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INNOVATIVE SOIL RECLAMATION METHODS IN THE CONTEXT OF FOOD SECURITY

Summary

Background. Soil contamination by heavy metals poses a significant threat to agricultural productivity and food security, requiring effective remediation technologies. Despite growing interest in innovative soil restoration methods, their economic efficiency and comparative effectiveness remain insufficiently studied. This research aims to assess the environmental and economic performance of three innovative soil remediation methods (phytoremediation, bioremediation and chemical stabilization) under the conditions of the Kyiv Region, Ukraine.

Results and conclusions. The study was based on experimental data from three 1-hectare agricultural sites monitored between 2023 and 2024. Chemical stabilization proved the most effective method for restoring acid-base balance, achieving a pH increase of +57.8 % (from 4.5 to 7.1) over 12 months, while phytoremediation showed the least effect (+15.6 %). For increasing soil organic carbon content, bioremediation demonstrated the best results (+28 %), whereas chemical stabilization provided only +10 %. Regarding heavy metal reduction, chemical stabilization was the most efficient, reducing cadmium by 45 % and lead by 50 %, while phytoremediation showed the lowest performance (cadmium: -18 %, lead: -22 %). From an economic perspective, bioremediation was the most advantageous method, generating a positive net profit (3,250 UAH/ha) and achieving a return on investment of 24.1 %, indicating full cost recovery within one year. Phytoremediation resulted in a negative net profit (-1,400 UAH/ha) and ROI of -10.6 %, while chemical stabilization yielded a minimal profit (200 UAH/ha) with ROI of only 1.45 %. The findings indicate that these unique soil remediation approaches were economically viable and constitute a promising agricultural soil restoration strategy in Ukraine. Bioremediation ensures an optimum balance between environmental effectiveness and economic profitability, whereas chemical stabilization guarantees the biggest reduction of heavy metals contamination.

Key words: return on investment, chemical stabilization, heavy metals, lead, cadmium, food security

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Introduction

Regular research into innovative soil remediation solutions is essential for increasing land fertility and ensuring food security under conditions of anthropogenic pressure. Heavy metal contamination can have an adverse impact on agriculture by reducing crop yield and diminishing the quality and safety of food products. According to a study conducted by Tsytsyura et al. [48], the use of phytoremediation significantly reduced the risk of contamination spread, which in turn contributed to improved economic efficiency in agricultural production through lower land reclamation costs and increased crop yields. Although contaminated soils may contain multiple potentially toxic elements, an agroecological remediation assessment commonly prioritizes metals as the most directly linked to food-chain transfer and regulatory thresholds. Accordingly, this manuscript focuses on cadmium (Cd) and lead (Pb) as the target contaminants and the primary effectiveness endpoints, reflecting their high relevance to cereal safety and their frequent use in agroecological risk and remediation assessment literature [3; 52; 47]. The issue was examined by Pidlisnyuk et al. [32], whose research demonstrated that the high phytoremediation potential of miscanthus serves as an effective tool for restoring soils contaminated with heavy metals.

A pressing challenge remains the lack of optimal technologies for rehabilitating degraded soils, particularly through the use of energy crops – plants capable of accumulating inorganic pollutants in their roots and decomposing organic contaminants in the soil. Research in this field has been conducted by Repetskyi and Yefremova [35], who studied various soil remediation methods, including phytoremediation, bioremediation and the use of sorbents to reduce heavy metal contamination. Based on their findings, the authors recommended the implementation of crop rotation, phytoremediation, chemical reclamation and land recultivation. The issue of soil contamination by radionuclides, heavy metals, pesticides, oil and petroleum products remains a significant concern for contemporary ecologists. Boretska et al. [1] addressed the problem of ecological rehabilitation of technogenically contaminated soils using phytoremediation. Their research recommended cultivating energy crops such as miscanthus, willow and poplar.

The study of the chemical effects of heavy metal emissions into the soil has gained particular importance as a consequence of military activities. According to Holubtsov et al. [15], the detonation of ammunition introduces substantial amounts of heavy fractions and metals directly into the soil environment, significantly exacerbating localized contamination. One of the major environmental issues is the contamination of soils by petroleum product emissions. In a study conducted by Nakonechnyi et al. [29], the feasibility of applying biological methods to restore soils contaminated with petroleum products was substantiated through the use of specialized microorganisms capable of hydrocarbon biodegradation. The authors demonstrated that the use of bioremediation, particularly phytoremediation and microbiological treatment, reduced the concentration of toxic substances and contributed to the restoration of soil natural properties.

The problem of soil contamination by heavy metals and their impact on the environment remains relevant under increasing anthropogenic pressure and the need to develop effective reclamation methods, as shown in the research of Mosayyebi & Zaimoğlu [28]. According to their findings, the phytoremediation method, which is less costly than physical and chemical remediation approaches, proved to be more effective when combined with electrostimulation technology. The application of electric current enhanced the removal of heavy metals from contaminated soil by stimulating plant uptake. The issue of soil degradation and environmental pollution remains significant under growing anthropogenic pressure and climate change, as noted in the scientific study of Phang et al. [31]. The researchers found that phytoremediation proved to be an economically viable strategy for reducing pollution levels, as it improved soil quality and was also applied for biofortification – enriching crops with essential trace elements and nutrients during their growth.

