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ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

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BIOREMEDIATION OF ZONAL SOILS IN AYIRTAY DISTRICT OF NORTH KAZAKHSTAN REGION

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Abstract. This article examines the methods of biological soil cleaning in Ayyrtau District of North Kazakhstan Region. It investigates existing pollutants, sources of pollution, and the effectiveness of biological methods for restoring the ecological state of soils. The results of studies on the biological cleaning of soils in Ayyrtau District are presented. Concentrations of heavy metals, pesticides, and petroleum products were studied before and after the application of phytoremediation and bioremediation methods. The use of sunflower, alfalfa, and willow for phytoremediation showed a significant reduction in concentrations of cadmium, lead, petroleum products, and pesticides. Sunflower and alfalfa were found to be the most effective plants. In bioremediation, methods such as biostimulation, bioventing, and bioaugmentation were applied, which also demonstrated significant reductions in pollutant levels. Combined methods, combining the use of plants and microorganisms, were the most effective for soil cleaning. These methods not only reduce pollution levels but also restore soil fertility, improving the ecological situation and increasing the agricultural potential of the region. The choice of a specific cleaning method depends on the type of pollutant and soil characteristics. The study results showed that the application of phytoremediation and bioremediation significantly reduced the concentrations of heavy metals and organic pollutants in the soil. The most effective were combined methods, combining the use of plants and microorganisms. The choice of a specific method depends on the type of pollutant and soil characteristics. The conducted studies emphasize the need for an integrated approach to solving soil pollution problems, which improves the ecological situation in the region and promotes sustainable land resource management.

Keywords: biological cleaning, phytoremediation, bioremediation, heavy metals, Ayyrtau District

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СОЛТҮСТІК ҚАЗАҚСТАН ОБЛЫСЫ АЙЫРТАУ АУДАНЫ АЙМАҚТЫҚ ТОПЫРАҒЫНЫҢ БИОРЕМЕДИАЦИЯСЫ

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Аннотация. Бұл мақалада Солтүстік Қазақстан облысының Айыртау ауданындағы топырақты биологиялық тазарту әдістері қарастырылады. Қолданыстағы ластанулар, ластану көздері, сондай-ақ топырақтың экологиялық жағдайын қалпына келтіру үшін биологиялық әдістерді қолдану тиімділігі зерттелуде. Солтүстік Қазақстан облысы Айыртау ауданының топырағын биологиялық тазарту бойынша зерттеу нәтижелері ұсынылды. Фиторемедиация және биоремедиация әдістерін қолданар алдында және одан кейін ауыр металдардың, пестицидтердің және мұнай өнімдерінің концентрациясы зерттелді. Фиторемедиация үшін күнбағыс, жоңышқа және Талды қолдану Кадмий, Қорғасын, мұнай өнімдері мен пестицидтер концентрациясының айтарлықтай төмендегенін көрсетті. Күнбағыс пен жоңышқа ең тиімді өсімдіктер болып шықты. Биоремедиацияда биостимуляция, биовентиляция және био күшейту әдістері қолданылды, бұл сонымен қатар ластаушы заттардың айтарлықтай төмендеуін көрсетті. Өсімдіктер мен микроорганизмдерді қолдануды біріктіретін аралас әдістер топырақты тазарту үшін ең тиімді болып шықты. Бұл әдістер ластану деңгейін төмендетіп қана қоймай, топырақтың құнарлылығын қалпына келтіруге мүмкіндік береді, бұл экологиялық жағдайды жақсартуға және аймақтың аграрлық әлеуетін арттыруға ықпал етеді. Белгілі бір тазарту әдісін таңдау ластаушы заттардың түріне және топырақтың сипаттамаларына байланысты. Зерттеу нәтижелері фиторемедиация мен биоремедиацияны қолдану топырақтағы ауыр металдар мен органикалық ластаушы заттардың концентрациясының айтарлықтай төмендеуіне ықпал еткенін көрсетті. Өсімдіктер мен микроорганизмдерді қолдануды біріктіретін аралас әдістер ең тиімді болып шықты. Белгілі бір әдісті таңдау ластаушы заттардың түріне және топырақтың сипаттамаларына байланысты. Жүргізілген зерттеулер аймақтағы экологиялық жағдайды жақсартуға мүмкіндік беретін және жер ресурстарын тұрақты басқаруға ықпал ететін топырақтың ластану мәселесін шешуге кешенді көзқарастың қажеттілігін көрсетеді.

