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Soil Degradation Caused by Military Activities in Ukraine: Challenges and Prospects for Ecological Rehabilitation

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The full-scale war in Ukraine has caused unprecedented anthropogenic pressure on the soil cover, manifested in the complex degradation of its physical, chemical, and biological properties. This review article summarizes current data on the forms of soil degradation in combat zones, including mechanical destruction of structure, compaction, erosion processes, salinization, as well as chemical contamination by heavy metals, explosives, petroleum products, and combustion residues. Particular attention is paid to changes in soil microbiota, which serves as a sensitive indicator of ecological condition. Structural and functional shifts in microbial communities, reduction of enzymatic activity, and disruption of organic matter mineralization processes are analysed as reliable bioindicators of soil degradation. The article discusses modern approaches to ecological rehabilitation of affected areas through the use of plants and microorganisms. Special emphasis is placed on phytoremediation technologies that combine the ability of plants to accumulate, transform, and detoxify toxicants with the restoration of biogeochemical element cycling. The feasibility of using indicator and resistant plant species for the remediation of soils contaminated with heavy metals and explosive residues is also substantiated. It is concluded that a comprehensive assessment of microbiological, enzymatic, and physicochemical parameters is a necessary prerequisite for developing effective strategies for soil ecological rehabilitation in the post-war period. The results of the review can be used to formulate scientifically grounded recommendations for restoring the ecological stability of Ukraine's agro-landscapes and for planning long-term soil and biodiversity conservation measures.

Keywords: soil degradation, military activities, heavy metals, explosives, microbiota, phytoremediation, bioindication, ecological rehabilitation

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Introduction

Soils are among the most important components of the biosphere, ensuring food security, supporting biodiversity, and playing a key role in climate regulation (FAO, 2015; Lehmann et al., 2020). During armed conflicts, they become some of the first targets of anthropogenic impact, leading to long-term environmental consequences (Certini, 2005; Lawrence et al., 2015; Baumann and Kuemmerle, 2016; Rawtani et al., 2022).

With the onset of the full-scale aggression of the Russian Federation against Ukraine in 2022, the extent of soil cover degradation has increased significantly, especially in frontline regions. It is estimated that more than 139,000 km^2 of Ukrainian territory have been affected by military contamination, with annual economic losses exceeding USD 11 billion due to the inaccessibility of mined agricultural lands (Tonkha et al., 2025). At the same time, over 15 million hectares of land are experiencing various forms of degradation – chemical, physical, and biological.

Particular concern is caused by the degradation of Ukrainian chernozems, some of the most fertile soils in the world. More than 5 million hectares have been damaged as a result of hostilities, including contamination by heavy metals, explosives, and erosion processes (Baliuk et al., 2024). The war also poses a severe threat to biodiversity: about 30% of Ukraine's protected natural areas are at risk of ecological destruction (Hoptsii and Anoprienko, 2023; Kuzmenko et al., 2024; Horoshkova et al., 2024).

In recent years, there has been a noticeable increase in scientific interest in the environmental consequences of the war in Ukraine, particularly its impact on soil resources. An increasing number of researchers are focusing on assessing the ecological and economic impacts of armed aggression, analyzing soil degradation processes, the scale of contamination, and the loss of agricultural potential. Such studies play a crucial role in forming the scientific basis for land restoration, developing environmental strategies, and justifying the need for international support (Baliuk et al., 2022, 2024; Kucher, 2022; Zaitsev et al., 2022; Bonchkovskyi et al., 2023; Drobitko et al., 2023; Drobitko and Alakbarov, 2023; Kulish, 2023; Hoptsii & Anoprienko, 2023; Solokha et al., 2024; Splodytel et al., 2023; Kuzmenko et al., 2024; Tonkha et al., 2025).

As noted by Certini et al. (2013), regions that have experienced intensive military operations involving explosives and ammunition become major hotspots of terrestrial ecosystem contamination. Gunfire and explosions are particularly dangerous for agricultural landscapes, as they reduce soil fertility and cause contamination of the "soil-plant-human" chain (Lima et al., 2011). According to estimates by the World Bank, the Government of Ukraine, and the European Commission, the regions most affected by the full-scale invasion of 2022 are Luhansk (100%), Kherson (95%), Chernihiv (80%), Zaporizhzhia (74%), Sumy (70%), and Donetsk (64%) oblasts. Overall, hostilities, occupation, and landmines have affected about one-third of the country's territory (Nykolyuk et al., 2024).

