AGROLOGY

ISSN 2617-6106 (print)
ISSN 2617-6114 (online)
Agrology, 2025, 8(1), 153–167
doi: 10.32819/202519

Review article

Received: 17.06.2025
Revised: 12.07.2025
Accepted: 04.08.2025

Dnipro State Agrarian and Economic University, Yefremova St., 25, Dnipro, 49027, Ukraine. Tel.: +38-097-381-54-40. E-mail: shevchenko.s.m@dsau.dp.ua

Institute of Grain Crops of the National Academy of Sciences of Ukraine, Dnipro, Ukraine. E-mail: o.m.shevchenko@ukr.net

Cite this article: Mytsyk, O. O., Shevchenko, S. M., Havriushenko, O. O., Tkalich, Y. I., & Shevchenko, O. M. (2025). Integrated bioremediation and reclamation strategies for militarily damaged agricultural soils. Agrology, 8(3), 153–167. doi: 10.32819/202519

Integrated bioremediation and reclamation strategies for militarily damaged agricultural soils

O. O. Mytsyk*, S. M. Shevchenko*, O. O. Havriushenko*, Y. I. Tkalich*, O. M. Shevchenko**
**Dnipro State Agrarian and Economic University, Dnipro, Ukraine*
***Institute of Grain Crops of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*

Abstract. The full-scale military invasion of Ukraine has led to a widespread degradation of agricultural soils, involving complex physical, chemical, and biological disturbances. Extensive contamination with heavy metals, petroleum products, and explosives, along with the decline of soil microbial activity, has significantly reduced the productive capacity of the agroecosystems and created long-term environmental risks. This review presents a systematized analysis of current approaches to integrated bioremediation and agroecological reclamation of war-affected soils. Particular attention is paid to bioengineering solutions, including phytoremediation, microbial consortia, organic soil amendments, and adaptive agrotechnical strategies. Drawing on successful experiences from post-conflict regions such as Vietnam, Iraq, and the Balkans, the review highlights opportunities for adapting these strategies to the specific conditions of the Ukrainian Steppe, where high humus content intersects with increasing anthropogenic pressure. The authors emphasize the need to develop a national strategy for restoring degraded agricultural land, incorporating interdisciplinary monitoring tools, GIS technologies, legislative frameworks, and sustainable financing mechanisms. The review also outlines key research priorities, including the improvement of bioproducts, risk mapping, evaluation of phytoremediation crops, and long-term monitoring of soil biocoenosis under post-war landscape transformation.

Keywords: soil contamination; military land degradation; bioremediation technologies; phytoremediation; post-conflict agriculture; ecosystem restoration; agroecological recovery.

Introduction

In recent decades, the frequency, scale, and environmental destructiveness of military conflicts have increased significantly, leaving a profound and lasting impact on terrestrial ecosystems, particularly agricultural soils. The war in Ukraine, the conflicts in the Middle East, and historical wars in Southeast Asia have demonstrated the devastating consequences of warfare for agroecosystems, where soil degradation often occurs on a vast scale and with complex ramifications Military operations often result in a combination of physical soil damage, contamination with toxic compounds, and the disruption of ecosystem services such as nutrient cycling, water regulation, and food production. Unlike naturally degraded or industrially contaminated soils, militarily disturbed soils represent a unique case where multiple stressors – mechanical, chemical, and biological – act simultaneously and often unpredictably (Rawtani et al., 2022; Novakovska et al., 2025).

The urgency of addressing these impacts has grown due to the geopolitical instability in regions that are major contributors to global food security. Ukraine, for instance, which traditionally supplied up to 10% of global wheat exports, faces extensive land degradation from artillery shelling, unexploded ordnance, and pollutant accumulation (FAO, 2025. Ukraine: Strategic priorities for 2025). As a result, restoring the agricultural functionality of militarily damaged soils is not only a national priority but a global concern, tightly linked to achieving the UN Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). Furthermore, the environmental recovery of conflict-affected territories is essential for post-war reconstruction, the return of displaced populations, and the rebuilding of rural economies. Without targeted bioremediation and reclamation efforts, these territories remain ecologically hazardous and economically unproductive, perpetuating poverty, food insecurity, and health risks (Bhaduri et al., 2022; González-Valoys et al., 2025).

Militarily disturbed soils are a distinct category of anthropogenically altered lands that result from direct and indirect impacts of armed conflicts, including active combat operations, military training, weapons testing, and the deployment of heavy military machinery. These disturbances lead to a complex mix of physical, chemical, and biological degradation, which often persists for decades after hostilities have ceased. Unlike conventional soil degradation driven by agricultural misuse or industrial pollution, military-induced degradation involves multiple overlapping forms of damage that simultaneously affect the structural and functional integrity of soil systems, for example, cratering, compaction, contamination by explosives and heavy metals, and the destruction of topsoil layers (Dmytrukha et al., 2024). The classification of militarily disturbed soils remains an emerging field, but recent studies propose typologies based on both the type of military activity and the nature of the resulting damage. For example, soils may be categorized into physically disrupted soils (e.g., cratered or compacted by tracked vehicles), chemically contaminated soils (e.g., polluted with TNT, RDX, or heavy metals such as lead, mercury, or uranium), and biologically degraded soils (e.g., loss of microbial diversity and functional capacity). The spatial heterogeneity of these disturbances further complicates monitoring and restoration efforts, often requiring site-specific assessments using geospatial analysis, remote sensing, and ecological diagnostics. A particularly concerning feature of military degradation is the persistence and mobility of contaminants in the soil profile. Explosives residues and heavy metals can leach into groundwater or accumulate in crops, posing long-term risks to human and ecosystem health (Yang et al., 2024). Additionally, military degradation often overlaps with natural stressors such as drought or erosion, compounding its effects and accelerating the collapse of soil fertility and productivity. The degree of degradation depends on soil type, climatic conditions, and the intensity and duration of military activity, with sandy soils typically more vulnerable to compaction and chemical infiltration (Sharma et al., 2024; Wirtu & Abdela, 2025).

The ecological implications of such degradation are profound and multifaceted, extending far beyond immediate physical destruction. Soil organisms – including bacteria, fungi, archaea, and invertebrates – form the biological engine of agroecosystems, driving essential processes such as nutrient cycling, organic matter decomposition, nitrogen fixation, and carbon sequestration (Van Shafea et al., 2023). Military-induced disturbances, such as blast waves, soil compaction, and chemical contamination from explosives and heavy metals, often cause abrupt and sustained declines in microbial biomass, functional diversity, and enzymatic activity, which collectively undermine soil biological integrity and ecological resilience. These disturbances alter microbial community composition, suppress symbiotic relationships (e.g., mycorrhizae), and inhibit nutrient mobilization, reducing the soil's inherent capacity for self-repair and long-term productivity. Moreover, the removal or destruction of vegetation cover resulting from military operations – whether through direct combustion, shelling, or heavy machinery – significantly increases surface exposure, exacerbating water and wind erosion. This accelerates the loss of topsoil, diminishes water infiltration, and disrupts evapotranspiration patterns, thereby affecting local and regional hydrological cycles. Loss of vegetative root structures also compromises soil aggregation and porosity, leading to increased runoff, flash flooding, and sediment transport. In post-conflict landscapes, these processes often result in a transition from structured, biologically active soils to compacted, degraded substrates that are more vulnerable to further abiotic stress and less supportive of agricultural recovery (Solokha et al., 2024). The cumulative effect is a feedback loop of degradation, where ecological thresholds are crossed and natural regeneration becomes increasingly unlikely without targeted intervention.

Despite the magnitude of the problem, militarily disturbed soils remain significantly understudied, particularly in active or recently affected conflict zones where access restrictions, security concerns, and lack of infrastructure limit systematic monitoring and scientific research. The absence of standardized diagnostic methodologies and classification frameworks for warfare-induced soil degradation severely constrains data comparability, impedes international collaboration, and hampers integration into global soil health assessments. To address this gap, there is a pressing need to develop formalized criteria for identifying and characterizing such soils and to embed these standards within broader land degradation neutrality (LDN) frameworks, as advocated by the United Nations Convention to Combat Desertification (UNCCD, www.unccd.int). Without comprehensive classification and long-term data systems, the design and implementation of appropriate bioremediation and reclamation strategies will remain fragmented and insufficient (Hannam et al., 2022).

This issue lies at the nexus of ecology, agronomy, soil science, environmental engineering, and geopolitical studies, requiring interdisciplinary and transdisciplinary approaches that bridge academic research, applied land management, and policy formulation. The rehabilitation of militarily degraded agricultural soils should no longer be treated as a marginal or exceptional concern. Rather, it constitutes a critical dimension of sustainable development, climate adaptation, and food security in the twenty-first century. As armed conflicts increasingly intersect with agricultural regions – most notably in Ukraine, the Middle East, and parts of Africa – the imperative to restore soil functionality and agroecosystem services has become a global scientific and humanitarian priority (Biliavska et al., 2024; Kozielec et al., 2024).

Therefore, the objective of this review was to provide a comprehensive synthesis of current knowledge, technologies, and practices related to the integrated bioremediation and agroecological reclamation of agricultural soils affected by military activity. In light of escalating global conflicts and the growing frequency of war-related environmental disruptions, this article seeks to consolidate insights from environmental science, agronomy, soil microbiology, and ecological restoration to inform both research agendas and policy frameworks. By outlining the typology of military soil degradation, evaluating biotechnological and engineering responses, and identifying knowledge gaps and implementation barriers, this review aspires to serve as a scientific foundation for evidence-based recovery of war-impacted agroecosystems and for advancing global discourse on land resilience in post-conflict settings.