The study of the underexplored aspects of the limited application of phytoremediation has become increasingly urgent in modern conditions. Wang and Delavar [51] recommended the use of phytoremediation in peri-urban regions and on low-value land, as this technology proved to be economically viable in rural areas and enabled long-term restoration of vegetation cover. Wang et al. [52] highlighted the need to develop more productive and better-adapted cultivars of Miscanthus×giganteus. They found that the root system of miscanthus effectively enhanced the distribution and transformation of key heavy metals, notably Pb and Cd.

Heavy metal soil pollution, especially Cd and Pb, hinders sustainable agricultural output in intensive land use and military locations [18, 17]. Chemical stabilization, bioremediation and phytoremediation have been studied, but their environmental efficacy and short-term economic performance in post-conflict agricultural landscapes are still difficult to quantify. Scientifically, it evaluates three Kyiv Region cleanup approaches in constant field settings. It quantifies Cd and Pb reduction, analyses soil chemical parameters (pH and organic carbon) and calculates crop productivity cost-benefit and return-on-investment over a year. While biodiversity and ecosystem-service benefits are crucial tothe sustainability of remediation, the current assessment program did not quantify them. They should be prioritized by future monitoring. The study quantifies Cd and Pb reduction kinetics, soil chemical parameters (pH and organic carbon) and crop productivity-related cost-benefit and return-on-investment assessments. An annual analysis of environmental and economic variables provides an evidence-based framework for selecting remediation options to minimize Cd and Pb mobility, restore soil fertility and increase food security.

The aforementioned research studied several remediation options, however, they did not compare their short-term environmental efficacy and economic performance under specific region conditions. In particular, these strategies must be assessed for their effects on pH, organic carbon and heavy metal concentrations and agricultural output. Their implications on biodiversity and ecosystem services must be studied over time. The primary aim of this research was to evaluate the comparative effectiveness of three innovative soil remediation methods (phytoremediation, bioremediation and chemical stabilization) using a clearly defined primary endpoint – the percentage reduction in Cd and Pb concentrations in soil after a 12-month remediation period. The objectives of the study were: (1) assessing changes in soil pH and organic carbon (OC) content; (2) evaluating the impact of remediation on wheat yield; and (3) determining the economic performance of each method through a net profit, return on investment (ROI) and a payback period analysis.

Materials and methods

The research was conducted between 2023 and 2024 on three sites (each with an area of 1 hectare) of agricultural land (arable fields and shelterbelts) located in the Kyiv Region. The aim was to improve the ecological condition of soil through the application of innovative remediation methods, including phytoremediation, bioremediation and chemical stabilization. Although the scope of the study is limited to these three experimental sites, they were purposefully selected to reflect typical soil characteristics and environmental conditions prevalent in the specific agricultural zones under investigation. The study was carried out in several stages: the selection of contaminated sites, the application of remediation agents, and the monitoring of changes over a 12-month period.

Potentiometric and titrimetric methods were employed to measure soil pH and organic carbon (OC). Flame AAS measured Cd and Pb concentrations. Based on DSTU ISO 10381 [44, 45], composite soil samples were taken from each 1-hectare plot for heavy metal analysis. Samples were homogenized, air-dried at room temperature and sieved through a 2 mm filter before analysis. Metal extraction required acid digestion of 1.0 g of dried soil with concentrated HNO_3 and HCl (*aqua regia*) under regulated heating conditions till mineral matrix breakdown. Filtered digests were diluted with deionized water.

Certified standard solutions of Cd and Pb with at least five concentration points encompassing the predicted sample concentration range were calibrated. To quantify, calibration curves with R^2 values of at least 0.995 were acceptable. LOD and LOQ were calculated using three and ten times the blank measurement standard deviation, respectively. For contamination control, procedural blanks were examined with each sample batch. Using certified reference soils, accuracy was verified with 90 ÷ 110 %

recovery rates. Triplicate samples were examined, and mean values with standard deviations under 5 % were provided. Cd and Pb concentration data was reliable and reproducible due to these quality assurance and quality control processes. The efficacy of remedial measures was assessed using an economic analysis.

The study employed methods for examining the physicochemical properties of soil, as established by legislative standards: State Standard of Ukraine (DSTU) and the International Organization for Standardization (ISO) – ISO 10381-1:2004 "*Soil quality – Sampling – Part 1: Guidance on the Design of Sampling Programs*" [46]; DSTU ISO 10381-2:2004 "*Soil quality – Sampling – Part 2: Guidance on Sampling Methods*" [44]; and DSTU ISO 10381-5:2009 "*Soil quality – Sampling – Part 5: Guidance on the Investigation Procedure of Urban and Industrial Sites for Soil Contamination*" [45].

During the 2024 monitoring phase, key soil parameters were measured, including pH, OC content and the concentrations of heavy metals (Cd and Pb), as well as wheat yield, which served as an indicator of the effectiveness of the implemented measures. The chemical characteristics of the soil included: pH – acidity or alkalinity of the soil, influencing nutrient availability to plants; OC content (%) – a measure of the level of organic matter in the soil, crucial for soil fertility and water-holding capacity; heavy metals Cd and Pb (mg/kg) – toxic elements that may accumulate in the soil and negatively affect vegetation and human health; wheat yield (c/ha) – the amount of grain produced per unit area (centners per hectare), serving as the main indicator of crop productivity and soil quality following remediation or exposure to pollutants. To calculate the percentage reduction in heavy metal content, the following formula (1) was used:

$$\text{Percentage reduction} = \frac{\text{Initial content} - \text{Final content}}{\text{Initial content}} \times 100\ \% \qquad (1)$$

where: percentage reduction in heavy metal content (%); initial content is the concentration of heavy metals in the soil before the influence of a specific factor (for example, before remediation measures or exposure to a pollution source) (mg/kg); and final content is the concentration of heavy metals in the soil after the influence of the studied factor (mg/kg).