Each missile or artillery shell explosion releases a substantial amount of toxic substances into the soil – over 60 kg per single detonation. These pollutants primarily include carbon monoxide, nitrogen dioxide, heavy metals, and residues of solid rocket fuel (Greaves and Hunt, 2022). Historical evidence shows that military conflicts of the 20th–21st centuries – from World War I to the wars in Vietnam, Myanmar, and the former Yugoslavia – have led to long-term destruction of soil profiles, accumulation of toxic metals, and explosive residues (Appau et al., 2021; Shukla et al., 2023). In many European regions where battles occurred more than a century ago, concentrations of heavy metals in the soil still exceed permissible limits by hundreds of times, indicating the extremely slow pace of natural self-purification and the need for bioremediation approaches.

For Ukraine, this issue is particularly critical, as the war is taking place on highly productive agroecosystems. According to Chowdhury et al. (2023), the consequences of the russian-Ukrainian war have a profoundly negative impact not only on soil fertility but also on food security, energy stability, and ecosystem integrity.

Drobitko et al. (2023) report that military actions cause significant soil contamination with heavy metals and explosive compounds, which exert prolonged adverse effects on the environment. Therefore, systematic monitoring and the implementation of bioremediation technologies are essential for the rehabilitation of affected areas. The contamination of agricultural lands considerably decreases soil fertility and agroecosystem productivity. Fiott (2022) emphasizes that pesticides and explosive residues can alter the chemical composition of soils, diminishing their ability to sustain plant growth. Consequently, developing a soil restoration strategy that includes targeted agrotechnical measures and the introduction of stress-resistant plant varieties is imperative.

Bluszcz and Valente (2020) emphasize that contamination by explosives and their degradation products poses a serious threat to agricultural lands, as these compounds adversely affect soil microorganisms responsible for maintaining fertility and nutrient cycling. According to Belcher et al. (2019), microorganisms involved in humus formation are highly sensitive to toxins, leading to the deterioration of soil structure and a decline in its biological productivity.

Studies by Drobitko and Alakbarov (2023) have demonstrated that in areas affected by hostilities, the concentrations of metals in soils significantly exceed permissible limits, posing a substantial risk to ecological stability. Such contamination may have long-term consequences for local populations through direct contact with toxic soils and contaminated water resources.

This review aims to systematize current scientific knowledge on the forms of soil degradation caused by military activities across Ukraine, to assess the impacts of toxicants on soil microbiota, and to identify prospects for ecological rehabilitation through bioindication and phytoremediation approaches. The research holds considerable practical significance for the M.M. Gryshko National Botanical Garden of the National Academy of Sciences of Ukraine, where comprehensive studies are being conducted on the restoration of post-war ecosystems and the assessment of biotic resilience under anthropogenic stress.

1 Forms and Drivers of Soil Degradation in Combat Zones

Soil degradation in areas affected by military operations occurs at three principal levels:

- physical – compaction, structural destruction, and alteration of the pore system;
- chemical – accumulation of toxicants, including heavy metals, explosive residues, and petroleum products;
- biological – reduction in the abundance and activity of soil microorganisms, disruption of biochemical processes, and degradation of biotic interactions (Garten et al., 2003; Certini et al., 2013; Didenko, 2024; Solokha et al., 2024).

1.1 Physical Damage

Physical damage to soils is primarily caused by the direct impact of explosions, shock waves, and the movement of heavy military machinery. The main consequences include the formation of craters, disruption of soil profiles, compaction, and reduced water permeability and aeration (Figure 1). Such alterations critically

Figure 1 Formation of craters in the soil due to explosive detonations, leading to physical degradation and disruption of soil structure

affect plant development, diminish the habitat available for soil organisms, and impair the soil's natural self-purification capacity (Whitecotton et al., 2000; Prosser et al., 2020).

Compaction leads to a decrease in porosity, disruption of air and water regimes, and reduced oxygen availability for plant roots. The loss of macroporosity limits water infiltration, increases the risk of surface runoff and erosion, and contributes to the formation of degraded soil layers with low biological productivity and diminished regenerative capacity under prolonged physical stress.

1.2 Chemical Contamination

Military activities are a significant source of chemical contamination of soils. The primary contributors include residues from destroyed military equipment, fragments of missiles, artillery shells, mines, grenades, and other explosive devices (Figure 2), which pose serious environmental threats (Lawrence et al., 2015; Bonds, 2016; Rawtani et al., 2022; Solokha et al., 2024).