Түйін сөздер: биологиялық тазарту, фиторемедиация, биоремедиация, ауыр металдар, Айыртау ауданы

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БИОРЕМЕДИАЦИЯ ЗОНАЛЬНЫХ ПОЧВ АЙЫРТАУСКОГО РАЙОНА СЕВЕРО-КАЗАХСТАНСКОЙ ОБЛАСТИ

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Аннотация. В данной статье рассматриваются методы биологической очистки почв в Айыртауском районе Северо-Казахстанской области. Исследуются существующие загрязнения, источники загрязнений, а также эффективность применения биологических методов для восстановления экологического состояния почв. Представлены результаты исследований по биологической очистке почв Айыртауского района Северо-Казахстанской области. Были изучены концентрации тяжелых металлов, пестицидов и нефтепродуктов до и после применения методов фиторемедиации и биоремедиации. Использование подсолнечника, люцерны и ивы для фиторемедиации показало значительное снижение концентраций кадмия, свинца, нефтепродуктов и пестицидов. Подсолнечник и люцерна оказались наиболее эффективными растениями. В биоремедиации применялись методы биостимуляции, биовентиляции и биоусиления, которые также продемонстрировали значительное снижение уровней загрязнителей. Комбинированные методы, сочетающие использование растений и микроорганизмов, оказались наиболее эффективными для очистки почв. Эти методы позволяют не только снизить уровень загрязнений, но и восстановить плодородие почв, что способствует улучшению экологической ситуации и повышению аграрного потенциала региона. Выбор конкретного метода очистки зависит от типа загрязнителя и характеристик почвы. Результаты исследований показали, что применение фиторемедиации и биоремедиации способствовало значительному снижению концентраций тяжелых металлов и органических загрязнителей в почве. Наиболее эффективными оказались комбинированные методы, сочетающие использование растений и микроорганизмов. Выбор конкретного метода зависит от типа загрязнителя и характеристик почвы. Проведенные исследования подчеркивают необходимость комплексного подхода к решению проблемы загрязнения почв, что позволяет улучшить экологическую ситуацию в регионе и способствует устойчивому управлению земельными ресурсами.

Ключевые слова: биологическая очистка, фиторемедиация, биоремедиация, тяжелые металлы, Айыртауский район

Introduction

In the context of modern agriculture and environmental management, there is a need for detailed study of soil conditions and methods of soil restoration. Understanding the current state of soil cover and the factors influencing its degradation is key to developing effective sustainable land use strategies. This article examines various aspects of the state and restoration of soil cover in the northern region of Kazakhstan, as well as the impact of agronomic measures on the productivity of agricultural crops. Contemporary research in the fields of soil condition, agronomic practices, and biotechnology plays a key role in ensuring sustainable agriculture and environmental protection. The use of modern technologies (Salikhov et al., 2020; Salikhov et al., 2021), optimization of agronomic practices, and the introduction of biotechnologies (Popova et al., 2023) not only increase the productivity of agricultural crops but also preserve natural resources for future generations. In recent years, the problem of soil pollution has become increasingly urgent, especially in regions with intensive agricultural and industrial activities. Ayyrtau District of North Kazakhstan Region is no exception. The high level of land resource use leads to the accumulation of various pollutants such as heavy metals, pesticides, and petroleum products, which adversely affect the ecosystem of the region and reduce its agricultural potential. Figure 1 shows the natural-agricultural zoning of the North Kazakhstan region, demonstrating the share of each of the eight natural-agricultural districts in the overall structure of the region.