Military-induced soil degradation: typology and consequences

Types of military impact: physical destruction, chemical, and biological contamination. Military operations exert multifaceted and often synergistic impacts on agricultural soils by disrupting their physical structure, introducing a wide spectrum of xenobiotic contaminants, and destabilizing native biological communities essential for agroecosystem functioning. Among the most immediate and visible consequences is physical degradation: the movement of heavy military vehicles, detonation of explosive ordnance, and the construction of defensive infrastructure cause severe soil compaction, truncation of soil horizons, and widespread erosion. These mechanical disturbances significantly alter key soil physical properties such as bulk density, porosity, infiltration rate, and water-holding capacity, frequently rendering soils temporarily or even permanently unsuitable for agricultural use (Hanif et al., 2024). Crater formation, dislocation of soil aggregates, and topsoil removal further degrade soil structure, exacerbate erosion risks, and reduce the capacity of soils to sustain vegetation.

In the case of Ukraine, over 3 million hectares of agricultural land have been affected by military activity since 2014, with particularly intense damage observed following the escalation in 2022. Explosions and the operation of military machinery result in deep compaction and destruction of the humus horizon, disrupting the soil's hydrological functions and accelerating both wind and water erosion. Demining operations often lead to additional degradation through the mechanical displacement or removal of surface soil layers. Soil analyses in conflict-affected areas have revealed titanium concentrations up to 150 times above natural background levels, along with exceedances of maximum permissible concentrations (MPCs) for vanadium, lead, and cadmium. Artillery explosions contribute further to environmental contamination by releasing toxic gases and particles – including carbon monoxide (CO), nitrogen oxides (NO_x), hydrogen cyanide (HCN), and formaldehyde – which can leach into soils and water bodies, posing long-term ecological and human health risks. Between 2022 and 2023 alone, it is estimated that over 84,000 tons of petroleum products were incinerated and approximately 294,000 tons of hazardous substances were released into the atmosphere as a result of hostilities, with a portion settling onto agricultural land. Furthermore, artillery-induced forest fires have destroyed more than 400,000 hectares of vegetation, causing extensive biodiversity loss, habitat fragmentation, and local microclimate disruption. These compounding effects – physical, chemical, and biological – interact to reduce soil fertility, impair microbial activity, and destabilize key agroecological processes. Consequently, the recovery of such landscapes requires long-term, resource-intensive interventions, and coordinated efforts across environmental, agronomic, and political domains (Novakovska et al., 2025).

Chemical contamination represents another major vector of degradation. Explosives, propellants, heavy metals, hydrocarbons, and persistent organic pollutants (POPs) are commonly introduced into the soil environment during armed conflicts. Compounds such as TNT (2,4,6-trinitrotoluene), RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine), HMX, dinitrotoluenes, and their derivatives are often detected in high concentrations near conflict zones, posing significant risks to terrestrial and aquatic ecosystems as well as to human health. Furthermore, elevated levels of heavy metals such as lead, cadmium, copper, and zinc originate from munitions, armored vehicle abrasion, and combustion residues. These elements are not biodegradable and tend to accumulate in soil colloids, thereby impairing microbial activity, enzyme functioning, and crop safety (Dmytrukha et al., 2024).

The impact of Russia's large-scale military invasion of Ukraine has led to an extensive soil degradation resulting from both direct mechanical disturbance and complex chemical contamination. The passage of heavy armored vehicles causes compaction, horizon truncation, and structural destabilization, while debris from destroyed equipment, unexploded ordnance, and leaked fuels introduces xenobiotic compounds and persistent pollutants into the soil system. These processes produce both localized and landscape-scale degradation, leading to severe losses in soil quality and agroecological functionality. Field assessments consistently document concurrent mechanical, chemical, and physical degradation at sites impacted by explosions, fires, and vehicle incineration. Notably, explosion zones exhibit shifts in particle-size distribution, with an increase in the sand fraction (2.0–0.05 mm) by 1.2–1.8 times and a decrease in the clay fraction (<0.002 mm) by 1.1–1.2 times compared with the background levels, indicating pedostructural breakdown and compromised water retention capacity. Heavy metal concentrations in affected soils, particularly for lead (Pb), zinc (Zn), and cadmium (Cd), substantially exceed internationally accepted safety thresholds. Pyrolysis of vehicles and ammunition combustion further elevate the levels of persistent organic pollutants and polycyclic aromatic hydrocarbons. These chemical insults coincide with profound biological disruption. Across all the studied locations, the microbial biomass was reduced by 2.1 times, while overall microbial activity declined by 1.2 times. The structure of the microbiome shifted dramatically, with a 20.5-fold increase in the relative abundance of mycelial organisms, suggesting fungal dominance under stress conditions. Soil toxicity, as determined by biotesting, reached critical thresholds, with 99.8% inhibition observed in bioindicator species. Explosive residues and heavy metals also impact soil mesobiota and plant communities, reducing earthworm and nematode populations, which impairs decomposition processes and nutrient cycling efficiency (Khatoon et al., 2024; Solokha et al., 2024).

These biologically mediated effects are particularly severe in areas previously subjected to intensive agricultural use, where soils had already experienced elevated anthropogenic pressure. The compounding of prior stress with military disturbance accelerates ecological degradation and undermines the resilience of soil systems. Additionally, recent findings suggest that contaminated war-affected soils may serve as hotspots for the proliferation of antibiotic-resistant or stress-adapted microbial taxa, with long-term implications for ecosystem stability and public health (Mohammadipanah & Zamanzadeh, 2019). The evidence highlights the highly integrated nature of post-conflict soil degradation, where mechanical, chemical, and biological factors interact to disrupt soil functionality and hinder natural recovery trajectories.

Equally alarming is the biological disruption that occurs in militarily disturbed soils. Explosive residues and heavy metal contamination negatively affect microbial biomass, alter community composition, and suppress key functional groups such as nitrogen-fixing bacteria and mycorrhizal fungi. Soil biodiversity, including mesofauna such as earthworms and nematodes, also declines markedly, reducing decomposition rates and nutrient cycling efficiency. These impacts are particularly pronounced in war-affected regions characterized by prior intensive agriculture, where the soil biota had already been subjected to anthropogenic stressors. Moreover, military contamination may facilitate the emergence of antibiotic-resistant or stress-tolerant microbial taxa, shifting the ecological balance in ways that are still poorly understood (Ray et al., 2023).

The synergistic interaction of these degradation pathways often leads to complex, site-specific soil conditions that defy traditional remediation approaches. For instance, soils that are simultaneously compacted, hydrologically disrupted, and chemically polluted may exhibit low microbial activity, elevated toxicity, and poor plant establishment even after surface-level interventions (Liu et al., 2023). In some cases, secondary effects such as salinization, acidification, or altered redox potential may emerge due to disturbed drainage or oxidation of exposed subsoil horizons. Such transformations complicate the diagnosis and treatment of soil degradation and necessitate integrative, interdisciplinary approaches to recovery.

In summary, the typology of military-induced soil degradation encompasses a spectrum of interrelated processes – mechanical, chemical, and biological – that act individually or in concert to reduce soil health, fertility, and ecosystem functionality. Understanding the mechanisms and dynamics of these disturbances is critical for designing effective bioremediation and reclamation strategies tailored to the unique challenges of post-conflict agricultural landscapes. The persistence of many contaminants, the depth of physical damage, and the complexity of biological disruption underscore the need for robust assessment protocols and context-specific recovery frameworks that can guide long-term restoration efforts (Lawrence et al., 2015).

Consequences for soils, agroecosystems, and productivity. Military activities exert profound and multifaceted consequences on soils, agroecosystems, and their overall productivity, posing critical challenges to environmental sustainability and agricultural resilience worldwide. Physical disturbances resulting from explosions, troop movements, and heavy machinery cause soil compaction, disruption of soil structure, and loss of topsoil, which directly degrade soil fertility and its capacity to support vegetation growth. The destruction of soil aggregates leads to reduced porosity and aeration, impairing water infiltration and root penetration, thereby accelerating surface runoff and erosion processes. Such mechanical degradation alters hydrological cycles within agroecosystems, negatively affecting soil moisture retention and nutrient availability, which are essential for crop development (Dmytruk et al., 2023). These changes in the physical soil environment are often irreversible without intervention, leading to long-term productivity decline.

Physical disturbances resulting from explosions, troop movements, and the passage of heavy military equipment lead to severe soil compaction, disruption of structure, and loss of the fertile topsoil layer, all of which directly impair soil productivity and its capacity to support vegetation. In Ukraine, where over 24 million hectares are covered by highly fertile chernozem soils – comprising approximately 30% of all European and 9% of global black soils – such physical degradation represents a critical threat to national and global food security. Field studies conducted in zones of intense hostilities reveal that bulk density in the topsoil layer (0–10 cm) on tracks formed by military vehicles reaches 1.37 g/cm³, exceeding the control (uncultivated agricultural field) by 0.39 g/cm³. Notably, an increase in soil bulk density of just 0.1 g/cm³ is associated with a reduction in grain yield of up to 2 centners per hectare. Explosions of shells, mines, and missiles form craters range in diameter from 1 m (82 mm mortars) to 7 m (220 mm MLRS) and depths of up to 5 m (cruise missiles). Soils in these impact zones are subject to dynamic compaction, degradation of particle-size distribution, and a decline in agronomically valuable fractions. These alterations lead to reduced porosity, impaired water infiltration and retention, hindered aeration, and accelerated erosion (Trokhaniak, 2024).

Moreover, mechanised agricultural operations become hazardous due to the presence of shell craters, posing serious risks for machinery. Thermobaric munitions intensify the destruction through rapid temperature changes and combustion, disrupting the soil's thermal and moisture regimes and causing widespread destruction of soil biota. These physical impacts, combined with structural degradation of the soil profile, necessitate urgent land levelling, removal of compacted and contaminated soil, and post-conflict agro-reclamation efforts to restore soil functionality and fertility in affected regions (Menshov et al., 2023).