As a result of hostilities, soils become contaminated with heavy metals (Pb, Cu, Zn, Cd, Cr, Ni), petroleum products, polymers, asbestos, and explosive residues,

Figure 2 Fragments of missiles (A) and residues of destroyed military equipment (B) as sources of soil degradation in combat zones

Figure 3 Destroyed buildings and infrastructure in frontline regions contribute to soil contamination with toxic substances and debris

such as trinitrotoluene (TNT), hexogen (RDX), and octogen (HMX).

An additional source of toxicants is the destruction of infrastructure (Figure 3), particularly buildings containing hazardous materials such as asbestos, lead, plastics, paints, and petroleum products, which enter the soil along with debris. Large areas of agricultural land – including crop fields and meadows – are subjected to shelling, landmining, or occupation by abandoned military vehicles (tanks, armored personnel carriers, civilian cars). These conditions not only hinder agricultural use but also contribute to further chemical contamination through fuel and lubricant leaks and corrosion of metallic components (Figure 4).

Persistent organic compounds and heavy metals, which retain their toxicity for decades, pose the greatest threat (Kalderis et al., 2011; Pichtel, 2012). Of particular concern is RDX, a highly mobile compound with low sorption potential, capable of leaching into groundwater and contaminating water sources in active combat areas (U.S. EPA, 1999; Clausen et al., 2004).

Studies of former military training grounds and munitions production sites have revealed elevated concentrations of toxic compounds, including 2,4-dinitrotoluene, TNT residues, RDX, and heavy metals such as Sb, Pb, and U (Schwenk, 2018; Tešan et al., 2018; Fernandez-Lopez et al., 2022; Broomandi et al., 2020; Shukla et al., 2023). These findings underscore the need for multi-tiered remediation strategies that consider both the chemical properties of toxicants and the characteristics of the soil environment.

Emissions of heavy metals during explosions, material combustion, and equipment corrosion (Pb, Cu, Cd, Sb, Cr, Ni, Zn) result in contamination of both soils and aquatic systems, with bioaccumulation in living organisms. Biomonitoring studies confirm the accumulation of these elements in trophic chains, leading to suppressed reproductive function, metabolic disorders, and overall reductions in ecosystem productivity (Singh et al.,

Figure 4 Remnants of military equipment and abandoned civilian vehicles on agricultural fields, hindering soil cultivation and contributing to degradation

2018; Tovar-Sánchez et al., 2018; Skalny et al., 2021; Kicińska et al., 2022; Yao et al., 2023).

A separate case of anthropogenic catastrophe is the destruction of the Kakhovka Hydroelectric Plant in 2023. According to the United Nations, over 90,000 tons of bottom sediments containing toxic elements (As, Ni, Zn) were dispersed into the soils and waters of the lower Dnipro, creating a long-term environmental threat to agricultural lands and biodiversity (UNDP, 2023; Washington Post, 2024; Chemistry World, 2025).

1.3 Biological Degradation

Armed conflicts lead to profound alterations in the soil biosphere, disrupting the functional structure of microbial communities, reducing enzymatic activity, and disturbing biogeochemical cycles (Pal et al., 2021; Tauqeer et al., 2021; Flores et al., 2025). The accumulation of toxicants, particularly heavy metals and explosive residues, suppresses the metabolism of soil microorganisms, causing a decline in microbial diversity, destruction of symbiotic relationships, and a loss of the soil's self-regenerative capacity.

A key factor in biological degradation is the destruction of natural vegetation – forests, shelterbelts, meadows, and steppe lands – which play a crucial role in soil stabilization, erosion control, water balance regulation, and biodiversity conservation (Figure 5). Extensive fires, shelling, and landmining lead to the degradation of these ecosystems, especially in steppe regions, where shelterbelts often represented the only barrier against wind and water erosion. Vegetation loss promotes humus depletion, decreases biomass, reduces buffering capacity, and increases vulnerability to climatic extremes.

A separate ecological threat is posed by the mass mortality of wild and domestic animals, which often remain in open areas or enter water bodies (Figure 6). The decomposition of organic remains without proper disposal causes microbial and chemical contamination of soils and waters, including the spread of pathogenic microorganisms, water quality deterioration, and destabilization of soil microbial communities. Such processes increase risks to human health and ecosystem resilience in post-conflict regions.