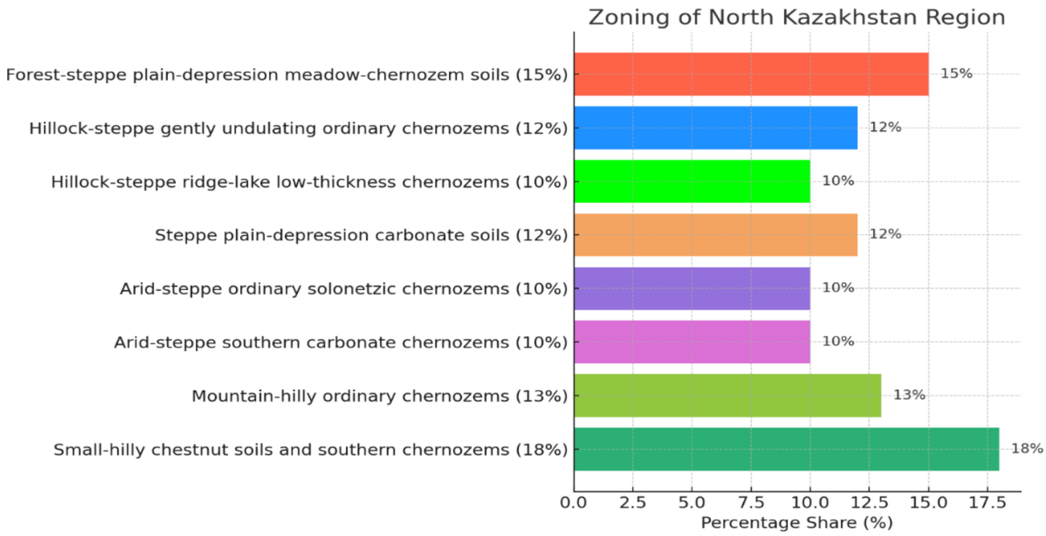

Figure 1 - Natural-agricultural districts of the North Kazakhstan region

According to Figure 1, the presence of small-hilly relief forms and various types of soils, such as chestnut soils and southern chernozems, characterize the small-hilly district of chestnut soils and southern chernozems (18 %). The mountain-hilly district of ordinary chernozems (13 %) includes mountain-hilly landscapes with a predominance of ordinary chernozems. The dry-steppe district of southern carbonate chernozems (10 %) is represented by southern carbonate chernozems in dry steppe conditions, which constitute 10% of the total area of the region. The dry-steppe district of ordinary solonetzic chernozems (10 %) is characterized by ordinary solonetzic chernozems in dry climate conditions, also accounting for 10 % of the total area. The steppe plain-depression district of carbonate soils (12 %) covers plain and depression areas with carbonate steppe soils. The hillock-steppe ridge-lake district of low-thickness chernozems (10 %) includes ridge-lake landscapes with low-thickness chernozems, which account for 10% of the region's area. The hillock-steppe gently undulating district of ordinary chernozems (12 %) is characterized by gently undulating landscapes with ordinary chernozems, occupying 12% of the total area. The forest-steppe plain-depression meadow-chernozem district (15 %) is represented by forest-steppe landscapes with meadow-chernozem soils.

The soil map of Ayyrtau District of North Kazakhstan Region, indicating various types of soils, is presented in Figure 2.

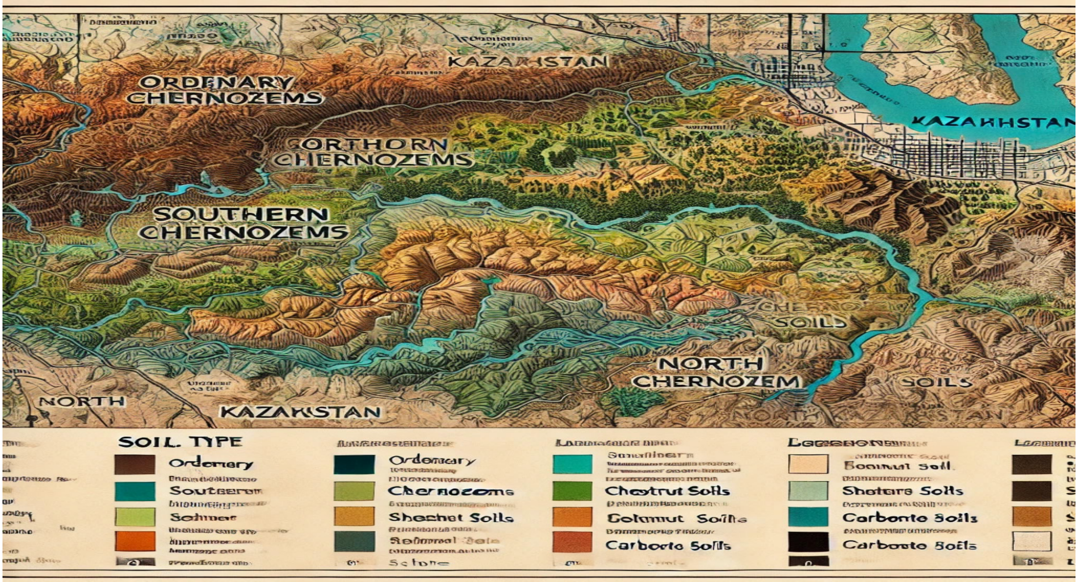

Figure 2 - Soil map of Ayyrtau District, North Kazakhstan Region

However, intensive land resource use leads to the accumulation of various pollutants in soils, which adversely affects the region's ecosystem. One of the promising methods of soil restoration is biological cleaning, which includes the use of plants (phytoremediation) and microorganisms (bioremediation) (Porsev et al., 1995). The main soil pollutants in Ayyrtau District are heavy metals, pesticides, and petroleum products. Sources of these pollutants include industrial emissions, the use of mineral fertilizers and pesticides, transport infrastructure, and accidental chemical spills, atmospheric precipitation containing metals from anthropogenic sources, as well as pesticides (Akimov, 2010).

Heavy metals, such as cadmium (Cd) and lead (Pb), pose a serious threat to the environment and human health. These elements accumulate in soil and plants, entering food chains. Pesticides used in agriculture to control pests and plant diseases are also significant soil pollutants. Pesticide residues can persist in soil for a long time, having a toxic effect on soil microflora and plants. Biological cleaning methods include bioremediation and phytoremediation, which are actively studied and applied in various regions of the world for cleaning contaminated soils. Bioremediation involves the use of microorganisms to decompose organic pollutants and transform inorganic pollutants into less toxic forms. Bioremediation uses microorganisms to decompose organic pollutants and transform inorganic pollutants into less toxic forms. This method is widely used to clean soils from petroleum products, pesticides, and other organic substances (ZHuravlev et al., 2018). Research has shown that sunflower, alfalfa, and willow are effective plants for phytoremediation, as they can extract significant amounts of heavy metals (Sidorova et al., 2015; Gribskij, 2004).