To calculate an increase in crop yield after remediation, the formula (2) was applied:

$$\text{Yield increase} = \frac{\text{Yield after remediation} - \text{Yield before remediation}}{\text{Yield before remediation}} \times 100\ \% \qquad (2)$$

where: yield increase after remediation (c/ha); yield after remediation represents the yield of the agricultural crop following soil remediation measures (c/ha); and yield before remediation represents the yield of the same crop on the same field prior to remediation (c/ha). The cost of each remediation method (including expenses for materials, labor and infrastructure) was calculated using formula (3), which allows for the assessment of total expenditures for each soil remediation approach:

$$\text{Method cost} = \text{Material costs} + \text{Labor costs} + \text{Infrastructure costs} \quad (3)$$

where: method cost (UAH/ha); material costs is the total cost of all substances and components used in the remediation process (adsorbents, reagents, biopreparations, etc.) (UAH/ha); labor costs represent expenditures related to personnel wages and associated payments involved in soil decontamination activities (salaries, insurance contributions, etc.) (UAH/ha); and infrastructure costs include expenses for the rental, maintenance and operation of equipment, transport, facilities and sites required for the remediation process (UAH/ha). The payback period was calculated using the formula (4):

$$\text{PP} = \left(\frac{\text{Remediation costs}}{A\text{nnual profit}}\right) \quad (4)$$

where: PP is the payback period (years); remediation costs are the total expenses associated with remediation (UAH/ha); and annual net profit is the yearly net income from crop production after remediation (UAH/ha). Special cases:

- if a net profit is negative, the payback period cannot be determined (the investment is unprofitable);
- if a net profit equals zero, payback is unattainable (ROI = 0 %);
- the shorter the payback period, the faster invested funds are recovered.

The economic effect of the yield increase was calculated using the formula (5):

$$\text{EE} = \text{Income from yield after remediation} - \text{Income from yield before remediation} \quad (5)$$

where: EE is the economic effect (UAH/ha); income from yield after remediation is the income in 2024 (UAH/ha); and income from yield before remediation is the income in 2023 (UAH/ha).

The study employed the following instruments, tools and devices: a potentiometric meter for determining soil pH (manufactured in the USA), which enabled the measurement of soil acidity or alkalinity, essential for assessing nutrient availability to plants; a titrator for determining the OC content in soil (manufactured in Germany), selected for its ability to accurately assess the level of organic matter contributing to soil fertility and water retention capacity; an atomic absorption spectrophotometer for measuring the concentrations of heavy metals, specifically Cd and Pb, in soil (manufactured in Japan), chosen for its precision in detecting toxic element concentrations critical for evaluating soil contamination and potential ecological impacts; and agronomic instruments for monitoring wheat yield, including grain scales produced by Ukrmetkomplekt Limited Liability Company (LLC) and measuring devices for calculating yield per unit area, such as agronomic yield sensors (manufactured in Ukraine), which ensured an accurate assessment of harvested crop data and supported the optimization of agrotechnical measures and planning.

Results and discussion

Food security is a condition in which all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and preferences for an active and healthy life. It is based on four key components: food availability, access, stability of supply and proper food utilization. Soil quality directly affects all these aspects, as soil degradation, contamination with toxic substances, depletion of organic matter or changes in the acid-base balance reduce both the yield and quality of agricultural produce. In this context, innovative remediation methods, such as phytoremediation, biological detoxification, the application of nanotechnologies and the use of microbiological consortia, are becoming critically important for restoring soil fertility, preventing crop losses and ensuring sustainable agricultural production. Ensuring food security under conditions of climate change, population growth and anthropogenic pressure is impossible without a systematic approach to soil restoration.

In contemporary conditions, the concept of food security is increasingly integrated with sustainable development, ecological balance and climate change adaptation [27, 38, 54]. According to the definition of the Food and Agriculture Organization of the United Nations (FAO), food security is achieved when every person, at all times, has physical, social and economic access to sufficient, safe and nutritious food necessary for an active and healthy life. According to Shebanin et al. [41], effective remediation of war-damaged soil is a critically important prerequisite for restoring agricultural potential and ensuring food security in Ukraine. Soil forms the foundation of agricultural productivity [2, 11]. Soil health is directly linked to crop yield, food quality and the stability of agricultural production. Degraded, polluted or depleted soil cannot sustain adequate levels of agricultural output, leading to reduced food resources, rising food prices and increased social tension [26, 39, 49]. This issue is particularly relevant in the countries where a significant proportion of their population is engaged in agriculture or relies on local food production. As noted by Drobitko and Alakbarov [7], the restoration of soil following demining is an essential condition for returning land to agricultural use, while bioremediation and phytoremediation can ensure safe and effective decontamination.