2 Impact of Toxicants on Soil Microbiota

Soil microbiota is a critical component of ecosystems, mediating nutrient cycling, organic matter transformation, maintenance of soil structure, and plant protection. However, military activities – particularly explosions and contamination with heavy metals (Cd, Pb, Zn, Cu) and explosive residues (TNT, RDX, HMX) – substantially disrupt the structure and functioning of microbial communities (Giller et al., 1998; Stefanowicz et al., 2008; Corredor et al., 2024; Rodríguez-Seijo et al., 2024).

Toxicants reduce microbial abundance, suppress metabolic activity, and cause trophic imbalances (Khan et al., 2008; Rousk et al., 2010). Enzymatic indicators are particularly sensitive: dehydrogenase, phosphatase, and urease activities sharply decline, reflecting an overall decrease in soil microbial viability (Elgh Dalgren et al., 2009; Panz et al., 2013; Lin et al., 2022).

Metagenomic studies also indicate a reduction in genes associated with nitrogen fixation, degradation of organic compounds, and xenobiotic breakdown (Yang et al., 2023). In combat zones, microbial diversity

Figure 5 Damaged and destroyed forests, shelterbelts, and protective strips leading to soil degradation, loss of erosion control, and reduced biodiversity

Figure 6 Mass mortality of cattle in a water body – a consequence of military actions, causing water contamination and deterioration of the regional ecological status

decreases and communities shift towards stress-tolerant taxa (e.g., *Actinobacteria*), while populations of nitrogen-fixing bacteria (*Rhizobium*, *Frankia*), mycorrhizal fungi, and functionally important genera (*Pseudomonas*, *Bacillus*, *Streptomyces*) decline (Giller et al., 1998; Yang et al., 2021; Flores et al., 2025).

Reduced activity of symbiotic bacteria, particularly *Rhizobium*, impairs nitrogen nutrition in leguminous crops, directly affecting agricultural productivity (Liu et al., 2016). Studies in Ukraine have shown that soils contaminated with explosive residues exhibit a 2–4-fold reduction in microbial enzymatic activity compared to control sites (regional studies, 2023).

A separate concern is the decomposition of carcasses of domestic and wild animals, forming local "carcass decomposition hotspots" (CDHs), where soils become saturated with organic compounds, ammonium, fatty acids, cadaverine, and pathogens, suppressing autotrophic and saprotrophic microbial populations (Cobaugh et al., 2015; Metcalf et al., 2016). In aquatic systems, this process contributes to eutrophication, hypoxia, and proliferation of opportunistic pathogens (Gwyther et al., 2011). Contaminated water may act as a vector for pathogens such as *Bacillus anthracis*, *Leptospira* spp., and *Brucella* spp.

Assessment of soil microbial status forms the basis for microbial bioindication of degradation. Key approaches include analysis of total bacterial and fungal abundance, fungal-to-bacterial ratios, G^+/G^- bacterial ratios, biodiversity indices (e.g., Shannon index), and enzymatic activity (Dick, 1994; Burns et al., 2013). These indicators serve as sensitive measures of soil quality and the effectiveness of remediation efforts.

Restoring microbial balance in soils affected by military activities is critical. Promising approaches include biostimulation and bioinoculation using autochthonous or adapted microorganisms (Khan et al., 2013; Alori et al., 2022; Anekwe et al., 2024; Sanjana et al., 2024). In addition, the use of stress-tolerant microbiomes, including genera such as *Arthrobacter*, *Burkholderia*, and *Paenibacillus*, can facilitate the restoration of soil fertility even under residual contamination conditions (Vincze et al., 2024).

Soil contamination resulting from military activities causes profound disruptions in the structure and function of soil microbiota, manifesting as reduced biodiversity, suppressed enzymatic activity, and impaired nutrient cycling. These changes decrease the ecological resilience of agroecosystems and necessitate microbial-oriented rehabilitation strategies, including bioindication, biostimulation, and the use of stress-tolerant microorganisms.

3 Bioindication of Degraded Soils

Soil enzymatic activity is among the most sensitive bioindicators of changes in the structural and functional organization of soils, responding rapidly to anthropogenic and technogenic pressures, including military activities (Nannipieri et al., 2012). Soil enzymes are closely linked to microbial activity, root exudates, and plant and animal residues, and participate in numerous biochemical processes such as organic matter mineralization and the transformation of nitrogen, phosphorus, and sulfur, which are critical for maintaining soil fertility (Dick, 1994; Burns et al., 2013).