Some scientists (Aksyonov et al., 2019) in their work, studying the use of phytoremediation on agricultural soils of Northern Kazakhstan, noted a significant decrease in the concentration of heavy metals in soils after using this method. Brown S., Hinchman R. and Angle J.S. (Brown et al., 1994) explore the possibility of using plants to remove heavy metals from soils. In their work, they emphasize the importance of selecting the right plant species capable of effectively absorbing and accumulating metals such as lead and cadmium. Their research shows that some plant species have a high capacity for phytoextraction, making them ideal candidates for phytoremediation. Microorganisms inhabiting the rhizosphere of plants play an important role in phytoremediation processes. A team of scientists (Chaudhry et al., 2005) having investigated the synergy between plants and microorganisms in the decomposition of organic pollutants, concluded that microorganisms can significantly accelerate the decomposition of pollutants such as pesticides and petroleum products in the presence of plants. Glick B.R. (Glick, 2010) studied the use of soil bacteria to facilitate phytoremediation. In his work, he showed that certain types of bacteria can stimulate plant growth and increase their ability to absorb and decompose pollutants. These bacteria can be used to increase the effectiveness of phytoremediation.

A.A. Juwarkar et al. (Juwarkar et al., 2010) present a comprehensive review of the elements of bioremediation. The authors considered various types of microorganisms, their mechanisms of action and effectiveness in removing pollutants from the soil. Foreign Research (Khan et al., 2010) show that plants can effectively absorb heavy metals, reducing their bioavailability in the soil and reducing the risk to human health. Khan M. and Lee S. (Khan et al., 2020) in their work discussed concepts and applications of phytoremediation of heavy metals. The authors emphasize the importance of developing new approaches and technologies to improve the efficiency of this method, including genetic modification of plants and the use of nanotechnologies. A number of scientists (Salt et al., 1995) propose a new strategy for removing toxic metals from the environment using plants. Their work demonstrates that phytoremediation can be an effective method for cleaning soils and water bodies from heavy metals such as mercury and arsenic. J. Vangronsveld et al. (Vangronsveld et al., 2009) share their experience of using phytoremediation on contaminated soils and groundwater. The authors provide examples of successful application of this method in various countries and emphasize the importance of an integrated approach to solving pollution problems.

Materials and мethods

A comprehensive approach, including both laboratory and field studies, was chosen for conducting bioremediation studies in Ayyrtau District of North Kazakhstan Region. Initially, sites with varying levels of contamination by heavy metals, petroleum products, and pesticides were identified.

These sites were selected based on a preliminary analysis of soil samples taken from various points in the area. Soil sampling was carried out in accordance with GOST 17.4.3.01-83. Soils. General requirements for sampling, GOST 17.4.3.06-86. Soils. Methods of biological reclamation of contaminated soils, and GOST 28168–89. Soils. General requirements for methods for determining contamination. Samplers were used to collect samples from a depth of 0–30 cm. The samples were then thoroughly mixed and combined to obtain averaged samples.

Chemical Analysis of Pollutants. The analysis of the content of heavy metals, pesticides, and petroleum products was carried out in the laboratory using modern instruments, such as an AA-7000 atomic absorption spectrometer (Shimadzu) for determining the content of heavy metals and an Agilent 7890B gas chromatograph with a mass spectrometric detector for analyzing pesticides and petroleum products.

Growing Plants for Phytoremediation. In laboratory conditions, controlled environments were created for growing plants used in phytoremediation. Plant growth chambers (Climacell): provided optimal conditions of lighting, temperature, and humidity for growing sunflower, alfalfa, and willow. These plants were selected based on their ability to effectively extract various pollutants from the soil. Control and monitoring of plant growth: carried out using a spectrophotometer to analyze the content of chlorophyll and other photosynthetic pigments, as well as microscopes to assess the condition of the root system and the overall health of the plants.

Microbiological Studies. Various approaches were used for bioremediation of soils, including the application of local and adapted strains of microorganisms. BIOSTAT® B-DCU fermenters (Sartorius): used for cultivating microorganisms in controlled conditions. The fermenters created optimal conditions for the growth and reproduction of bacteria capable of decomposing organic pollutants and transforming heavy metals into less toxic forms. Portable gas analyzer MultiRAE: used to measure oxygen and carbon dioxide content in soil air, allowing control of aerobic and anaerobic conditions in soils during bioremediation. Leica DM2500 microscopes: used for analyzing microbiological samples and assessing the quantity and activity of microorganisms. Quantitative and qualitative characteristics of soil microflora were determined, including the identification of key bacterial strains involved in bioremediation processes.

Field Studies Selection and Preparation of Sites. For conducting field experiments, sites with varying levels of contamination in Ayyrtau District were selected. These sites represented typical agricultural lands with a history of intensive use, leading to the accumulation of pollutants. The following activities were performed at each site. Marking and dividing sites: sites were divided into control and experimental zones. Control zones were not subjected to bioremediation interventions, while experimental zones were treated with various phytoremediation and bioremediation methods. Sampling: soil samples were taken before the start of the experiments and after each stage of bioremediation for subsequent analysis of pollutant content.