In this context, food security directly depends on a society’s ability to maintain or restore soil fertility, including in the areas affected by anthropogenic impact, industrial pollution, unsustainable land use or military activity. Therefore, innovative soil remediation technologies represent not only an environmental solution, but also a socioeconomic instrument for ensuring national food independence. Moreover, climate instability poses a particular threat to food security, leading to droughts, erosion, loss of soil cover, alterations in the hydrological regime and an increasing extent of degraded land. According to United Nations (UN) estimates, around 33 % of the world's soils are already degraded, posing a threat to 95 % of global food production, which directly depends on soil condition. Therefore, food security in the twenty-first century represents, on the one hand, a strategic national priority and, on the other, a challenge for science, which must develop effective, scalable and safe methods for soil restoration. The application of innovative bio-, eco- and nanotechnologies in soil remediation not only improves land use quality, but also ensures stable conditions for cultivating environmentally friendly produce, which serves as a foundation for food security at both local and global levels [14, 23, 24, 33].

With the growing demand for food and increasing soil degradation caused by anthropogenic factors, innovative remediation methods have become key tools for ensuring sustainable agriculture. Phytoremediation employs plants to extract, stabilize or degrade pollutants and is particularly effective for removing heavy metals (phytoextraction) and organic contaminants (phytodegradation). Bioremediation involves the use of microorganisms (bacteria and fungi) to decompose pollutants, proving to be effective for the breakdown of organic compounds such as petroleum products and pesticides. Chemical stabilization is defined as the application of chemical reagents (such as phosphates, hydroxides and silicates) to bind pollutants and reduce their mobility. This method is the most effective for treating heavy metals, as they form insoluble compounds. The objects of comparison among the three innovative technologies influencing soil ecological condition were phytoremediation, bioremediation and chemical stabilization. The comparison criteria concerned the effectiveness of each soil restoration method in altering pH levels over a 12-month period. Table 1 presents the results of a comparative analysis of the efficiency of different soil remediation methods based on the pH dynamics from 2023 to 2024. Phytoremediation contributed to a slight increase in pH in 2024, whereas bioremediation and chemical stabilization led to a more pronounced improvement in the acid-base balance. This indicated that bioremediation proved to be the most effective method for achieving a neutral pH, while chemical stabilization resulted in an alkaline environment. Each method enhanced soil pH to varying degrees, with chemical stabilization demonstrating the most substantial capacity to neutralize acidity, effectively shifting the environment from highly acidic to neutral.

Table 1. Dynamics of soil pH changes from 2023 to 2024

Method	Initial soil pH (2023)	Soil pH after 12 months (2024)	Relative change in soil pH (2023 ÷ 2024) [%]
Phytoremediation	4.5	5.2	+15.6
Bioremediation	4.5	6.3	+40
Chemical stabilization	4.5	7.1	+57.8

Explanatory notes: compiled by the authors

Bioremediation closely followed, also significantly shifting the soil towards a more neutral state, whereas phytoremediation offered only a marginal improvement in the acid-base balance, suggesting it might be less suitable for highly acidic soils requiring rapid neutralization. The shift in pH towards a neutral or slightly alkaline environment, particularly as a result of bioremediation and chemical stabilization, improved conditions for the growth of most agricultural crops, thereby reducing the need for liming and other costly agrotechnical measures. In the study of soil OC content before and after remediation, the comparison criteria included the effectiveness of different remediation methods, the dynamics of OC changes, the percentage increase in OC following remediation, and the duration of the impact of the methods. Table 2 presents the dynamics of soil OC content before and after remediation activities during the 2023 ÷ 2024 period.

Table 2. Soil OC content before and after remediation [%] from 2023 to 2024

Method	Initial soil OC content before remediation [%] (2023)	Soil OC content after remediation (12 months later) (2024) [%]	Relative change in soil OC content (2023 ÷ 2024) [%]
Phytoremediation	2.1	2.42	+15
Bioremediation	2.1	2.69	+28
Chemical stabilization	2.1	2.31	+10

Explanatory notes: compiled by the authors

The data presented show an increase in OC levels 12 months after the application of different remediation methods. All tested methods successfully enriched the organic matter of the soil over the monitoring period. Bioremediation emerged as the vastly superior approach for organic carbon accumulation, significantly outperforming both phytoremediation, which yielded a moderate enhancement, and chemical stabilization, which provided the least benefit in terms of organic enrichment. The findings indicate that bioremediation exhibited the greatest potential for enhancing the organic component of the soil. The 10 ÷ 28 % rise in OC content contributed to improved soil fertility, which can reduce fertilizer costs and enhance the resilience of agroecosystems to climate change – an important factor for long-term economic sustainability.

According to Gamayunova et al. [12], straw, as a resource-saving technology element, represents an effective bioremediation method that enhances fertility and supports a sustainable agricultural production cycle. During their study, Ndour et al. [30] found that the application of organic, mineral and microbial amendments during phytoremediation not only enhanced the phytostabilization, phytoextraction and phytodegradation of pollutants, but also positively affected soil microbiota, nutrient enrichment, plant growth and carbon sequestration processes. Singh et al. [42] reported that the heavy metal pollution index ranged from 1.84 to 6.62, with particularly high metal concentrations accumulating in plants growing on plots from S10 to S17. Shahini et al. [40] demonstrated that organic nitrogen fertilizers not only increase crop yield, but also contribute to the restoration of soil structure and biological activity, making them an effective tool for soil remediation.