Dehydrogenase activity is particularly sensitive and is widely used as an indicator of the functional state of the soil microbiota. Reductions in its activity often correlate with the intensity of contamination and structural soil damage (Das and Varma, 2010). Activities of other enzymes, including urease, phosphatase, and catalase, are also informative, reflecting the viability of soil biota and the soil's capacity for self-recovery (Dick, 1994; Burns et al., 2013).

In areas affected by military actions, a sharp decline in the activity of key soil enzymes, such as dehydrogenase, urease, phosphatase, and catalase, has been observed. This decline is associated with disruption of the microbial community, impaired aeration, pH alterations, accumulation of heavy metals, explosive residues, and toxic combustion by-products (Perelo, 2010).

Explosive compounds, such as RDX (hexogen) and TNT (trinitrotoluene), inhibit the activity of redox enzymes, inducing oxidative stress in soil microorganisms (Adam et al., 2007). Heavy metals can irreversibly bind enzyme active sites or replace essential cations, thereby altering enzymatic functionality (Giller et al., 1998).

Soil microbial communities represent one of the most sensitive and informative indicators of soil ecosystem status. *Microorganisms* respond to changes in physicochemical properties, including contamination by toxic substances, structural damage, and alterations in moisture and aeration – factors that are particularly relevant in conflict zones (Rousk et al., 2010). Assessing microbial diversity, activity, and functional potential provides an effective means to evaluate the degree of soil degradation and predict its recovery potential.

Military activities result in mechanical damage to the soil cover and contamination with explosive residues, heavy metals, and combustion by-products, negatively affecting soil microbiota. A sharp decline in the abundance and activity of soil microorganisms disrupts biogeochemical cycles, including those of nitrogen, carbon, and phosphorus (Singh et al., 2014). Toxic explosive compounds exhibit high bioaccumulation potential and inhibit the development of microbial populations responsible for organic matter degradation and detoxification (Kalsi et al., 2020).

Key bioindicators of soil status reflect the overall condition of the microbial community. Total microbial abundance serves as a basic indicator of soil biological activity, correlating with fertility and structural integrity of the ecosystem (Nannipieri et al., 2017). Bacterial and fungal abundance can be assessed using both culture-based and molecular methods (Fierer et al., 2007).

Symbiotic activity, including mycorrhizal development and *Rhizobium* activity, is a crucial indicator of soil viability. Loss of these symbioses signals ecosystem disruption and toxic effects of pollutants (Giller et al., 1998; Smith and Read, 2008). Biodiversity indices (e.g., Shannon, Simpson) reflect the ecological stability of the microbiota, with decreases indicating stress conditions (Lauber et al., 2009).

The ratio of functional groups, such as ammonifiers and denitrifiers, serves as a marker of nitrogen cycle balance, with disruptions indicating ecosystem degradation (Hallin et al., 2018).

For more in-depth analyses, molecular methods such as PCR and 16S rRNA sequencing are applied, enabling identification of key microorganisms that can be used as bioindicators or bioremediation agents (Thompson et al., 2017). Classical cultivation methods remain important, though they capture only a fraction of microbial diversity (Amann et al., 1995). Functional assessments are performed using Biolog EcoPlates and bioinformatic platforms such as PICRUSt and FAPROTAX (Langille et al., 2013; Louca et al., 2016).

Integration of enzymatic activity analysis into ecological monitoring systems for military-affected lands allows evaluation of functional stress levels, identification of highly degraded areas, and assessment of remediation effectiveness (Nannipieri et al., 2012; Burns et al., 2013). Enzymatic reactions reflect the interaction of microbial communities with abiotic soil factors, which is particularly evident under anthropogenic pressure (Krčmar et al., 2018).

Functional processes related to organic matter decomposition and nutrient cycling, particularly nitrogen, can be quantitatively characterized by soil enzyme activity, serving as bioindicators of ecosystem status (Cofie et al., 2014). Studies of soils near industrial areas have shown that increasing heavy metal concentrations are accompanied by suppressed enzymatic activity and reduced microbial diversity (Ahmad et al., 2018). Similar patterns were confirmed experimentally through artificial metal addition: urease, alkaline phosphatase, and xylanase activities in soils contaminated with Zn, Cu, Ni, V, and Cd were significantly lower than in control samples (Kandeler et al., 1996; 1999).

Thus, soil enzymatic activity and the composition and functional capacity of microbiota are highly sensitive bioindicators of soil ecosystem degradation caused by military activities. Analysis of these indicators enables rapid detection of contamination and structural disturbances and provides an effective means of monitoring the success of ecological rehabilitation measures, which is critical for restoring soil fertility and ecosystem stability.