In addition to physical damage, military activities induce significant chemical contamination of soils. The deposition of heavy metals, hydrocarbons, explosives residues, and radionuclides contaminates the soil matrix, creating toxic conditions that inhibit microbial communities essential for nutrient cycling and organic matter decomposition. The persistence of such contaminants alters soil enzymatic activities and reduces biodiversity, disrupting ecological balance and soil resilience. For example, soils contaminated with lead, mercury, or TNT residues exhibit decreased microbial biomass and functional diversity, leading to impaired nitrogen fixation and carbon sequestration processes (Gębka et al., 2016). Consequently, the chemical degradation exacerbates the physical impacts, severely diminishing soil health and fertility.

Biological impacts of military disturbances on agroecosystems further intensify land degradation processes. Field assessments in eastern and southern Ukraine have revealed a 35–60% decline in soil microbial biomass carbon (SMBC) in areas directly affected by explosive contamination compared with undisturbed control sites. This reduction is primarily attributed to the combined effects of heavy metal toxicity (e.g., elevated levels of Cu, Zn, and Pb exceeding threshold values by 2.5–5.0 times), thermal disruption, and physical compaction. Vegetation cover is often completely obliterated within blast radii of 5–15 meters for conventional shells and up to 50 meters for thermobaric munitions, significantly lowering net primary productivity and exposing soils to accelerated wind and water erosion. The destruction of plant root systems reduces organic carbon inputs, leading to declines in soil organic matter content by up to 40% within the top 10 cm of the soil profile (Shevchenko et al., 2024). Furthermore, military activity alters the composition and abundance of soil biota, disrupting essential ecological functions such as nutrient cycling, litter decomposition, and mycorrhizal symbioses. The loss of these biotic interactions impairs plant nutrient acquisition and tolerance to abiotic stress, thereby diminishing the self-regulatory capacity and long-term resilience of agroecosystems. This biological degradation increases susceptibility to secondary processes such as desertification, surface crusting, and salinization, particularly in steppe and arid regions (Afrasinei et al., 2016; Saljnikov et al., 2022).

These combined physical, chemical, and biological effects culminate in a marked reduction of agricultural productivity in militarily impacted regions. Crop yields decline due to compromised soil quality, increased toxicity, and unfavorable water regimes, threatening local food security and economic livelihoods. Empirical studies in post-conflict areas demonstrate yield reductions ranging 30% to over 70%, depending on contamination severity and soil degradation extent. The economic repercussions extend beyond immediate losses, as long-term soil degradation necessitates costly remediation and restricts land-use options (Chihwai et al., 2024). Such impacts also cascade through the food supply chain, increasing vulnerability of rural communities and exacerbating socioeconomic instability.

The convergence of physical, chemical, and biological disturbances associated with military activity leads to a profound and multifaceted degradation of agroecosystems, culminating in significant declines in agricultural productivity. Damage to soil structure, contamination with heavy metals and persistent organic pollutants, and loss of microbial and faunal biodiversity impair essential soil functions such as nutrient cycling, water retention, and root development. Vegetation destruction further exposes soils to erosion and reduces organic matter input, exacerbating long-term fertility loss. These processes collectively reduce crop yields – empirical data from post-conflict zones indicate declines ranging 30% to over 70%, depending on the degree of contamination and the intensity of soil degradation (Chihwai et al., 2024). For instance, in war-affected areas of Vietnam, a 10% increase in bombing intensity was found to decrease the rice productivity by 2.94% and total agricultural productivity by 3.21% in the long term. Exposure to chemical agents such as Agent

Orange was also shown to negatively impact yields, with additional effects mediated through diminished social capital and economic production capacity. These outcomes extend beyond agricultural losses, contributing to chronic food insecurity, limiting land-use opportunities, and exacerbating socioeconomic instability in rural communities (Appau et al., 2024). As demonstrated in Ukraine and other conflict-affected regions, the economic consequences of military-induced soil degradation require costly remediation efforts and pose long-term threats to sustainable development.

Addressing these consequences requires integrated remediation approaches that restore soil physical properties, detoxify chemical pollutants, and rehabilitate biological functions within agroecosystems. Agronomic interventions such as deep tillage, organic amendments, and contour farming can mitigate compaction and erosion (Shevchenko et al., 2024). Bioremediation using microbial consortia and phytoremediation with hyperaccumulator plants target chemical contaminants, restoring microbial diversity and enzymatic functions. Concurrently, restoring vegetation cover stabilizes soils and reestablishes ecosystem services critical for sustainable productivity (Alves et al., 2022). Implementing such multidisciplinary strategies is imperative for the recovery of soils and agroecosystems affected by military activities, particularly in regions affected by ongoing or recent conflict.

In summary, military-induced degradation profoundly undermines soil integrity, agroecosystem health, and agricultural productivity through intertwined physical, chemical, and biological mechanisms. Comprehensive understanding and management of these impacts are crucial for designing effective restoration strategies to ensure environmental sustainability and food security in affected regions. Continued research and international cooperation are essential to advance remediation technologies and support recovery efforts in post-conflict agricultural landscapes.

Examples of military-induced soil degradation from Ukraine and other countries. Military operations in Ukraine, particularly in the Donbas and Kharkiv regions, have led to profound degradation of agricultural soils, posing grave threats to ecological stability and food security. Remote sensing analyses identified 420,615 craters affecting 3,411 hectares, with bombturbation covering 4,212 ha, indicating widespread soil mixing, compaction, and burial under explosion ejecta (Bonchkovskyi et al., 2025) Field studies in Sumy and Okhtyrka confirmed that equipment incineration increased the sand fraction by 1.2–1.8× and reduced the clay fraction by 1.1–1.2×; the microbial biomass carbon dropped by a factor of 2.1, the microbial activity decreased by 1.2×, and the overall soil toxicity reached 99.8% – reflecting near-complete suppression of soil biological function (Zaitsev et al., 2024) Concurrent chemical assessments in Dnipropetrovsk, Mykolaiv, and Zaporizhzhia oblasts revealed that the lead concentrations exceeded maximum permissible limits by 3×, 5×, and 11.17×, respectively; and zinc, fluoride, oil products, and phosphates were elevated by 25–50% (Bulba et al., 2024) These compounded physical, chemical, and biological alterations severely impair soil structure, fertility, and resilience, significantly diminishing crop productivity. For example, in Kharkiv Oblast alone, over 160,000 ha of agricultural land were cratered, triggering multi-billion dollar restoration costs – estimated at $20 billion for soil reclamation nationwide (WUR, 2025) Globally, similar patterns emerge: armed conflict not only triggers immediate soil disruption but also leaves persistent legacies of contamination and ecological harm, underscoring the urgency of integrated remediation and sustainable recovery efforts in post-conflict landscapes.

International case studies confirm that military activity induces long-lasting degradation of soil systems across diverse ecological zones. During the Vietnam War, over 72 million liters of Agent Orange (a dioxin-contaminated herbicide) were sprayed across approximately 1.5 million hectares, making up nearly 10% of southern Vietnam. The soil analyses from Bien Hoa and A So airbase hotspots – areas used for storage, spraying, and disposal – revealed dioxin (2,3,7,8 TCDD) concentrations up to 4,534 ng/kg (approx. 746 ng TEQ/kg) in soils and sediments, exceeding the Canadian soil quality guidelines by up to 20–46×. In these zones, 2, 3, 7, and 8 TCDD accounted for 72–91% of the total TEQ, and contamination persisted predominantly in the top metre of soil, indicating the depth priority for remediation (Dat et al., 2019).

In arid and semi arid regions such as Iraq and Afghanistan, combat operations and tracked vehicle movements have severely disrupted the soil structure and moisture regimes. Research shows that heavy machinery operations compact soils and accelerate surface runoff, leading to increased erosion and diminished water retention capacity (Banout et al., 2014).

Collectively, these global cases illustrate that physical disturbance combined with chemical contamination dramatically reduces soil fertility, disrupts microbial function, and undermines food production potential. Agent Orange–contaminated soils in Vietnam continue to present toxicological and agronomic challenges decades after the conflict, while mechanical degradation in the Middle East presents ongoing erosion and hydrological deficits. Therefore, post conflict soil restoration must integrate chemical cleanup, physical restructuring, and ecological regeneration to support sustainable land use and food security.

Historical conflicts across Europe have left enduring legacies of soil degradation due to unexploded ordnance (UXO), heavy metal contamination, and structural disruption. After World War I, some European battlefields received approximately 15 million tons of copper, iron, lead, nickel, and zinc from over 1.45 billion artillery shells, resulting in elevated levels of toxic metals in soils – even 90 years post-conflict. Notably, arsenic enrichment exceeding the background by 1,400 times has been documented in the former combat zones in Germany and France, indicating intrusion of chemical warfare or tracer ammunition residues (Geris et al., 2024).

In the Balkans, unexploded ordnance continues to threaten both human safety and soil recovery in Bosnia and Herzegovina, where approximately 1,230 km² (≈2.4% of the country) remained contaminated as of 2014, impacting over 538,000 people, primarily in rural agroecosystems. The soil contamination studies in Croatia revealed elevated concentrations of antimony (Sb) up to 3.1 mg/kg in bombed zones such as near the Erdut Bogojevo Bridge – 10 to 19 times higher than background in the nearby regions, linked explicitly to intense wartime use of tracer ammunition. Lead (Pb), arsenic (As), and mercury (Hg) were also enriched, compromising ecological production and necessitating costly soil remediation (e.g. $500–1,000 USD/m² for advanced decontamination) (Vidosavljević Geris et al., 2013).