Eissa and Rekaby [10] investigated the use of halophytic crops for remediating contaminated soils and showed that halophytes such as *Salicornia europaea, Suaeda maritima, Atriplex halimus, Spartina alterniflora, Tamarix* spp. and *Limonium vulgare* were highly effective in accumulating heavy metals, particularly, Kaddour and Kissar [22] noted that soil contamination was especially pronounced for Cd and lead (Pb), with concentrations exceeding the recommended maximum permissible limits (MPLs). As reported by Makarova et al. [25], agroamelioration using phosphogypsum is an effective technology for remediating saline soils and improving their productivity under the conditions of the northern steppe of Ukraine. The comparison criteria included the effectiveness of innovative methods in reducing the concentrations of heavy metals in soil, specifically Cd and Pb, over a 12-month period. The reduction in Cd content using the different methods was calculated as follows:

1. Effectiveness of phytoremediation (formula 6):

$$\%\text{reduction} = \frac{1.5 - 1.23}{1.5} \times 100\ \% = \frac{0.27}{1.5} \times 100\ \% = 18\ \% \tag{6}$$

2. Effectiveness of bioremediation (formula 7):

$$\%\text{reduction} = \frac{1.5 - 0.98}{1.5} \times 100\ \% = \frac{0.52}{1.5} \times 100\ \% = 34.67\ \% \approx 35\ \% \tag{7}$$

3. Effectiveness of chemical stabilization (formula 8):

$$\%\text{reduction} = \frac{1.5 - 0.83}{1.5} \times 100\ \% = \frac{0.67}{1.5} \times 100\ \% = 44.67\ \% \approx 45\ \% \tag{8}$$

The reductions in Pb content were calculated similarly:

1. Effectiveness of phytoremediation (formula 9):

$$\%\text{reduction} = \frac{40 - 31.2}{40} \times 100\ \% = \frac{8.8}{40} \times 100\ \% = 22\ \% \tag{9}$$

2. Effectiveness of bioremediation (formula 10):

$$\%\text{reduction} = \frac{40 - 24}{40} \times 100\ \% = \frac{16}{40} \times 100\ \% = 40\ \% \tag{10}$$

3. Effectiveness of chemical stabilization (formula 11):

$$\%\text{reduction} = \frac{40 - 20}{40} \times 100\ \% = \frac{20}{40} \times 100\ \% = 50\ \% \tag{11}$$

Table 3 presents the results of changes in Cd and Pb concentrations (mg/kg) in the soils of the Kyiv Region from 2023 to 2024, according to the different remediation methods. An analysis of the data indicated that chemical stabilization exhibited the highest efficacy in immobilizing heavy metals, reducing soil Cd from 1.5 to 0.83 mg/kg and Pb from 40 to 20 mg/kg over 12 months [4, 13]. For wheat, the most directly relevant food-safety benchmarks are the maximum levels in Regulation (EC) No. 1881/2006 [5] and Regulation (EC) No. 396/2005 [34]: 0.20 mg/kg for Pb in unprocessed cereals and pulses and 0.20 mg/kg for Cd in wheat grain (and rice grain) intended for direct consumption. For the soil compartment, hygienic guidance values specify a permissible total Pb content of 32 mg/kg and indicative permissible total Cd concentrations of 0.5 ÷ 2.0 mg/kg depending on soil group [20, 21]. Accordingly, Pb after chemical stabilization remained below the soil threshold, while Cd fell within the indicative range; however, compliance with food-product limits requires direct Cd/Pb analysis of harvested grain [19].

Table 3. Changes in Cd and Pb concentrations [mg/kg] in soils of the Kyiv Region from 2023 to 2024

Method	Initial Cd concentration in soil in 2023 [mg/kg]	Cd concentration in soil in 2024 (after 12 months) [mg/kg]	Relative change in Cd concentration over 12 months (2023 ÷ 2024) [%]	Initial Pb concentration in soil in 2023 [mg/kg]	Pb concentration in soil in 2024 (after 12 months) [mg/kg]	Relative change in Pb concentration over 12 months (2023 ÷ 2024) [%]
Phytoremediation	1.5	1.23	-18	40	31.2	-22
Bioremediation	1.5	0.98	-35	40	24	-40
Chemical stabilization	1.5	0.83	-45	40	20	-50

Explanatory notes: compiled by the authors

Based on the findings of Drobitko et al. [8], in the areas affected by military activity, the levels of multiple toxic substances (e.g. polycyclic aromatic hydrocarbons

(PAHs), sulphur dioxide and nitrogen oxides) may exceed permissible limits, while elevated soil acidity can facilitate the spread of potentially toxic elements (including Pb, Cu and molybdenum (Mo)) and explosive residues (TNT, RDX, pentaerythritol tetranitrate). This underscores the need to identify effective remediation approaches as a prerequisite for ecosystem restoration.

In this context, the study by Zgorelec et al. [53] demonstrated that miscanthus is suitable for phytostabilization and biomass cultivation on soils contaminated with Cd and mercury (Hg). These conclusions are consistent with the view that the use of this plant represents a promising strategy for soil remediation, while also providing biomass that can be utilized as an energy source or for biofuel production.

Measurable improvements in soil ecological indicators directly underpin the subsequent financial outcomes of the remediation efforts. Specifically, the shift in pH towards a more neutral or slightly alkaline environment improves growth conditions for most agricultural crops. Concurrently, the 10 ÷ 28 % rise in organic carbon content enhances soil fertility, which is an important factor for long-term economic sustainability. Furthermore, the substantial reduction in cadmium and lead concentrations makes the agricultural products safer, consequently increasing their market value and enhancing their price competitiveness. These combined environmental benefits create optimal conditions for plant development, seamlessly translating into higher crop yields that ultimately reduce per-unit production costs and boost the overall profitability of agricultural enterprises.

