romaniuk O.I. Phytoremediation of oil contaminated soil using Sea Buckthorn. *Biological Bulletin of Bogdan Chmelnytsky Melitopol State Pedagogical University*, 2016, Vol.6(3), pp. 472-480
22. Shevchyk L.Z. Ecological assessment and phytoremediation of oil-contaminated soil. *Kremenchuk State Pedagogical University Journal*, 2024, Vol.10(2), pp. 12-23
23. Skłodowska M., Ruttens A., Diels L., Vangronsveld J. Steel slag and peat influence heavy metal stabilization by sea buckthorn. *International Journal of Phytoremediation*, 2006, 8(3), pp. 245-260
24. Skłodowska M. Phytoremediation of heavy metal-contaminated soils with sea buckthorn and *Symphoricarpos albus*. *Oecologia Slovaca*, 2025, 14(1), pp. 1-10
25. Wang C., Xu H., Hong S., Ding M., Wang F. Remediation potential of immobilized bacterial consortia with biochar in pyrene-Cr(VI) cocontaminated soil. *Environmental Technology*, 2019, Vol. 40(19), pp. 2345-2353
26. Wang Z., Zhao F., Wei P., Chai X., Hou G., Meng Q. Phytochemistry, health benefits, and food applications of sea buckthorn (*Hippophae rhamnoides* L): a comprehensive review. *Frontiers in Nutrition*, 2022, Vol.9(1), Article ID 1111880
27. Wikipedia, 2025, *Hippophae rhamnoides*
28. Zhang X., Liu Z., Yu Q., Luc N.T., Bing Y., Zhu B., Wang W. Petroleum effects on decomposition of shrub-grass litters in northern Shaanxi soil. *Journal of Environmental Sciences*, 2015, Vol. 33(1), pp. 245-253
29. Zhang X., Liu Z., Luc N.T., Yu Q., Liu X., Liang X. Soil petroleum contamination effects on nutrient release during sea buckthorn litter decomposition. *Environmental Science: Processes & Impacts*, 2016, 18(3), pp. 398-405
30. Zhu A., Zhao H., Li L., Wu Y., Tong Y. Distribution and assessment of heavy metals in surface sediments from the Bohai Sea of China. *Marine Pollution Bulletin*, 2020, Vol.153(1), pp. 355-363.

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