Military training and testing grounds further exacerbate soil degradation across Europe, including Poland and Czech Republic. In Poland's Piekary Śląskie and Bukowno, industrial and military influence elevated the heavy metal levels (Pb, Zn, Ni, Cd, Cu), negatively altering the microbial community composition and reducing the microbial metabolic activity, as indicated by the PLFA and BIOLOG assays (Jarosławiecka & Piotrowska Seget, 2022). Soil from the former Czech military ranges also revealed considerable accumulations of potentially toxic elements (As, Cd, Co, Cr, Ni, Cu, Pb, Zn) despite decades since decommissioning in 1991, highlighting persistent risks (Broomandi et al., 2020).

Collectively, these European cases underline that military-derived contamination – whether from munitions residue or soil disturbance – leads to long-term disruptions of microbial and faunal soil communities, increased soil toxicity, and impaired agricultural usability. Such damage impedes reclamation and demands ongoing monitoring and investment in advanced remediation strategies such as phytoremediation, *in situ* chemical stabilization, and microbial community restoration (Rodríguez-Seijo et al., 2024).

Ukraine faces a particularly challenging soil degradation scenario, where compaction, erosion, heavy-metal pollution, and biological suppression coincide, severely hindering rehabilitation efforts. In the field trials at contaminated municipal sites near Kamianets Podilskyi, *Miscanthus × giganteus* demonstrated strong growth over two seasons in military-polluted soils measuring high concentrations of Fe, Mn, Cu, Zn, Pb, Sr, Ti, and As. Initial foliar uptake peaked mid-season – especially for Cu and Zn – though most non-essential elements remained rooted, minimizing entry into biomass and allowing continued rhizosphere activity (Pidlisnyuk et al., 2019). In a recent Ukrainian study, combinatory application of phytoremediation with hyperaccumulators, microbial inoculants, and mechanical loosening achieved 35%–50% reductions in extractable Pb and Zn within 12 months, alongside a 30% increase in microbial respiration rates – restoring partially soil biological function (Melnychenko, 2024).

Parallel success has been achieved in Slovakia with the Miscanthus trials showing a 40–60% reduction in bioavailable heavy metals over two growing seasons, without aerial translocation, making it suitable for contaminated military sites with ongoing risk of explosive residue exposure (Pidlisnyuk et al., 2019). These findings underscore the effectiveness of integrated treatment: combining mechanical decompaction, hyperaccumulator cropping, and microbial enhancement notably accelerates ecosystem service recovery in post-conflict soils. Remote sensing driven by GIS provides vital support for targeting and evaluating interventions. A land-cover study using Landsat 8 and Sentinel-2 time-series across eastern Ukrainian regions (Kherson, Luhansk, and Donetsk oblasts, and

Crimea) identified persistent cropland fallowing hotspots, and erosion-sensitive zones aligned with shelling intensity data, enabling prioritization of remediation zones (Ma et al., 2022).

In conclusion, evidence from Ukraine and international cases confirms that military-induced soil degradation is a multifaceted problem necessitating interdisciplinary approaches for sustainable land restoration. Physical destruction, chemical contamination, and biological alterations of soil environments are interconnected factors that directly affect agroecosystem productivity. Considering regional specificities and integrating modern bioremediation, agronomic practices, and policy support are critical for restoring the functional capacity of soils disturbed by military activities. This is especially pertinent for Ukraine amid ongoing security challenges and its imperative to maintain agricultural resilience and food sovereignty.

Bioremediation approaches for contaminated agricultural soils

Microbial methods: bacteria, fungi, bioproducts. Microbial bioremediation harnesses the metabolic diversity of bacteria, fungi, and formulated bioproducts to reconstruct soil functionality in contaminated agricultural lands. For instance, *Pseudomonas spp.* and *Bacillus subtilis* isolates from diesel-contaminated soils degraded up to 84% and 83% of diesel-range hydrocarbons, respectively, within three weeks under laboratory conditions (Bekele et al., 2022). Field-derived consortia have shown even higher performance: a mixed culture of *P. putida*, *Bacillus megaterium*, and *Arthrobacter spp.* achieved a 98.3% degradation of diesel hydrocarbons in soil microcosms in Nigeria (Saidu et al., 2019), while another study reported 83–89% total petroleum hydrocarbon breakdown after 30 days using bacterial consortia (Ahmed et al., 2024). By contrast, heavy-metal remediation benefits from metal-resistant bacteria. *Bacillus subtilis* was found to biosorb 67% of Pb^{2+} from contaminated media within 72 hours in controlled conditions (Bekele et al., 2022). Furthermore, inoculating *Miscanthus × giganteus* rhizosphere with metal-tolerant PGPR such as *Mycolicibacterium sp*. Pb113 and *Chitinophaga sp*. Zn19, in the soil containing 1,650 mg/kg Zn, resulted in improved plant growth and enhanced Zn accumulation compared with the uninoculated controls (Muratova et al., 2023). Fungal agents also play a pivotal role: white-rot fungi, such as *Phanerochaete chrysosporium*, produce ligninolytic enzymes capable of degrading TNT, RDX, and petroleum PAHs into non-toxic compounds, achieving 60–80% reduction under ideal conditions. Additionally, embedding microbes into bioproducts – like biochar or alginate beads – improves their survival and efficacy. For example, biochar-based carriers enhanced the hydrocarbon degradation and supported the plant-microbe synergies in contaminated soils (Pandolfo et al., 2023).

By combining hydrocarbon-degrading bacteria, heavy-metal sorbing fungi, and supportive carriers, microbial remediation offers robust and scalable solutions for diverse pollutant types, essential for restoring ecological and agronomic functions of soils impaired by military activities.

Fungal bioremediation offers a potent complement to bacterial remediation by deploying ligninolytic enzymes – such as lignin peroxidase (LiP) and manganese peroxidase (MnP) – which are able to oxidize recalcitrant pollutants including polycyclic aromatic hydrocarbons (PAHs) and nitroaromatic explosives. In the soil incubation trials, *Phanerochaete chrysosporium* achieved a degradation of 72–73% of phenanthrene and pyrene, and ~25–26% of benzo[a]pyrene over 19 days, with a concurrent LiP and MnP enzymatic activity ranging 0.16 U/g to 1.92 U/g, depending on the soil organic matter content (Wang et al., 2009). In the related studies, *P. chrysosporium* removed between 70% and 100% of a mixture of 22 PAHs in 27 days (Bumpus, 1989). For explosive residues, *Irpex lacteus* – another white-rot fungus – degraded approximately 95% of TNT (2,4,6-trinitrotoluene) within 48 hours in liquid culture, producing intermediate ADNT metabolites. The additional research on *P. chrysosporium* demonstrated a significant TNT mineralization under ligninolytic conditions (Chapter data, ~60–70% reduction) (Kim & Song, 2000). Furthermore, fungal mycelium plays a structural role in soil restoration: in the mesocosm experiments, inoculation with white rot fungi like *Trametes versicolor* improved the aggregate stability by ~30% and reduced simulated wind erosion by 25% relative to the uninoculated controls, enhancing the soil cohesion and resilience (Stahl & Aust, 1995). These results highlight the dual benefit of fungal bioremediation – not only degrading persistent organic contaminants, but also enhancing soil structure and promoting agroecosystem recovery.

Commercial microbial bioproducts – formulations combining microbial inoculants with organic amendments – are increasingly employed for field-scale soil remediation due to their capacity to revitalize indigenous microbial communities and accelerate contaminant degradation across diverse environmental conditions. For example, in a study involving heavy-metal–contaminated soils, a strain of *Serratia marcescens* combined with leguminous shrubs (*Robinia pseudoacacia* and *Sophora xanthantha*) significantly increased the levels of soil ammonium nitrogen and organic carbon, while reducing the lead and cadmium contents compared with teh plant-only controls (Zheng et al., 2023). Plant growth–promoting bacterial inoculants have also demonstrated remarkable effects on soil enzyme activity. In sandy soil conditions, specific inoculants (denoted P1) increased the total carbon enzyme activity by 58.3%, the nitrogen enzyme activity by 32.3%, and the phosphorus enzyme activity by 53.3%, while under drought stress the carbon enzyme activity rose by 116.7% for certain wheat cultivars compared with the uninoculated controls (Li et al., 2023).

The four-year field trials in abandoned mining soils in temperate regions revealed dramatic improvements in soil multifunctionality: microbial inoculants increased the nutrient cycling rates for carbon, nitrogen, phosphorus, and sulfur and improved the overall enzyme activity and microbial diversity compared with the untreated plots (Li et al., 2023).

These commercial bioformulations generally involve selecting resilient microbial strains with proven catabolic or plant-growth-promoting abilities, incorporating them into carriers such as compost or biochar to enhance their survival, and optimizing application protocols to suit local soil conditions. Although many are proprietary, they have been shown to enhance soil microbial biomass, elevate enzymatic activities, and boost plant growth parameters significantly – often increasing plant biomass by 30–60%, enzyme activities by 30–50%, and reducing bioavailable heavy metal levels by 25–50% in field conditions (Romero-Estonllo et al., 2023).

An effective microbial bioremediation paradigm integrates bioaugmentation – the strategic introduction of pollutant-degrading strains – with biostimulation, which modifies soil conditions to amplify the activity of native microbial communities (Gadd, 2010). In a loessal soil contaminated with petroleum, biostimulation alone using nitrogen and phosphorus nutrients yielded a 28.3% degradation of total petroleum hydrocarbons (TPHs) after 12 weeks, outperforming bioaugmentation alone, which achieved a 13.9% degradation; however, combining both approaches is often superior in complex contexts (Wu et al., 2021). In another microcosm study of an aged diesel-contaminated soil, a bacterial consortium plus nutrients (ammonium nitrate and phosphate) achieved as high as a 99.0% TPH removal in 60 days, while the nutrient-only and consortium-only treatments yielded 97.9% and 97.4%, respectively (Chaudhary et al., 2021).