For comparing different remediation methods, it is necessary to establish criteria for evaluating effectiveness, such as crop yield (c/ha) before remediation in 2023 and yield (c/ha) twelve months later at the end of 2024. The calculation of the yield increase following remediation in 2024 was conducted as follows:

1. Effectiveness of phytoremediation (formula 12):

$$\text{Yield increase} = \frac{33.6 - 30}{30} \times 100\ \% = 12\ \% \tag{12}$$

2. Effectiveness of bioremediation (formula 13):

$$\text{Yield increase} = \frac{37.5 - 30}{30} \times 100\ \% = 25\ \% \tag{13}$$

3. Effectiveness of chemical stabilization (formula 14):

$$\text{Yield increase} = \frac{36 - 30}{30} \times 100\ \% = 20\ \% \tag{14}$$

Table 4 presents the results before and after the implementation of remediation measures. The restorative effects on soil health directly translated into enhanced agricultural productivity across all experimental plots. Bioremediation fostered the most significant surge in crop yield, underscoring its dual benefit of soil restoration and agronomic promotion, while chemical stabilization and phytoremediation offered moderate and modest productivity boosts, respectively. The 12 ÷ 25 % rise in yield following the use of innovative remediation techniques had a direct impact on the agro-industrial economy. Increased yields reduced production costs per unit of output and enhanced the profitability of agricultural enterprises. Rusănescu et al. [37] recommended bioremediation methods to reduce soil contamination with PAHs, specifically rhizoremediation, phytoremediation and electrokinetic bioremediation, as effective strategies for detoxifying polluted areas. Cosmo et al. [6] examined the remediation of contaminated sites using bioremediation (employing living organisms) and phytoremediation with plants such as Cajanus cajan and Crotalaria.

Table 4. Increase in crop yield following remediation in 2024

Method	Yield before remediation in 2023 [c/ha]	Yield after 12 months in 2024 [c/ha]	Relative change in yield after remediation over 12 months (2023-2024) [%]
Phytoremediation	30	33.6	+12
Bioremediation	30	37.5	+25
Chemical stabilization	30	36	+20

Explanatory notes: compiled by the authors

In this study, the main criteria for comparison were based on key performance indicators, including remediation costs, yield growth before and after remediation, income from crop production before and after remediation, total costs following remediation, and the payback period for each method. An economic analysis was conducted, including the calculation of the costs of each remediation method (materials, labor and infrastructure), the balance before and after remediation, the payback period and the economic effect of increased crop yield following remediation. Table 5 presents the results of the economic analysis of various soil remediation methods.

Additional information regarding the distribution of costs, based on the nature of each remediation method, is presented as follows:

1. Phytoremediation (13,200 UAH/ha):
    - materials – 40 % (5,280 UAH): costs for purchasing plants, fertilizers and plant protection products;
    - labor – 40 % (5,280 UAH): costs for the workforce involved in planting, plant care and harvesting;
    - infrastructure – 20 % (2,640 UAH): costs for equipment, transportation, land rental and technical maintenance.

Table 5. Economic analysis of innovative soil remediation methods

Method	Total costs and remediation costs (materials, labor, infrastructure) in 2024 [UAH/ha]	Production costs (materials, labor, infrastructure) [UAH/ha]	Yield before remediation [c/ha]	Yield after remediation in 2024 [c/ha]	Revenue 2023 [UAH/ha]	Revenue 2024 [UAH/ha]	Balance 2023 [UAH/ha]	Balance 2024 [UAH/ha]	Economic effect [UAH/ha]*
Phytoremediation	13,200	12,000	20	23.6	10,000	11,800	-2,000	-1,400	+600
Bioremediation	13,500	12,000	26	33.5	13,000	16,750	+1,000	+3,250	+2,250
Chemical stabilization	13,800	12,000	22	28	11,000	14,000	-1,000	+200	+1,200

Explanatory notes: compiled by the authors; * – this indicator reflects the difference in revenue.

Explanatory notes on calculations:

1. Remediation costs: separately calculated costs associated directly with the soil-cleaning process (materials, labor, equipment).

Production costs: typical agronomic expenses for crop cultivation (sowing, soil treatment, fertilizers, etc.).

2. Revenue: yield × 500 UAH/c (average market price in 2023).
3. Revenue: yield × 500/550/600 UAH/c (reflecting potential quality premiums after remediation; average market price in 2024).
4. Profit: revenue 2024 − total costs 2024.
5. ROI calculation was performed using the following formula (15):

$$\mathrm{ROI} = (\text{Additional profit from remediation}/\text{Remediation costs}) \times 100\,\% \tag{15}$$

6. Economic effect: revenue 2024 − revenue 2023.

2. Bioremediation (13,500 UAH/ha):
   - materials – 50 % (6,750 UAH): costs for bioproducts, microbial growth stimulators and materials for soil application;
   - labor – 30 % (4,050 UAH): costs for soil preparation, application of bioproducts and monitoring and controlling the process;
   - infrastructure – 20 % (2,700 UAH): costs for specialized equipment, machinery for material distribution and logistics.
3. Chemical stabilization (13,800 UAH/ha):
   - materials – 45 % (6,210 UAH): costs for chemical reagents, stabilizers and additional soil treatment materials;
   - labor – 35 % (4,830 UAH): costs for applying chemicals and monitoring the stabilization process;
   - infrastructure – 20 % (2,760 UAH): costs for soil treatment equipment and transportation of chemical reagents.