Application of Phytoremediation. Plants capable of effectively extracting pollutants from the soil were planted on experimental sites. Sunflower (Helianthus annuus): used to extract heavy metals such as cadmium and lead. Plants were planted in rows with a specified planting density to ensure maximum coverage of the area. Alfalfa (Medicago sativa): used to degrade organic pollutants, including pesticides. Alfalfa was sown on sites with high organic pollutant content. Willow (Salix spp.): planted on sites contaminated with petroleum products and heavy metals. Willow is capable of rapid growth and development of a deep root system, which promotes effective soil cleaning.

*Application of Bioremediation***.** Various bioremediation methods were applied on experimental sites. Biostimulation - adding nutrients and organic substrates to stimulate the growth of local microorganisms. This included the addition of compost, organic fertilizers, and nitrogen-containing compounds. Bioventing - introducing air into the soil using special aeration installations to activate aerobic microorganisms. Soil ventilation improved conditions for microbial activity and the decomposition of organic pollutants. Bioaugmentation – introducing specialized strains of microorganisms capable of decomposing specific pollutants. These microorganisms were pre-cultivated in the laboratory and introduced into the soil in the form of suspensions.

Control and Monitoring. To assess the effectiveness of bioremediation methods, regular control and monitoring of soil and plant conditions were conducted. Analysis of pollutant content: soil samples were regularly taken to analyze the content of heavy metals, petroleum products, and pesticides. Analyses were conducted in the laboratory using an atomic absorption spectrometer and a gas chromatograph. Phytometric parameters of plants:

the growth, biomass, and chlorophyll content of plants were measured. These indicators allowed the assessment of the health and productivity of plants used in phytoremediation. Microbiological analysis of soil: quantitative and qualitative characteristics of soil microflora were determined, including the quantity and activity of key microorganism strains. This allowed the assessment of the effectiveness of bioremediation processes and the adaptation of microorganisms to soil conditions.

Statistical Data Processing. Research results were subjected to statistical processing to determine the significance of changes in pollutant concentrations and the effectiveness of applied methods. Methods of variance analysis (ANOVA): used to compare pollutant concentrations before and after the application of bioremediation and phytoremediation methods. This allowed the identification of statistically significant differences and the assessment of method effectiveness. Correlation analysis: conducted to identify dependencies between plant growth parameters, microorganism activity, and changes in pollutant concentrations. Correlation analysis allowed the identification of the main factors influencing the effectiveness of bioremediation. Regression analysis: used to model bioremediation processes and predict changes in pollutant concentrations depending on time and applied methods. This allowed conclusions to be drawn about the long-term effectiveness of bioremediation and phytoremediation.

Research results

During the research conducted in Ayyrtau District of North Kazakhstan Region, the concentrations of various pollutants in soils before and after the application of biological cleaning methods were studied. Sites contaminated with heavy metals, pesticides, and petroleum products were used as research objects. Table 1 shows the change in concentrations of various pollutants in the soils of Ayyrtau District before and after the application of phytoremediation using different plants: sunflower, alfalfa, and willow.

Table 1 - Pollutant Concentrations Before and After Phytoremediation (mg/kg)

№	Pollutant	Before Cleaning	After Cleaning (Sunflower)	After Cleaning (Alfalfa)	After Cleaning (Willow)
1	Cadmium (Cd)	5.8	2.1	3.5	2.8
2	Lead (Pb)	45.2	18.6	22.4	19.7
3	Petroleum Products	320	110	95	105
4	Pesticides	12.5	4.5	3.8	4.2

The data in the table show that all three plants - sunflower, alfalfa, and willow - were effective in reducing the concentrations of heavy metals, petroleum products, and pesticides in the soil. The most significant reduction in pollutant concentrations was observed with the use of sunflower and alfalfa, making them preferable for phytoremediation in Ayyrtau District of North Kazakhstan Region. The effectiveness of various bioremediation methods in reducing pollutant concentrations in soil is presented in Table 2, i.e., the measurement results before cleaning, after biostimulation, bioventing, and bioaugmentation for four types of pollutants: cadmium (Cd), lead (Pb), petroleum products, and pesticides.

Table 2 - Pollutant Concentrations Before and After Bioremediation (mg/kg)

№	Pollutant	Before Cleaning	After Biostimulation	After Bioventing	After Bioaugmentation
1	Cadmium (Cd)	5.8	3.2	2.9	2.5
2	Lead (Pb)	45.2	24.8	22.3	20.1
3	Petroleum Products	320	135	125	115
4	Pesticides	12.5	5.6	4.9	4.3

Table 2 shows that bioremediation methods significantly reduced the concentration of cadmium. The most effective method was bioaugmentation, which reduced the concentration by 56.9 % from the initial value. The concentration of lead also decreased significantly after the application of all bioremediation methods. The most effective method was bioaugmentation, which reduced the lead level by 55.6 %. The levels of petroleum products also decreased significantly. Bioaugmentation showed the greatest efficiency, reducing the concentration of petroleum products by 64.1 %. Pesticides demonstrated a significant reduction in concentration. Bioaugmentation was the most effective method, reducing pesticide levels by 65.6 %. All bioremediation methods (biostimulation, bioventing, and bioaugmentation) showed a significant reduction in the concentrations of all studied pollutants. Bioaugmentation showed the greatest effectiveness among the methods, providing the most significant reduction in concentrations for all types of pollutants, thus being the most effective for soil cleaning. Change in the concentration of cadmium (Cd) in soils after various methods of biological remediation is shown in Figure 3.