Organic amendments such as vermicompost or compost from water hyacinth significantly enhance biostimulation. In highly petroleum-polluted soils, water-hyacinth compost achieved a 93% TPH degradation in 56 days (SMC WH mix achieved 89%), while mineral NPK fertilizer alone resulted in a 86% degradation. By contrast, the untreated control soils achieved only a 4% degradation under natural attenuation (Udume et al., 2023). Similarly, in a burned forest soil in Italy, biostimulation (nutrient amendment) removed ~70% of high molecular weight hydrocarbons within 60 days, compared with 55% for bioaugmentation and 45% under natural attenuation (Andreolli et al., 2015).

These results underscore that bioaugmentation enhances catabolic potential, while biostimulation ensures nutrient availability and community richness, making their combination particularly effective. Advances in metagenomics and metatranscriptomics further support this approach: by characterizing functional gene abundance (e.g., dioxygenases, alkB, nah genes) and microbial community shifts in contaminated soils, researchers can optimize strain selection and amendment regimes to align with site-specific needs (Cui et al., 2020).

Despite significant advances, considerable challenges remain in scaling microbial bioremediation technologies to diverse field scenarios. Field studies reveal a wide range of degradation efficiencies – for instance, petroleum hydrocarbon degradation in temperate soils varies from 40% to over 80%, influenced by pollutant concentration, moisture, nutrient levels, and seasonality (Margesin & Schinner, 2001). Co-contamination with heavy metals often inhibits microbial activity, further complicating remediation efforts. In China, a study combining bioaugmentation and organic amendments achieved a 70% PAH reduction, compared with 40% with inoculants alone (Cao et al., 2022).

Integrative remediation approaches – combining microbial consortia with organic matter addition, nutrient supplementation, or aeration – have shown greater resilience. For example, nutrient biostimulation (N & P addition) in Antarctic hydrocarbon-contaminated soils boosted the degradation from 49.5% (control) to 75.8% over 50 days (Álvarez et al., 2017). Additionally, combining anaerobic sludge and biochar resulted in a 25% increase in phenanthrene removal compared with sludge alone, achieving a 72% total removal (Xue et al., 2023). Advances in metagenomic and transcriptomic analyses now enable detailed profiling of microbial functional genes, providing insights for tailored interventions. These molecular tools unveil shifts in catabolic gene abundances (e.g., alkB, dioxygenases) and community composition in response to treatments (Yap et al., 2021).

Thus, while microbial bioremediation remains a cost-effective and eco-friendly strategy for remediating soils affected by military and industrial activities, site-specific optimization of consortia, carriers, and agronomic integration – supported by molecular diagnostics – is critical to ensure effective outcomes across diverse environmental conditions.

Phytoremediation: accumulator plants, cover crops. Phytoremediation is an increasingly recognized and eco-friendly approach to the rehabilitation of contaminated agricultural soils, utilizing the natural capacity of plants to uptake, accumulate, stabilize, or degrade pollutants. Accumulator plants, particularly hyperaccumulators, have developed physiological mechanisms that allow them to tolerate and sequester high concentrations of heavy metals and organic contaminants within their tissues, thereby decreasing soil toxicity and supporting gradual ecological restoration. For instance, *Brassica juncea* (Indian mustard), *Helianthus annuus* (sunflower), and *Populus* species have shown significant efficacy in the phytoextraction of heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) from polluted soils (Ali et al., 2013; Pilon-Smits, 2005). The effectiveness of phytoremediation depends on the selection of suitable plant species based on the nature and concentration of contaminants, local climatic conditions, and soil properties, with the goal of optimizing both pollutant removal and biomass yield for safe disposal or potential valorization (Yan et al., 2020).

Cover crops play a complementary role in phytoremediation by protecting soil from erosion, enhancing organic matter content, and stimulating microbial degradation of contaminants in the rhizosphere. Species such as clover (*Trifolium* spp.) and vetch (*Vicia* spp.), particularly legumes, contribute to soil fertility through biological nitrogen fixation, thereby promoting the development of microbial consortia involved in contaminant breakdown (Finney et al., 2016). Moreover, root exudates from cover crops have been shown to increase rhizospheric microbial activity, enhancing the biodegradation of hydrocarbons, nitroaromatic compounds, and other residues commonly present in military-affected soils (Ali et al., 2013; Brar et al., 2010). In addition, the integration of cover crops improves soil structure and moisture retention, factors that are essential for the successful establishment and sustainability of phytoremediation systems in contaminated agricultural landscapes.

Phytostabilization, a key mechanism within the broader framework of phytoremediation, utilizes plants to immobilize contaminants within the root zone, thereby preventing their migration into groundwater or entry into the food web (Khan et al., 2009). This technique is especially effective for sites with high levels of contamination, where active extraction is either too slow or environmentally risky. Species such as *Festuca arundinacea* and *Miscanthus* × *giganteus*, characterized by dense root systems and substantial biomass production, have been shown to reduce the mobility and bioavailability of heavy metals and organic pollutants by promoting adsorption, precipitation, and complexation in the rhizosphere (Pulford & Watson, 2003; Nsanganwimana et al., 2014). In such systems, the vegetation acts as a living barrier that supports natural attenuation and mitigates erosion, dust dispersion, and off-site contaminant transport.

Combining accumulator plants with cover crops in phytoremediation systems has demonstrated synergistic benefits, enhancing both contaminant removal and overall soil recovery. Mixed plantings can increase total biomass production, improve soil cover, and stimulate microbial diversity and enzymatic activity in the rhizosphere – key factors for efficient degradation of organic pollutants and stabilization of heavy metals (Weyens et al., 2009; Blum et al., 2019). Moreover, integrating phytoremediation with agronomic practices such as crop rotation, application of organic amendments (e.g., compost, biochar), and optimized irrigation strategies contributes to improved soil structure, nutrient availability, and contaminant bioavailability, thereby increasing the efficiency and sustainability of remediation efforts (Salt et al., 1998). Such integrated strategies are particularly relevant for post-conflict agricultural landscapes, where soils are often physically disturbed, chemically contaminated, and biologically impoverished.

One of the promising approaches to phytoremediation of degraded Technosols is the cultivation of high-yielding crops capable of simultaneously accumulating nutrients and partially immobilizing heavy metals, for example, sweet sorghum (*Sorghum bicolor* L.). Studies have shown that the application of untreated sewage sludge significantly improves soil fertility by increasing humus content by 40–80% and the nitrogen mass fraction by 22.9–59.5%, depending on the dose, resulting in a biomass yield increase of 14.5–41% at the maximum rate of 60 t/ha. Sorghum exhibits a high capacity for nitrogen, potassium, and phosphorus uptake, with biogeochemical mobility coefficients of 10.9–13.2 for potassium and 3.9–5.7 for phosphorus. Among the micronutrients, zinc is absorbed most intensively, followed by iron, copper, and manganese. The uptake of heavy metals by sorghum biomass remains low, not exceeding 100 g/ha, with cadmium accumulation being the smallest. In addition, sewage sludge application affects the thermal degradation of sorghum biomass by lowering decomposition temperatures and increasing reaction rates, thereby contributing to more complete combustion – an important factor for bioenergy use. The most efficient fertilization strategy was found to be sewage sludge treated with flocculant at a dose of 40 t/ha, which proved optimal for growing sweet sorghum for bioethanol and pellet production on loess-like loam Technosols (Kharytonov et al., 2023).

Phytoremediation, while environmentally friendly and cost-effective, faces several practical challenges that limit its widespread application. These include the relatively slow pace of contaminant removal, the risk of pollutant translocation into edible plant tissues and subsequent entry into the food chain, and the reduced effectiveness of phytoremediation under conditions of extreme contamination, poor soil fertility, or climatic stress. To address these constraints, current research explores the genetic enhancement of hyperaccumulator species, harnessing plant–microbe symbioses (e.g., mycorrhizal fungi and plant growth-promoting rhizobacteria), and the breeding of multifunctional cover crops tailored to specific pollutant profiles and stress conditions (Ali et al., 2013). Additionally, advances in molecular biology, genomics, and remote sensing technologies offer tools for real-time monitoring and improved management of phytoremediation systems at landscape scales.

Rapid industrialization, increased waste production, and a surge in agricultural activities, mining, contaminated irrigation water, and industrial effluents contribute to the contamination of water resources due to heavy metal (HM) accumulation. Humans use HM-contaminated resources to produce food, which eventually leads to accumulation of these metals in the food chain. Decontamination of these valuable resources, as well as prevention of further contamination, is essential to avoid detrimental health impacts. Phytoremediation is a realistic and promising strategy for heavy metal removal from polluted areas, based on the use of hyperaccumulator plant species that are highly tolerant to HMs present in the environment and soil. This technique employs green plants to remove, decompose, or detoxify hazardous metals. For soil decontamination, five main phytoremediation methods are used: phytostabilization, phytodegradation, rhizofiltration, phytoextraction, and phytovolatilization. However, traditional phytoremediation methods face significant limitations when applied at large scales, prompting biotechnological efforts to modify plants and enhance their efficiency in HM phytoremediation. Considered a relatively new technology, phytoremediation is widely regarded as economical, efficient, unique, and environmentally friendly. New metal hyperaccumulators with high efficacy are continuously explored and employed for phytoremediation and phytomining purposes. Therefore, various strategies and biotechnological approaches for the removal of heavy metal contaminants from the environment are being comprehensively investigated, with emphasis on recent advancements and practical applications for removing toxic pollutants. Additionally, sources, effects of heavy metals, and factors affecting phytoremediation efficiency are important areas of study (Shakeel et al., 2022).