The calculation of the total cost of each remediation method (materials, labor, infrastructure) was performed as follows:

1. For phytoremediation (formula 16):

$$\text{Method cost} = 5{,}280 + 5{,}280 + 2{,}640 = 13{,}200\ \text{UAH/ha} \tag{16}$$

2. For bioremediation (formula 17):

$$\text{Method cost} = 6{,}750 + 4{,}050 + 2{,}700 = 13{,}500\ \text{UAH/h} \tag{17}$$

3. For chemical stabilization (formula 18):

$$\text{Method cost} = 6{,}210 + 4{,}830 + 2{,}760 = 13{,}800\ \text{UAH/ha} \tag{18}$$

Economically, the methods presented divergent viabilities. Despite its low initial implementation costs, phytoremediation failed to generate a positive financial return within the given timeframe. Bioremediation proved to be the most economically sound strategy, successfully balancing implementation expenses with substantial agricultural revenue gains. Conversely, steep costs associated with chemical stabilization largely negated its agricultural benefits, rendering it an economically inefficient option for a short-term profit. Ultimately, the biologically driven methods promoted the most lucrative harvests, directly mirroring these economic outcomes. The main criteria for comparison were net profit growth, gross profit and ROI. For the price sensitivity analysis, the baseline crop sale price (500 UAH/c) was adjusted by ±20 %. Calculations were performed for the following price scenarios:

1. Price decrease by 20 %: 400 UAH/c.
2. Baseline price: 500 UAH/c.
3. Price increase by 20 %: 600 UAH/c.

The impact of price changes on crop revenue (profit from the sale of 1 c) and their effect on net profit and ROI is presented in Table 6.

Table 6. Impact of price changes on net profit and ROI

Method	Sale price [UAH/c]	Crop revenue [UAH/ha]	Net profit/loss [UAH/ha]	ROI [%]
Phytoremediation	400	9,440	-3,760	-28.5
	500	11,800	-1,400	-10.6
	600	14,160	960	7.3
Bioremediation	400	13,400	-100	-0.7
	500	16,750	3,250	24.1
	600	20,100	6,600	48.9
Chemical stabilization	400	1,200	-2,600	-18.8
	500	14,000	200	1.45
	600	16,800	3,000	21.7

Explanatory notes: compiled by the authors

Regarding the “Crop revenue” criterion, it should be noted that in all three methods, revenue increased proportionally with the sale price. The highest revenue in each price scenario was achieved with bioremediation. The sensitivity analysis highlighted the financial fragility of phytoremediation, which required optimal market conditions just to achieve marginal profitability. Bioremediation consistently demonstrated strong economic resilience, serving as the sole method to maintain robust profitability and a high return on investment across baseline and elevated market price scenarios. While chemical stabilization could achieve profitability under favorable market pricing, its heavy initial capital requirements severely depressed its overall return on investment compared to biological alternatives. According to the “Net profit” criterion, all methods were unprofitable at the minimum price of 400 UAH/c. At the baseline price (500 UAH/c), only bioremediation achieved a minimal loss (100 UAH/ha), while the other methods remained at the breakeven point or were still unprofitable. Regarding ROI, phytoremediation and chemical stabilization remained unprofitable under all price conditions. Bioremediation exhibited the highest ROI values: at the minimum price (400 UAH/c), ROI was -0.7 %, indicating inefficiency; at the baseline price (500 UAH/c), ROI was 24.1 %, demonstrating profitability and economic effectiveness; and at the increased price (600 UAH/c), ROI reached 48.9 %, the only positive indicator among all methods. Table 7 summarizes the economic consequences of the absence of soil remediation.

Opting against soil remediation carries a severe economic penalty. The cumulative financial burden of unabated soil degradation, driven by plummeting crop yields and escalating compensatory agronomic costs, threatens to compound into staggering long-term capital losses that far exceed the price of implementing restorative measures.

Dudiak and Strohanov [9] analyzed the ecological and economic consequences of wind erosion in the steppe soils of Ukraine. They noted that the absence of anti-deflationary measures could result in soil losses of up to 600 c/ha in dust storm epicenters, causing substantial economic damage to agriculture. While the present research focuses primarily on direct financial losses due to the lack of remediation, the authors emphasized the loss of soil fertility from wind erosion and the potential for mitigation through soil conservation practices, such as contour amelioration and anti-deflationary measures integrated into conservation agriculture.

Table 7. Economic consequences of the absence of remediation

Parameter	Value
Yield reduction [%]	20 ÷ 50
Loss of income [UAH/ha]	3,000 ÷ 12,000
Increased costs (due to erosion and degradation) [UAH/ha]	500 ÷ 2,000
Total losses over 5 years [UAH/ha]	17,500 ÷ 70,000

Explanatory notes: compiled by the authors

The study by Hospodarenko et al. [16] demonstrated that in Ukraine, the liming of podzolized chernozem, combined with the application of varying doses of mineral fertilizers, had a positive effect on winter wheat yields. The use of a complete mineral fertilizer (N120P90K90) increased yields up to 11.12 c/ha, while liming further enhanced the efficiency of these fertilizers [43, 36]. In Table 8, a comparison is drawn between traditional methods of yield enhancement, such as liming and mineral fertilizer application, and the innovative technology of bioremediation.