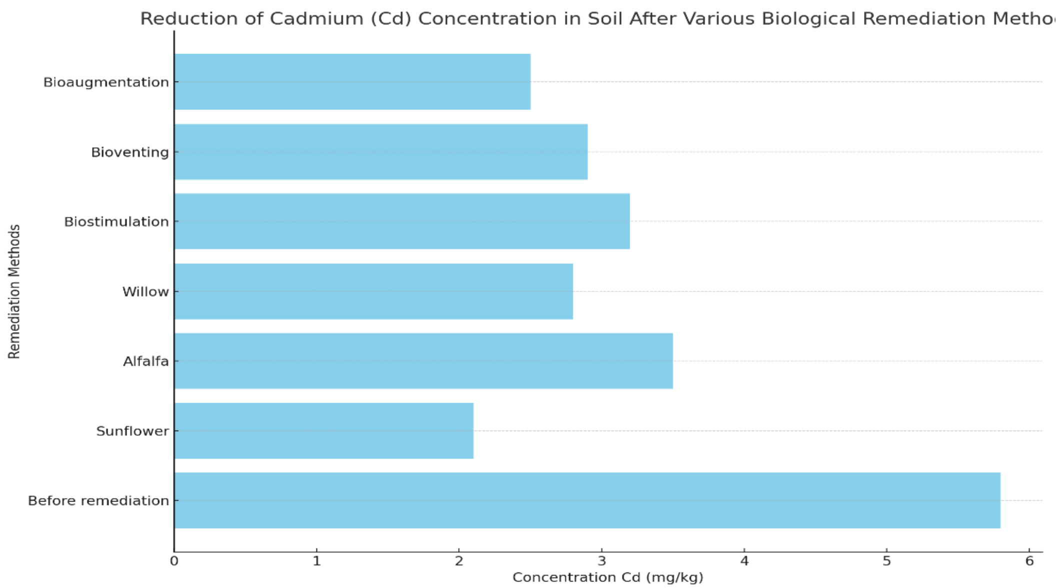

Figure 3 - Reduction of Cadmium (Cd) Concentration in Soils After Various Biological Cleaning Methods (Remark: Y-axis - Cd Concentration (mg/kg); X-axis Remediation Methods)

Figure 2. Proposed oil production waste management scheme. Oil waste streams. Figure 5 demonstrates the effectiveness of various biological methods in reducing cadmium (Cd) concentration in soil. The initial concentration of cadmium in the soil before remediation was 5.8 mg/kg, indicating a significant level of contamination. Phytoremediation using sunflower reduced the cadmium concentration to 2.1 mg/kg, showcasing its high efficiency in extracting cadmium from the soil. The application of alfalfa also significantly decreased the cadmium levels to 3.5 mg/kg. The use of willow further reduced the cadmium content to 2.8 mg/kg. The biostimulation method lowered the cadmium concentration to 3.2 mg/kg, while bioventing reduced it to 2.9 mg/kg. The bioaugmentation method proved to be effective as well, reducing the cadmium concentration to 2.5 mg/kg. These findings indicate that all examined biological remediation methods were effective in reducing cadmium concentrations in soil, with sunflower and bioaugmentation showing particularly high efficiency.

Figure 4 shows a decrease in the concentration of petroleum products in the soil after the application of various methods of biological remediation shows the reduction of oil products concentration in soil after applying various biological remediation methods. Bioaugmentation. This method shows a significant reduction in oil product concentration compared to the initial concentration before remediation. Bioventing. This method also effectively reduces the concentration, but slightly less than bioaugmentation. Biostimulation. This method is on par with bioventing in terms of reducing oil product concentration. Phytoremediation (using plants).