In summary, phytoremediation using accumulator plants and cover crops represents a promising, sustainable, and cost-effective approach for remediating contaminated agricultural soils. When integrated with microbial consortia and complementary agronomic practices – such as organic amendments, crop rotation, and precision irrigation – this strategy enhances soil detoxification, improves physicochemical properties, and supports biodiversity. Such holistic interventions are especially relevant in post-conflict and industrially degraded landscapes, where conventional remediation techniques are often economically or logistically unfeasible. Therefore, phytoremediation not only contributes to environmental restoration but also to the long-term resilience and productivity of agroecosystems.

Organo-mineral sorbents, biostimulants, and composts. Organo-mineral sorbents, biostimulants, and composts represent essential components in the integrated remediation of contaminated agricultural soils, contributing to pollutant immobilization, enhancement of soil biological activity, and restoration of soil fertility. Organo-mineral sorbents such as biochar, zeolites, and clay-based materials amended with organic matter have demonstrated significant capacities to adsorb heavy metals (e.g., Pb, Cd, Zn), hydrocarbons, and other toxic compounds, thereby reducing their bioavailability and environmental mobility. For example, Lehmann & Joseph (2015) reported that biochar application at 5% reduced the bioavailable lead concentrations by up to 50%, while increasing the soil water retention by approximately 20%. Similar results were obtained by Ahmad et al. (2024), showing a 40–60% reduction in the bioavailable heavy metals following amendment with biochar and zeolite. These sorbents also improve soil physical properties by increasing porosity and water-holding capacity, providing habitats and substrates for beneficial microorganisms that facilitate natural attenuation processes (Lehmann & Joseph, 2015).

Biostimulants, including microbial inoculants, humic substances, and plant extracts, are critical in promoting microbial activity and enhancing plant growth under stress conditions caused by soil contamination. Rouphael & Colla (2020) demonstrated that microbial biostimulants increased the soil enzymatic activities (e.g., dehydrogenase and phosphatase) by 30–40% and enhanced the nutrient cycling. Humic acids are known to chelate heavy metals, thereby reducing phytotoxicity (Calvo et al., 2014). Moreover, Yakhin et al. (2017) reported that microbial inoculants accelerated the degradation of organic contaminants and improved the soil enzymatic functions, increasing the microbial biomass carbon by 25% in the treated soils. The combined use of biostimulants with organo-mineral sorbents synergistically improves remediation outcomes by fostering a more supportive environment for both plants and microorganisms.

Composts derived from organic waste materials provide multiple benefits in soil remediation by supplying essential nutrients, improving soil structure, and enhancing microbial diversity. Brown et al. (2019) showed that compost amendments increased the soil organic matter content by 15–25% and significantly restored the microbial communities impaired by contamination. Riaz et al. (2021) reported that compost applied at rates of 10–20 t/ha reduced the bioavailable cadmium by nearly 50%, decreasing uptake by crops. Compost also supports phytoremediation efforts by improving soil conditions favorable to plant growth and establishment of cover crops or accumulator species.

The integrated application of organo-mineral sorbents, biostimulants, and composts provides a holistic approach to soil restoration by combining chemical, biological, and physical remediation mechanisms. Wang et al. (2019) demonstrated that combined amendments improved the soil microbial biomass by up to 35%, enhanced the enzymatic activities critical for nutrient cycling, and stabilized contaminants within the soil matrix. Field studies by Huang et al. (2016) documented yield improvements of 15–30% in crops grown in previously contaminated soils following treatment with such integrated amendments. Importantly, these materials often derive from sustainable sources, supporting circular economy principles and reducing environmental footprints.

Despite these positive outcomes, amendment applications require site-specific optimization considering contaminant types, soil properties, and climate to maximize efficiency. Lehmann & Joseph (2015) emphasized that soil texture and pH critically influence sorbent performance and metal immobilization. Rouphael & Colla (2020) highlighted the need for further research to optimize biostimulant formulations and assess long-term impacts for large-scale agricultural applications. The development of advanced organo-mineral and biological amendments remains a crucial frontier in sustainable remediation technologies aimed at mitigating military and industrial soil contamination globally.

Land reclamation and agroecological restoration

Agrotechnical and engineering approaches to land reclamation. The twenty-first century has witnessed an unprecedented intensification of human-induced disruptions to natural ecosystems, with soil degradation emerging as one of the most acute environmental threats. As modern industrial activities – ranging from open-pit mining to large-scale military operations – disturb and often obliterate topsoil layers, compromising the ecological functions of soils, reducing biodiversity, and driving entire agroecosystems toward collapse. The scale and complexity of these processes vary regionally, influenced by local climate, geomorphology, and the nature of anthropogenic pressures (Travleev et al., 2005; Uzbek, 2015; Mytsyk et al., 2024). The disruptive power of contemporary technologies has enabled humans to alter the biogeocenotic framework of entire landscapes. Modern interventions penetrate beyond surface layers, reshaping hydrological regimes, disrupting nutrient cycles, and triggering irreversible changes in biological connectivity. Such transformations often lead to cascading ecological consequences that jeopardize long-term sustainability (Demydov et al., 2013; Kharytonov et al., 2020) In this light, reclaiming degraded lands is not only a question of agricultural utility, but rather a broader ecological imperative.

Soils, while inherently resilient due to their high buffering capacity, remain among the slowest components of the ecosystem to recover post-disturbance. Formed over centuries through a delicate interplay of climatic, biological, and geological factors, soils do not simply regenerate through natural succession. Their recovery demands a deliberate and science-based approach. Recognizing this, researchers stress the importance of studying the evolving agrophysical properties of technosols – engineered or anthropogenically altered soils – and their capacity to sustain future land use. These studies are particularly relevant in Ukraine, where technosols are a growing component of the post-mining and post-conflict landscape (Demydov, 2012; Mytsyk et al., 2024).

In the arid steppe regions of Ukraine, where water availability is the limiting factor for plant growth, understanding the hydrological and thermal behavior of technosols becomes essential. Their structure, porosity, and bulk density all play a vital role in determining soil-water relations and, consequently, crop viability. Recent studies indicate that long-term agricultural exploitation of reclaimed soils initiates adaptive changes in soil density. For example, research by Mytsyk et al. (2023) highlights the dual and often opposing processes occurring in Technosol profiles: artificial compaction of the topsoil, edaphotop, layer via repeated mixing and the natural loosening of deeper horizons due to settlement.

Notably, a 38-year study by Buriak & Zabaluyev (2020) provided valuable longitudinal insights into Technosol fertility evolution in the Ukrainian steppe. They observed that a stratified soil profile – comprising a sludge layer, a 50 cm loess-like loam middle layer, and a 50 cm chernozem top layer – mirrored the productivity of natural soils. Over time, organic matter levels in the upper layers increased, indicating the gradual reestablishment of nutrient cycles and humification processes. These results affirm the viability of engineered soils when guided by sound agrotechnical principles.

The physical properties of Technosols, such as bulk density and texture, are critical determinants of their agricultural performance. Studies by Demydov et al. (2013) offer precise data on soil density ranges for various geological substrates, providing a foundation for optimizing substrate selection and tillage strategies in reclamation planning. Meanwhile, Mytsyk et al. (2024) has emphasized the hydrological potential of loamy and clayey substrates, cautioning that without continued soil enhancement, even favorable starting conditions may deteriorate over time.

Botanical composition is another decisive factor in reclamation success. Mytsyk et al. (2024) identifies perennial legume-grass communities – including alfalfa (*Medicago sativa*), sainfoin (*Onobrychis arenaria*), intermediate wheatgrass (*Thinopyrum intermedium*), and smooth brome (*Bromus inermis*) – as highly adaptable to technogenic environments. These species not only stabilize soil structure but also contribute to nitrogen fixation and forage production. Nonetheless, future models should expand to include economically valuable cereals and bioenergy crops, aligning ecological rehabilitation with market demands (Uzbek & Halahan, 2004).

Beyond biophysical considerations, recent geopolitical events in Ukraine have brought new urgency to land reclamation discourse. Warfare has introduced unprecedented forms of soil destruction, ranging from explosive cratering to the salinization and waterlogging caused by dam destruction, such as the catastrophic breach of the Kakhovka Reservoir. These events compound existing degradation and exacerbate the need for novel reclamation strategies tailored to post-conflict recovery. The loss of irrigated land and functional water systems threatens national food security and underscores the need for rapid yet ecologically sound intervention.

Collectively, over six decades of national and international research have culminated in a comprehensive body of knowledge that can guide both theory and practice in reclaiming technogenically degraded lands. From foundational studies on soil physicality to forward-looking models addressing climate resilience and post-war recovery, the agrotechnical and engineering approaches pioneered in Ukraine present a globally relevant blueprint for restoring ecological functionality in damaged landscapes.

Restoration of agrophysical, chemical, and biological soil properties. The restoration of agrophysical soil properties is a cornerstone of sustainable land rehabilitation, particularly in post-conflict settings where military operations have left millions of hectares severely degraded. In Ukraine alone, the war has affected over 3 million hectares of agricultural land, with more than 1.5 million hectares rendered unsafe or unproductive due to heavy machinery, explosions, and soil contamination (FAO, 2025. Ukraine: Strategic priorities for 2025). These impacts disrupt the essential agrophysical characteristics of soil such as porosity, structure, compaction, and water retention, while often simultaneously impairing chemical and biological functions.

Military-induced soil compaction is among the most immediate and severe forms of physical degradation. Tank traffic, artillery shelling, and trench construction have been found to increase the bulk density from 1.1–1.2 to 1.6–1.8 g/cm³, leading to reductions in the infiltration rates by over 60% and severely restricting the root development and water movement. Deep tillage, subsoiling, and chiseling, often reaching depths of 40–60 cm, are essential to reversing compaction. These are complemented by organic interventions, such as the application of biochar (10–20 t/ha), compost, and green manures that foster aggregate stability, moisture retention, and microbial regeneration (Are et al., 2017).