Table 8. Comparison of traditional yield-enhancing methods

Method	Cost [UAH/ha]	Yield increase [%]	Additional income [UAH/ha]	Net profit [UAH/ha]
Liming	50 ÷ 150	10 ÷ 30	500 ÷ 1,500	350 ÷ 1,450
Mineral fertilizers	100 ÷ 300	15 ÷ 40	750 ÷ 2,000	450 ÷ 1,900
Bioremediation	200 ÷ 500	30 ÷ 70	1,500 ÷ 3,500	1,000 ÷ 3,300

Explanatory notes: compiled by the authors

Comparing established agronomic practices with innovative approaches reveals distinct trade-offs. Traditional liming remains highly accessible and cost-effective, securing reliable profit margins despite moderate productivity boosts. Mineral fertilization, while stimulating higher crop outputs, suffers from diminished overall profitability due to elevated input expenses. Conversely, bioremediation, though demanding the highest initial capital outlay, unlocks substantially greater agronomic potential and ultimately yields the most significant long-term financial returns.

Conclusions

1. According to the study, cutting-edge soil remediation technologies are a useful tool for repairing damaged agricultural land and enhancing food security in the face of human pressure. Bioremediation performed the best overall among the methods examined, combining significant environmental benefits with advantageous financial results. While phytoremediation is less intensive in a near term, it is nevertheless a viable alternative for low-contamination sites and environmentally sensitive locations. Chemical stabilization was found to be highly efficient in reducing heavy metal mobility. Practically speaking, the results show that the degree of contamination, the financial capability of farmers and long-term land-use goals should all be taken into consideration when choosing a restoration technique. Whereas chemical stabilization is better suited for locations with extremely high heavy metal concentrations, bioremediation can be suggested for the areas that need both soil detoxification and a quick return to productive capability. A moderately priced and environmentally beneficial alternative for sustainable land management plans is phytoremediation.
2. The findings further highlight the strategic significance of prompt action by showing that the lack of remediation results in cumulative economic losses and gradual soil degradation. When local monitoring systems and adaptive management frameworks are put in place, the tested technologies can be expanded to other agricultural areas with comparable soil and climate characteristics. A long-term evaluation of ecosystem services, such as possible carbon sequestration and biodiversity restoration, cost structure optimization and integrated remediation models that combine biological and chemical techniques should be the main areas of future research.

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INNOWACYJNE METODY REKULTYWACJI GLEB W KONTEKŚCIE BEZPIECZEŃSTWA ŻYWNOŚCIOWEGO

Streszczenie

Wprowadzenie. Zanieczyszczenie gleb metalami ciężkimi stanowi istotne zagrożenie dla produktywności rolnictwa oraz bezpieczeństwa żywnościowego, co wymaga stosowania skutecznych technologii rekultywacji. Pomimo rosnącego zainteresowania innowacyjnymi metodami odtwarzania gleb, ich efektywność ekonomiczna oraz skuteczność porównawcza pozostają niewystarczająco zbadane. Celem niniejszego badania jest ocena środowiskowej i ekonomicznej efektywności trzech innowacyjnych metod rekultywacji gleb (fitoremediacji, bioremediacji oraz stabilizacji chemicznej) w warunkach Obwodu Kijowskiego na Ukrainie.

Wyniki i wnioski. Badanie oparto na danych eksperymentalnych z trzech jednorodnych obiektów rolniczych o powierzchni 1 ha, monitorowanych w latach 2023 ÷ 2024. Stabilizacja chemiczna okazała się najskuteczniejszą metodą przywracania równowagi kwasowo-zasadowej gleby, powodując wzrost pH o 57,8 % (z 4,5 do 7,1) w ciągu 12 miesięcy, podczas gdy fitoremediacja wykazała najsłabszy efekt (+15,6 %). W zakresie zwiększenia zawartości węgla organicznego w glebie najlepsze wyniki uzyskano dzięki bioremediacji (+28 %), natomiast stabilizacja chemiczna przyniosła wzrost jedynie o 10 %. Jeśli chodzi o redukcję metali ciężkich, stabilizacja chemiczna była najbardziej efektywna, zmniejszając zawartość kadmu o 45 % oraz ołowiu o 50 %, podczas gdy fitoremediacja charakteryzowała się najniższą skutecznością (kadm: –18 %, ołów: –22 %). Z ekonomicznego punktu widzenia bioremediacja okazała się najbardziej korzystną metodą, generując dodatni zysk netto (3250 UAH/ha) oraz osiągając stopę zwrotu z inwestycji na poziomie 24,1 %, co wskazuje na pełny zwrot kosztów w ciągu jednego roku. Fitoremediacja skutkowała ujemnym zyskiem netto (–1 400 UAH/ha) oraz ROI na poziomie –10,6 %, natomiast stabilizacja chemiczna przyniosła minimalny zysk (200 UAH/ha) przy ROI wynoszącym jedynie 1,45 %. Uzyskane wyniki potwierdzają, że innowacyjne metody rekultywacji gleb są ekonomicznie uzasadnione i stanowią perspektywną strategię odnowy gleb rolniczych na Ukrainie. Bioremediacja zapewnia optymalną równowagę pomiędzy efektywnością środowiskową a opłacalnością ekonomiczną, natomiast stabilizacja chemiczna gwarantuje największą redukcję zanieczyszczenia metalami ciężkimi.

Słowa kluczowe: Stopa zwrotu z inwestycji, stabilizacja chemiczna, metale ciężkie, ołów, kadm, bezpieczeństwo żywnościowe