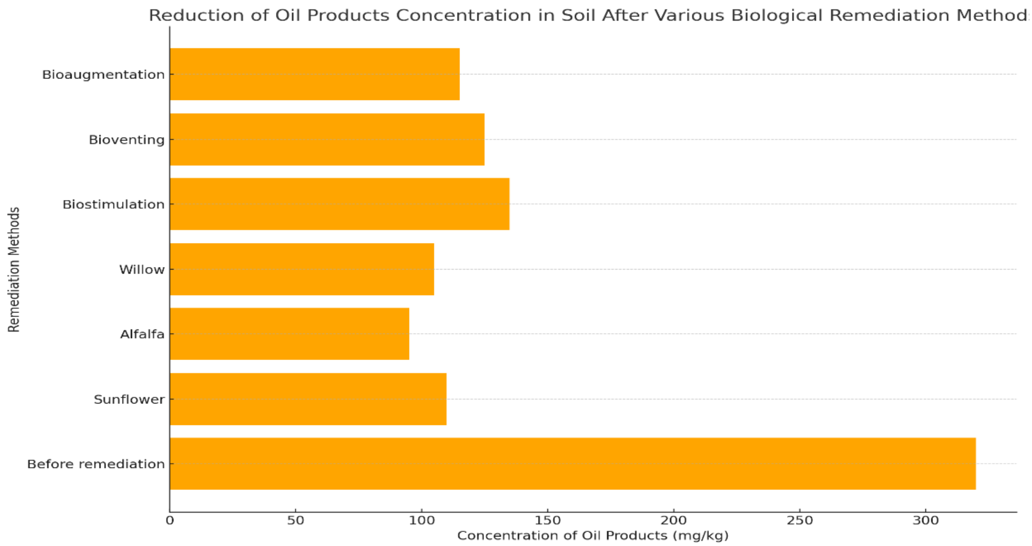

Figure 4 - Reduction of Petroleum Products Concentration in Soils After Various Biological Cleaning Methods

Willow: Shows a moderate reduction in oil product concentration. Alfalfa: Exhibits a lower reduction compared to willow but still effective. Sunflower: Demonstrates a significant reduction in oil product concentration, comparable to biostimulation. Comparison with Initial Contamination. The concentration of oil products before remediation is the highest, serving as a baseline. All tested methods show a substantial decrease in contamination levels, highlighting their effectiveness in reducing oil product concentration in soils. Biological methods such as bioaugmentation, bioventing, and biostimulation show higher efficiency in reducing oil concentrations compared to phytoremediation methods (using plants like willow, alfalfa, and sunflower).

Figure 5 illustrates the effectiveness of various biological methods in reducing pesticide concentration in soil.

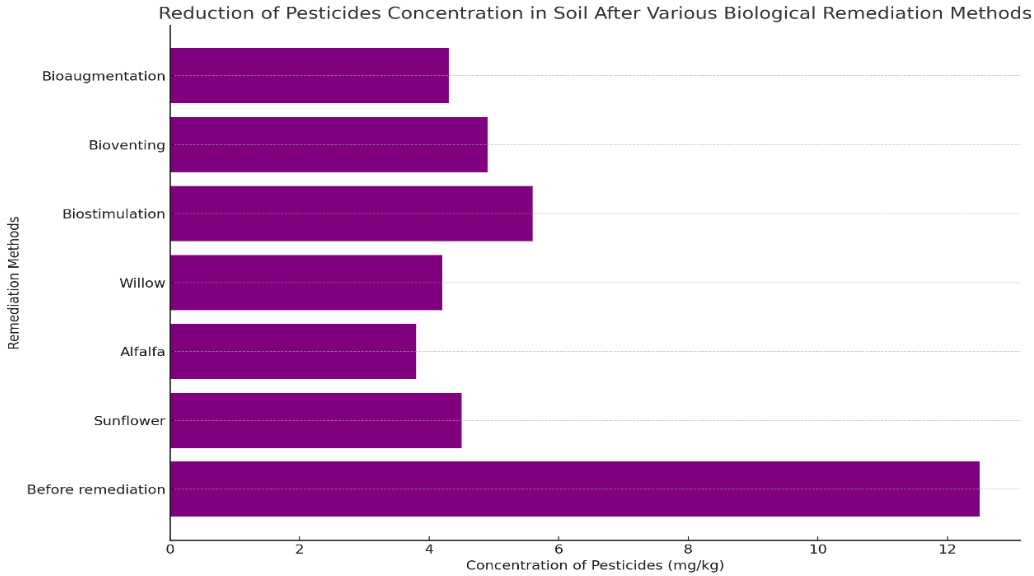

Figure 5 - Reduction of Pesticides Concentration in Soils After Various Biological Cleaning Methods

The initial pesticide concentration before remediation was 12.5 mg/kg, indicating a significant level of contamination. The application of phytoremediation using sunflower resulted in a reduction of pesticide concentration to 4.5 mg/kg, demonstrating its high efficiency in removing pesticides from the soil. Alfalfa also significantly reduced pesticide levels to 3.8 mg/kg, while willow decreased it to 4.2 mg/kg. The biostimulation method lowered the pesticide concentration to 5.6 mg/kg, while bioventing reduced it to 4.9 mg/kg. The bioaugmentation method proved to be effective as well, reducing the pesticide concentration to 4.3 mg/kg. These results indicate that all the examined biological remediation methods were effective in reducing pesticide concentrations in soil, with alfalfa and sunflower showing particularly high efficiency.