Particular emphasis is warranted for the Ukraine's Left-Bank Forest-Steppe region, where fertile chernozem soils – some of the most productive in the world – have a remarkable but vulnerable structural equilibrium. The research by Demydenko & Velichko (2016) proposes a system of soil-protective agriculture based on surface tillage and the energy-efficiency of natural soil-forming processes. They introduce the concept of a "thermodynamic code" of chernozem – a metaphor for the soil's memory and self-organizing properties. In this context, maintaining soil structure and regulating the amplitude of energy fluctuations helps extend the soil's homeostasis, allowing for its gradual and extensive regeneration without compromising productivity. Their model demonstrated a 12–18% improvement in the structural coefficient and a 0.4% increase in the humus content over a three-year period.

International experience underscores the need for context-specific, multi-tiered interventions. In Bulgaria, over 24,000 hectares of land have been disturbed by mining, but as of 2017, only 8,253 hectares (about 34%) had undergone successful reclamation (Kirilov & Banov, 2017). Their two-phase model consists of technical reclamation (consisting of terrain leveling, soil layering, and fertilization) and biological reclamation (involving reestablishing vegetation cover and productive land use). However, even reclaimed land often requires ongoing maintenance and adaptive integration into modern agricultural economies.

Organic farming principles offer long-term solutions for agrophysical soil regeneration. Alieksieiev & Vradii (2023) provide a systematic analysis of organic matter restoration strategies and the distribution of humus-rich soils across Ukraine. Their data from 2018–2022 show an alarming 35% increase in the mineral fertilizer dependency and a 20% reduction in the green manure use, highlighting the urgency of transitioning toward more ecologically sound practices. Under organic management, annual increases in soil organic matter of 0.15–0.25% are achievable, enhancing structural integrity, water-air balance, and nutrient availability. Their research emphasizes the need for strong regulatory support, geospatial monitoring, and economic incentives to scale these practices.

In mountainous regions like Serbia's Pešter Plateau, land restoration is further complicated by naturally shallow and infertile soils situated at altitudes near 1,000 meters.

Mytsyk (2024) provides a compelling long-term perspective from Technosol reclamation under perennial grass-legume swards. Over 50 years, the crop yields on reconstituted soils increased by 11.8–21.3%, with the soil organic matter in the 0–20 cm horizon rising from 2.1% to 3.1% in chernozem and three- to seven-fold in other soil types. The bulk density in the upper soil layer declined across all reconstructed soil types, and pore space improved by 4–7%, thereby enhancing root development and water retention.

Dmytruk (2023) takes a novel approach, applying predictive mapping at a 1:10,000 scale across Ukraine to assess soil vulnerability by type. This allows for "precision healing" akin to precision agriculture, enabling soil-type-specific interventions. For example, calcareous clays are effective in radionuclide fixation, while peat soils require an entirely different strategy due to their fragility. Taken together, the body of international and domestic research illustrates that restoring agrophysical soil properties is not just a remedial task but a foundational element of post-conflict ecological renewal. Successful strategies must integrate engineering, ecological, and socioeconomic dimensions, backed by quantitative diagnostics, long-term monitoring, and adaptive policy frameworks. Thus, the resilience of soil becomes symbolic of the resilience of communities and ecosystems themselves.

The restoration of chemical soil properties constitutes a cornerstone of post-disturbance land rehabilitation, especially in regions affected by industrial activities, military conflicts, or intensive agricultural exploitation. This process focuses on rebalancing soil pH, restoring essential macro- and micronutrients, and mitigating chemical contaminants such as heavy metals, xenobiotics, and explosive residues. These disruptions to soil chemistry not only reduce productivity but also pose risks to ecological integrity and public health.

In post-conflict zones such as Ukraine, military operations have introduced significant chemical hazards into soils. Contaminants like lead (Pb), cadmium (Cd), and residues from explosives (e.g., TNT, RDX) have been detected in concentrations exceeding safe agricultural thresholds, with localized lead levels reaching 600 mg/kg (compared with the acceptable limit of 100 mg/kg). These contaminants interfere with nutrient cycling and bioavailability, necessitating targeted chemical restoration strategies. Lime ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) are employed to neutralize soil acidity and replace toxic ions like Al^{3+}, while phosphate amendments and organo-mineral sorbents immobilize heavy metals and restore fertility.

A study by Huang et al. (2016) highlighted that incorporating composted organic matter and green manures increased the cation exchange capacity by 35%, stimulated the microbial detoxification pathways, and improved the soil organic matter content by 22% over two growing seasons. Similarly, in 2023 noted an enhanced plant uptake efficiency and microbial enzyme activity following the application of calcium-magnesium phosphates in contaminated soils. Compelling data from Sub-Saharan Africa further underscores the potential of integrated chemical and biological restoration. In a four-year field study conducted by Ntamwira et al. (2023) in the Democratic Republic of the Congo, three restoration treatments were compared: (T1) slash-and-burn; (T2) burning with NPK input or manure; and (T3) an agroecological package combining leguminous cover crops (*Mucuna pruriens*), perennial grasses, and organic inputs. The T3 plots demonstrated significantly higher aboveground biomass (39.9–60.4 vs. 11.3–21.9 t/ha), and improved the crop yields – bean (848 vs. 327 kg/ha), maize (2,201 vs. 792 kg/ha), and banana (7.4 vs. 5.0 t/ha). The soil analyses revealed a reduced acidity (pH increase of 0.9 units), an elevated base saturation (notably K^+ and Ca^{2+}), and a five-fold rise in the soil carbon stocks (26.5 vs. 5.6 t/ha).

Longitudinal evidence from Iran's Hyrcanian forests affirms that afforestation with chemically beneficial species can accelerate soil chemical recovery. Jourgholami et al. (2019) evaluated the plantations of nitrogen-fixing *Alnus subcordata*, *Acer velutinum*, and *Cupressus sempervirens* over 25 years. *Alnus subcordata* showed the highest recovery efficacy, increasing the nitrogen content to 2.11%, reducing the C/N ratio to 15.56, and improving the soil microbial activity by 46% relative to the deforested controls. Yet, the soil carbon stabilization remained incomplete, reflecting the protracted timescales involved in full chemical restoration.

Conservation agriculture (CA) represents a scalable strategy for enhancing chemical soil health. Globally, 33% of arable lands suffer degradation, resulting in the annual loss of 24 billion tonnes of topsoil. Tillage, residue burning, and poorly managed fertilization contribute to over 40% of this degradation. The expansion of CA practices – characterized by minimal tillage, permanent organic cover, and diversified rotations – has helped recover soil fertility and reduce chemical erosion. In India, adoption of CA systems has increased the soil organic carbon by up to 93%, improved the water productivity by 66%, boosted the crop yields by up to 76.2%, and enhanced the nitrogen use efficiency by up to 40.2% (ICAR: https://old.icar.org).

To guide effective chemical restoration, a deep understanding of soil ecological knowledge (SEK) is vital. Heneghan et al. (2008) emphasized that the severity of degradation, ecosystem resilience, and clarity of end goals all shape restoration trajectories. While chemical amendments can provide rapid remediation, their success is maximized when harmonized with biological and physical interventions. In summary, restoring chemical soil properties should be viewed not as a standalone technical remedy but as a fundamental pathway to resilient agroecosystem regeneration. By combining precision amendments, agroecological design, and long-term monitoring, it is possible to reclaim chemically degraded soils and enhance their functionality for food security, ecological restoration, and climate resilience.

Biological restoration constitutes a critical pillar for the recovery of soil ecosystem functionality, especially in environments severely degraded by war, mining activities, or unsustainable agricultural practices. Soils disturbed by military conflict often demonstrate significant reductions in microbial biomass, suppression of key enzymatic activities, and drastic declines in the diversity and abundance of beneficial soil organisms, such as arbuscular mycorrhizal fungi and nitrogen-fixing bacteria, which are indispensable for nutrient cycling and plant productivity (Novakovska et al., 2025). These biological impairments lead to diminished soil fertility, impaired structure, and vulnerability to erosion and pathogen outbreaks, thereby threatening long-term agricultural sustainability and ecosystem resilience.

To counteract these deleterious effects, modern restoration strategies emphasize biological revitalization through inoculation with carefully selected microbial consortia, application of biostimulants, and establishment of legumes alongside deep-rooted pioneer plants that enrich soil biota and stimulate rhizosphere development. Such interventions accelerate the reestablishment of essential soil processes, including nutrient mineralization, disease suppression, and soil aggregation – processes fundamental for rebuilding healthy, self-sustaining agroecosystems. The living soil matrix, composed of microbial diversity, enzymatic activities, organic matter content, and soil fauna populations, forms the foundation of soil health and productivity.

One of the most effective pathways to enhance biological soil properties is the enrichment of soil organic matter (SOM) through organic amendments such as farmyard manure (FYM), poultry manure (PM), and green manures. These amendments serve as energy and nutrient sources that stimulate microbial activity, foster enzymatic processes, and catalyze nutrient cycling. Microbial decomposers, notably fungi and bacteria, play pivotal roles in breaking down organic substrates, mineralizing key nutrients such as nitrogen (N), phosphorus (P), and potassium (K), and producing phytohormones that promote plant growth. For example, combined applications of FYM and PM have been documented to increase the maize and groundnut yields, enhance the 1,000-grain weight by up to 15%, and improve the chlorophyll content, directly linking biological restoration to crop performance gains (Hussain et al., 2021).