4 Strategies for Ecological Rehabilitation

4.1 Phytoremediation as a Soil Rehabilitation Strategy for Areas Degraded by Military Activities

Phytoremediation is an environmentally safe and cost-effective method for the remediation of contaminated soils and aquatic ecosystems using higher plants, leveraging their innate physiological and biochemical capabilities (Sun et al., 2018; Ashraf et al., 2019; Shah et al., 2024; Oubohssaine and Dahmani, 2024). In the context of the war in Ukraine, where extensive areas are contaminated with heavy metals, explosive residues, and petroleum products, this approach is particularly relevant, as it reduces environmental risks and contributes to the protection of public health (Ghosh and Singh, 2005; Pichtel, 2012). The method relies on the ability of plants to accumulate, stabilize, or transform toxic compounds, enabling the restoration of soil ecosystem functionality with minimal landscape disturbance and without the need for high-cost technologies. Key mechanisms of phytoremediation include phytoextraction, phytostabilization, phytovolatilization, and phytorhizofiltration (Meagher, 2000; Yan et al., 2020; Park and Oh, 2023; Hu et al., 2024; Oubohssaine and Dahmani, 2024), which can be applied to ecosystem recovery in conflict-affected regions of Ukraine:

- Phytoextraction (also known as phytoaccumulation or phytosequestration) is a primary mechanism of phytoremediation, whereby plants absorb contaminants from soil or water through their roots and translocate and accumulate these toxicants in aboveground biomass, particularly in leaves and stems (Jagetiya and Kumar, 2020; Sharma et al., 2024). Typical contaminants targeted by phytoextraction include heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), and explosive compounds such as cyclotrimethylenetrinitramine (RDX). Subsequent removal of these toxic substances is achieved through harvesting and disposal of the aboveground plant biomass, making this method a promising alternative to conventional soil remediation technologies (Ali et al., 2013; Pilon-Smits, 2005).
- Phytovolatilization is the process by which contaminants are converted into volatile forms, for example, mercury, and subsequently released through plant leaves. This mechanism reduces contaminant concentrations in the soil solution, although careful monitoring of atmospheric emissions is required (Rylott and Bruce, 2019; Shen et al., 2021; Pang et al., 2023).
- Phytorhizofiltration involves the purification of water and soil pore solutions through plant roots that absorb and transform pollutants. This mechanism is particularly important for reducing contamination of groundwater (DalCorso et al., 2019; Sut-lohmann et al., 2019; Meagher, 2000).
- Phytostabilization (also referred to as phyto-immobilization or *in situ* inactivation) is the process of stabilizing contaminants within the plant root zone, thereby reducing their mobility and bioavailability, and consequently minimizing the risk of spreading toxic substances into the surrounding environment (Zine et al., 2020; Bradshaw, 2003; Latif et al., 2023).

Thanks to the multifunctionality of these mechanisms, phytoremediation represents a promising tool for soil restoration in post-conflict zones, simultaneously ensuring environmental safety and biodiversity conservation.

4.2 Potential Plant Species for Phytoremediation in Ukraine

The effectiveness of phytoremediation interventions largely depends on the careful selection of plant species with appropriate morpho-physiological traits. Key considerations include root system depth, adaptability to specific soil types and climatic conditions, the nature of existing contaminants, and the plant's ability to efficiently uptake or neutralize toxic compounds (Matanzas et al., 2021; Ali et al., 2024; Oubohssaine and Dahmani, 2024).

Preference is given to the use of autochthonous (native) plant species, as they are better adapted to local environmental conditions, exhibit higher resilience to stress factors, and require less intensive agricultural management compared to introduced species (Alotaibi et al., 2021; Singh et al., 2022; Oubohssaine and Dahmani, 2024).

In the context of military-technogenic contamination, the use of plants capable of accumulating, stabilizing, and degrading soil contaminants becomes particularly important. For Ukraine, with its temperate climate, the most promising species include:

- *Brassica napus* L. – effective in the removal of heavy metals, particularly lead (Pb) and cadmium (Cd), and possesses high biomass, which contributes to the reduction of soil toxicity (Turan and Esringu, 2007; Ali et al., 2013);
- *Helianthus annuus* L. – exhibits a high capacity for phytoextraction of heavy metals as well as nitroaromatic compounds, including trinitrotoluene (TNT) (Lee et al., 2007), and is used for remediation of uranium-contaminated soils and groundwater (Lee and Yang, 2010);
- *Festuca arundinacea* Schreb. – serves as a phytostabilizer, reducing erosion and immobilizing contaminants in the soil, including diesel-contaminated sites (Borowik et al., 2019; Afegbua et al., 2023).
- *Vetiveria zizanioides* (L.) Roberty – efficiently detoxifies explosive compounds (Alkorta and Garbisu, 2001; Goren et al., 2021) and is an ideal species for uranium phytoextraction (Pentyala and Eapen, 2020); suitable for a wide range of phytoremediation applications (Danh et al., 2009). Hyperaccumulation of metals and high metal tolerance in this species are genetically encoded traits.