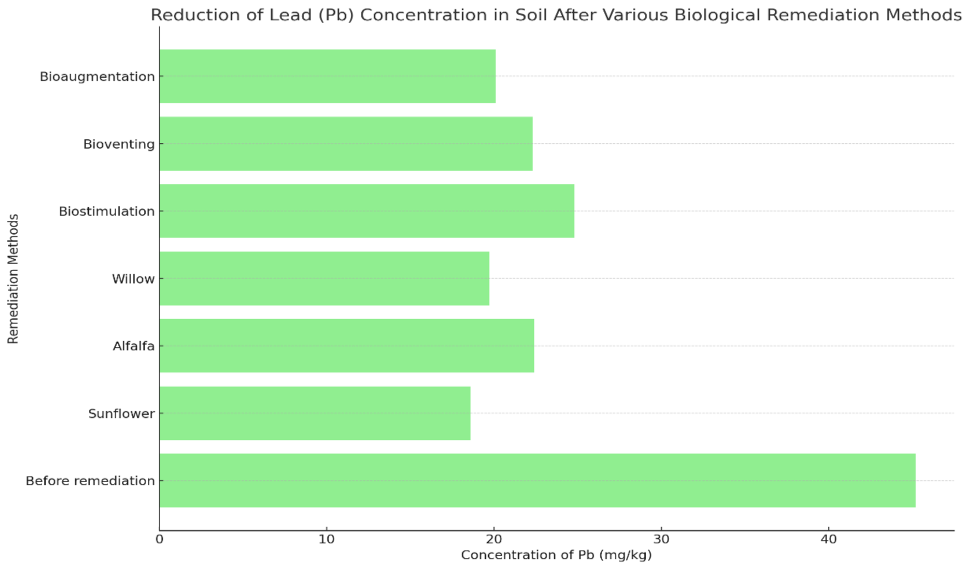

Figure 6 - Reduction of Lead (Pb) Concentration in Soils After Various Biological Cleaning Methods

Figure 5 illustrates the effectiveness of various biological methods in reducing lead contamination levels in soil. The initial concentration of lead in the soil before remediation was 45.2 mg/kg, indicating a significant level of pollution. Using the phytoremediation method with sunflower, the lead concentration decreased to 18.6 mg/kg, demonstrating the high efficiency of this plant in extracting lead from the soil. Application of alfalfa also resulted in a significant reduction of lead concentration to 22.4 mg/kg. The use of willow further reduced the lead content to 19.7 mg/kg. The figure shows that the biostimulation method decreased the lead concentration to 24.8 mg/kg, while the bioventing method reduced the lead content to 22.3 mg/kg. Meanwhile, the bioaugmentation method proved to be the most effective among the bioremediation techniques, lowering the lead concentration to 20.1 mg/kg.

Discussion

Data analysis showed that soil pollution levels in Ayyrtau District significantly exceed acceptable norms for agricultural lands. The concentrations of heavy metals, pesticides, and petroleum products indicate the need for soil cleaning and restoration measures.

Heavy Metals: The concentrations of cadmium and lead significantly exceed background values, requiring the use of bioremediation and phytoremediation methods for their reduction.

Pesticides: High concentrations of pesticides can adversely affect the health of the population and the ecosystem, necessitating the use of biological cleaning methods.

Petroleum Products: Pollution with petroleum products requires measures for the degradation of organic pollutants using microorganisms and plants. The conducted studies highlight the need for an integrated approach to solving the soil pollution problem in Ayyrtau District. Biological cleaning methods, such as phytoremediation and bioremediation, showed high efficiency in reducing pollutant concentrations and restoring soil fertility. Implementing these methods in practice can significantly improve the environmental situation in the region and contribute to sustainable land resource management.

Phytoremediation: Plants such as sunflower and alfalfa showed the greatest efficiency in reducing soil lead concentration. Sunflower especially stands out as the most effective plant for phytoremediation of lead.

Bioremediation: Bioremediation methods also demonstrate significant reductions in lead concentration, with the best results in bioaugmentation. Each of the bioremediation methods (biostimulation, bioventing, bioaugmentation) is effective in reducing the concentration of all considered pollutants. The most effective method for all pollutants is bioaugmentation, as it leads to the greatest reduction in pollutant concentrations. The reduction in pollutant concentrations varies depending on the method, but in all cases, there is a significant decrease compared to the initial values before cleaning. Research has shown that the application of phytoremediation and bioremediation in Ayyrtau District contributes to a significant reduction in the concentrations of heavy metals and organic pollutants in the soil. The most effective were combined methods that combine the use of plants and microorganisms. It is important to note that the choice of a specific method depends on the type of pollutant and soil characteristics.

Conclusion

Research has shown that combined methods (phyto- and bioremediation), combining the use of plants and microorganisms, are the most effective for reducing pollutant levels and restoring soil fertility. Implementing these methods in practice can significantly improve the ecological state of the region and increase its agricultural potential. When comparing bioremediation methods, the high effectiveness of the bioaugmentation method in reducing the concentrations of various pollutants in the soil has been demonstrated. The use of this method creates the prerequisites for effective cleaning of contaminated lands. Biological cleaning of soils in Ayyrtau District of North Kazakhstan Region is a promising and environmentally safe method of land resource restoration, as well as an effective method for reducing pollutant levels.

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