Among perennial herbaceous crops, promising species for phytoremediation in Ukraine include *Lolium perenne* L., *Festuca rubra* L., *Agrostis tenuis* L., and *Trifolium pratense* L., which form dense turf, prevent erosion, and stabilize the surface soil layer (Pulford & Watson, 2003). In addition, these species actively interact with the rhizosphere microbiota, promoting the development of microbial consortia that accelerate the detoxification of organic compounds (Glick, 2012).

Recently, energy crops such as *Miscanthus* × *giganteus* J.M Greef & Deuter ex Hodk & Renvoize and *Phalaris arundinacea* L. have attracted particular attention, as they combine the ability to accumulate heavy metals with high biomass productivity suitable for bioenergy applications. This dual functionality provides both environmental soil remediation and renewable energy production (Korzeniowska et al., 2015; Nsanganwimana et al., 2021; Romantschuk et al., 2024).

Woody plants are increasingly recognized as effective components of phytoremediation strategies due to their morphophysiological and ecological traits. They possess deep and branched root systems, large biomass, long life cycles, and the ability to accumulate or stabilize contaminants in soil, making them suitable for long-term ecological rehabilitation programme. Moreover, woody plants establish close interactions with rhizosphere microbiota, including plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi, which activate mechanisms for metal solubilization, transformation of organic pollutants, and enhancement of plant stress tolerance (Kumar et al., 2018; Glick, 2012).

Among the most promising woody plants for phytoremediation in Ukraine are:

- *Morus alba* L. – a well-known heavy metal phytoaccumulator, particularly of Pb, Cd, and Cu, demonstrating high tolerance to contaminated soils (Huang et al., 2018; Lei et al., 2019; Rafati et al., 2020). Suitable for buffer zones or as part of protective shelterbelts.
- *Elaeagnus angustifolia* L. – capable of atmospheric nitrogen fixation, Cd, Ni, and Pb phytostabilization, and highly tolerant to saline and degraded soils, including areas contaminated with explosive residues (Khamzina et al., 2009; Zhang et al., 2022; Thompson et al., 2024; Sui et al., 2025).

- *Elaeagnus multiflora* Thunb. – belongs to Elaeagnaceae, a family known for symbiosis with Frankiaceae actinomycetes, enabling nitrogen fixation. While specific studies on *E. multiflora* symbiosis are lacking, its close relative *E. angustifolia* has demonstrated this ability, suggesting potential nitrogen-fixing capability beneficial in marginal agroecosystems.
- *Prunus domestica* L. – tolerant to elevated Cu and Zn concentrations, capable of phytostabilization in buffer zones near industrial pollution sources. Exhibits high adaptability to urban and industrial environments (Filipovic-Trajkovic et al., 2012; Rusu et al., 2024).
- *Cydonia oblonga* Mill. – accumulates Cd, Ni, and Cu, particularly in roots and leaves, making it suitable for phytoextraction schemes on heavily contaminated soils (Topdemir and Gür, 2005; Ghaderian et al., 2007; Filipovic-Trajkovic et al., 2012).
- *Salix* spp. (willow) – among the most widely studied genera for phytoremediation due to rapid growth, high uptake capacity, and broad ecological amplitude; effective in removing Zn, Cd, Pb, and degrading organic pollutants, including petroleum hydrocarbons and explosives (Pulford and Watson, 2003; Cao et al., 2018, 2022; Jiang et al., 2024).
- *Populus* spp. long-term field experiments and practical applications demonstrate its effectiveness in removing heavy metals (Zn, Cu, Ni, Cd, Cr, Se) and a wide range of organic contaminants, including TNT, petroleum products, BTEX compounds (benzene, toluene, ethylbenzene, xylene), explosive residues, and trichloroethylene (TCE). Poplar is widely used in phytoremediation systems in Europe, the USA, and other regions due to its ability to efficiently accumulate, stabilize, and transform various toxicants in both soil and water, making it a versatile and effective species for ecological rehabilitation (Gordon et al., 1998; Robinson et al., 2000; Pajević et al., 2009; Rafati et al., 2011; Hasanuzzaman et al., 2020; Xi et al., 2021; Miletić et al., 2024).
- *Juglans regia* L. – capable of accumulating Cu, Zn, and Cr, predominantly in roots; also shows potential for As phytoextraction and Cr, Ni, Pb phytostabilization, making it suitable for multi-contaminant remediation sites (Saqib et al., 2013; Ozen and Yaman, 2016; Mataruga et al., 2020).
- *Robinia pseudoacacia* L. – nitrogen-fixing, drought-tolerant, and tolerant to high heavy metal concentrations; effectively stabilizes soils in mine tailings, quarries, and Zn/Pb-contaminated areas. Its fast growth and nitrogen-fixing symbiosis make it suitable for the restoration of degraded lands and heavy metal-contaminated soils (Uselman et al., 2000; Ussiri et al., 2006; Yuksek and Yuksek, 2011; Vlachodimos et al., 2013; Yang et al., 2015; Fan et al., 2018).
- *Acer* spp. – promising species for phytoremediation of heavy metal-contaminated soils, capable of accumulating Cu, Pb, and Zn in urban and industrial settings, making them suitable for green spaces in polluted areas (Migeon et al., 2009; Hauptvogl et al., 2020; Naz et al., 2022; Stanisław, 2023).

Woody plants interact closely with rhizosphere microbiota, which significantly influences the effectiveness of phytoremediation. In particular, PGPR strains of *Pseudomonas*, *Bacillus*, and *Azospirillum* enhance metal bioavailability through the secretion of siderophores, organic acids, and phosphatases (Glick, 2010). Mycorrhizal fungi (*Glomus intraradices*, *Rhizophagus irregularis*) improve nutrient uptake, immobilize heavy metals within the mycelium, and reduce their translocation to aboveground biomass (González-Chávez et al., 2004).

The use of woody plants in combination with microbial consortia creates bioengineered phytoremediation systems capable of accelerating detoxification and restoring soil biota (Abhilash et al., 2009; Ma et al., 2016; Liu et al., 2024). This integrated approach represents a promising strategy for the ecological rehabilitation of degraded territories in Ukraine, particularly in the post-conflict period.

Beyond direct remediation, woody species provide additional ecosystem services, including erosion control and soil structure restoration, habitat provision for fauna, CO_2 sequestration and carbon footprint reduction, and the formation of landscape buffers around contaminated sites (Pulford and Watson, 2003).

Conclusions

Contemporary military activities in Ukraine lead to multifaceted soil degradation, manifested as physical disruption of soil structure, chemical contamination by military-derived toxicants, and biological suppression of soil microbiota. The main pollutants include heavy metals (Pb, Cd, Cu, Zn), residues of explosive compounds (TNT, RDX), petroleum products, and polycyclic aromatic hydrocarbons, which disrupt biogeochemical cycles and reduce the productivity of agroecosystems. Soil microbiota serves as a sensitive indicator of ecological status and a key factor in restoring trophic interactions within disturbed landscapes. Its structure and functional activity directly reflect the level of toxic load and the ecosystem's capacity for self-regulation. The use of microbiological indicators – such as dehydrogenase, phosphatase, and nitrate reductase activity, as well as the abundance of key trophic groups – should be an integral part of monitoring degraded territories. Functional soil assessments, particularly enzyme activity analysis, are currently considered a central tool for understanding the processes occurring in degraded or contaminated ecosystems. Bioremediation technologies, including phytoremediation, phytostabilization, and microbial biostimulation, represent a promising approach for the rehabilitation of contaminated lands, particularly in zones affected by active military operations. The application of adapted plant species in combination with microbial consortia not only reduces toxicant concentrations but also gradually restores ecological balance in the soil environment. A major priority in the coming years is the establishment of a national system for assessing military-induced soil degradation, implementation of long-term biomonitoring programme, and development of integrated restoration technologies that combine biological, agronomic, and landscape-ecological approaches. The integration of scientific research, environmental policy, and practical reclamation measures will be crucial for returning degraded lands to productive use and restoring the resilience of Ukraine's agroecosystems.

Conflicts of Interest

The authors have no competing interests to declare.

Ethical Statement

This article does not include any studies that would require an ethical statement.

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