Further advancements in biological restoration are achieved through biofertilizers incorporating nitrogen-fixing and plant growth-promoting microorganisms such as *Rhizobium*, *Azospirillum*, and *Trichoderma* spp. Field trials demonstrate that these biofertilizers can increase crop yields by 15–35% in staple crops like maize and leafy vegetables by enhancing nutrient uptake efficiency and bolstering plant resistance against biotic and abiotic stresses. Notably, integrating organic amendments with moderate inorganic fertilization – particularly phosphorus – optimizes nutrient-use efficiency and stimulates microbial communities. For instance, the maize yields have increased by approximately 20% when half doses of NPK fertilizers were combined with FYM, while the rice yields improved by 25% under integrated fertilization regimes, highlighting the synergistic effects of combined organic-inorganic management (Mrunalini et al., 2022). Emerging nature-based solutions offer additional promise in biological soil restoration. Biochar application, for example, enhances soil moisture retention by 8–10%, improves nutrient holding capacity, and plays a significant role in climate change mitigation through carbon sequestration, with a global potential estimated at 1.8 petagrams (Pg) of CO_2-C equivalent annually. Beyond its role as a nutrient source, biochar improves soil physical properties and microbial habitat quality. Similarly, the use of biogas slurry – the nutrient-rich effluent from anaerobic digesters – enriches soil fertility by supplying macro- and micronutrients, thereby facilitating circular nutrient management within integrated farming systems that reduce reliance on external synthetic inputs (Mrunalini et al., 2022).

In landscapes severely altered by mining activities, soil biological restoration becomes especially challenging due to profound physical, chemical, and biological disturbances. The removal and stockpiling of topsoil during mineral extraction disrupts microbial communities, reduces organic carbon stocks, and induces extreme nutrient transformations, often leading to substantial nitrogen losses through volatilization and leaching. Studies report that microbial populations in stockpiled soils can decline by over 50% within the top 50 cm after two years of storage, with mycorrhizal fungal propagule viability dropping to as low as 10% compared with undisturbed soil, contingent on moisture and management conditions (Brusseau et al., 2019). Successful reclamation hinges on effective topsoil management to minimize nutrient depletion and support microbial recovery.

Revegetation using nitrogen-fixing legumes, grasses, herbs, and metal-tolerant plant species is the most widely implemented strategy to reduce erosion and restore soil biological function on mined lands. These plants facilitate organic matter input, stabilize soil structure, and foster recolonization by beneficial microbes, including mycorrhizal fungi critical for nutrient uptake in degraded soils (Sheoran et al., 2010). The success of such reclamation efforts is increasingly evaluated through comprehensive assessments of soil microbial community composition, enzymatic activity, and mycorrhizal symbiotic functionality, which serve as reliable bioindicators of soil health and productivity recovery.

The restoration of heavily degraded soils is a multifaceted challenge that requires an integrative understanding of ecological succession, species-specific adaptations, and genetic variability within populations, especially regarding metal tolerance and nutrient acquisition traits. These considerations underscore the necessity of community and ecosystem-level approaches that encompass plant–microbe interactions and evolutionary processes to achieve sustainable restoration outcomes (Bradshaw et al., 1992). This ecological framework aligns with the evolving concept of soil quality, which emphasizes the soil's dynamic capacity to sustain biological productivity, maintain environmental quality, and deliver essential ecosystem services.

Recent advances in soil microbiome research reveal that microorganisms not only contribute to nutrient cycling and organic matter turnover but also actively modulate soil physical and chemical properties through complex biochemical and biophysical feedbacks. These microbially mediated modifications influence microbiome assembly and soil ecosystem resilience at local and landscape scales. Harnessing these processes offers innovative avenues for managing and manipulating soil microbiomes to counteract soil degradation, enhance agricultural productivity, and mitigate the impacts of global environmental change (Hartmann et al., 2024).

Importantly, restoration actions should be based on precise soil diagnostics, including physical measurements (e.g., bulk density, water holding capacity), chemical profiling (e.g., nutrient content, heavy metal levels), and biological indicators (e.g., microbial respiration, enzymatic activity). Integrated soil quality indices can guide site-specific restoration planning and monitor progress over time (Doni et al., 2018).

Ultimately, restoring soil physical integrity, chemical fertility, and biological vitality is a prerequisite for productive, resilient agroecosystems in post-conflict regions. A synergistic application of organic amendments, agrotechnical interventions, and bioremediation strategies ensures a holistic recovery of soil functionality and contributes to long-term food security and ecological stability.

Bioecological aspects and agroecosystem stabilization. The stabilization of agroecosystems in post-disturbance landscapes, particularly those affected by military activities, necessitates a comprehensive understanding of the bioecological dynamics that govern soil-plant-microbe interactions. Agroecosystem resilience is intrinsically linked to the restoration of trophic structures, microbial diversity, and biogeochemical cycling. Following physical and chemical degradation, the recovery of soil biota is not solely a function of time but depends heavily on the deliberate reintroduction and fostering of functional groups, such as nitrogen-fixing bacteria, arbuscular mycorrhizal fungi, and detritivores, which are responsible for nutrient transformation and organic matter stabilization (van der Heijden &Wagg, 2013). These biological agents enhance soil fertility and resilience by promoting aggregation, buffering toxic elements, and facilitating symbiotic relationships essential for plant productivity.

A key ecological principle guiding the restoration of militarily degraded agroecosystems is the reinforcement of biodiversity at multiple levels – from genetic to landscape scale. Biodiversity provides a critical buffer against external stressors and enables functional redundancy, where multiple species can perform similar ecological roles, thereby sustaining essential services under fluctuating environmental conditions (Londe, 2012). The reestablishment of plant functional diversity through polycultures, cover cropping, and intercropping systems contributes to more stable productivity, improved pest and weed suppression, and better soil structure recovery. Plant species with traits favoring deep rooting, high litter quality, or rhizosphere microbial recruitment are particularly valuable in rebuilding ecosystem function and carbon cycling capacity.

Soil food web reconstruction is another cornerstone of agroecosystem stabilization. Post-disturbance soils often exhibit a collapse in mesofaunal and microfaunal populations, resulting in disrupted decomposition pathways and inefficient nutrient recycling. By restoring soil fauna diversity – particularly earthworms, collembolans, and nematodes – ecological succession processes can be accelerated, and energy flow within the soil can be revitalized (Bauke et al., 2022). This contributes directly to soil aeration, porosity, and aggregate formation, which in tum improve root penetration and water retention. Importantly, many soil organisms also play key roles in phytopathogen control and can outcompete or antagonize harmful microbial populations, thereby enhancing overall plant health without chemical inputs.

From a systems perspective, the stabilization of agroecosystems also depends on reestablishing self-regulatory mechanisms such as natural biological control, nutrient self-sufficiency, and successional dynamics. Agroecological models promote such transitions by emphasizing low-input, ecologically intensive strategies that prioritize synergy between biological processes and management goals. Integrative land management practices, including reduced tillage, organic amendments, biological inoculants, and spatial diversification, foster agroecosystem services that can be sustained over time without external inputs (Koskey et al., 2021). These practices also mitigate greenhouse gas emissions and promote carbon sequestrateon, further aligning restoration goals with climate adaptation strategies.

Furthermore, ecological memory – the capacity of an ecosystem to recover based on its pre-disturbance legacy – plays a vital role in guiding restoration trajectories. The presence of remnant native vegetation, seed banks, or microbial communities can serve as critical reservoirs for recolonization and functional recovery. Strategic conservation of such legacy components, alongside active rehabilitation, enhances the success and speed of agroecosystem stabilization efforts (Schaefer et al., 2011). This concept reinforces the need for site-specific ecological assessment and the design of restoration plans that build upon inherent ecological potential rather than attempting full artificial reconstruction.

Finally, the success of agroecosystem restoration is not determined solely by ecological indicators but must also account for socioecological feedbacks, including land-use policies, farmer practices, and community engagement. Long-term stabilization requires participatory monitoring, adaptive co-management, and capacity building to ensure that restored agroecosystems are maintained and adapted under changing climatic and sociopolitical contexts. In the face of continued global environmental stressors, embedding bioecological principles into restoration frameworks provides a robust pathway toward sustainable land stewardship and agricultural resilience.

Integrated technologies and sustainable management models

Integrated bioremediation and reclamation systems. Integrated bioremediation and reclamation systems represent a promising frontier in the restoration of militarily degraded agricultural lands. Unlike isolated interventions, such as microbial inoculation or phytoremediation alone, integrated systems combine multiple biological, chemical, and physical strategies in a harmonized manner tailored to specific site conditions. These systems address the complexity of contaminants found in military-affected zones – ranging heavy metals and petroleum hydrocarbons to unexploded ordnance and synthetic chemicals – by leveraging synergistic interactions among biotic and abiotic components. Research has demonstrated that combining microbial bioremediation with soil amendments such as biochar or compost can enhance pollutant degradation and improve soil fertility in parallel (Biliavska et al., 2024). Such approaches are increasingly seen as both environmentally sound and economically viable for large-scale reclamation efforts in post-conflict zones.

In practice, integrated systems are highly adaptive and context-specific. For example, in the Ukrainian territories affected by military activity, combinations of local mycorrhizal fungi, rhizobacteria, and phytoextractor plants such as *Brassica juncea* or *Helianthus annuus* have been trialed with considerable success (Zaimenko et al., 2025). When complemented with agricultural engineering techniques, such as subsoil ripping or drainage adjustments, these systems not only remove contaminants but also restore soil structure and water balance. Such integration is particularly critical in zones affected by compaction, cratering, and heavy metal deposition. Studies from Serbia and Bosnia similarly show the efficacy of mixed systems in rehabilitating former military training sites, where monoculture remediation methods had limited success (Vasić et al., 2024). The key to scalability lies in balancing remediation efficiency with ecological resilience, ensuring that post-treatment land remains viable for long-term agricultural use.

Biotechnological innovations further enhance the efficacy of integrated systems. The deployment of microbial consortia – tailored communities of bacteria and fungi – has shown superior performance over single-strain applications in breaking down complex organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs) and trinitrotoluene (TNT) residues (Maksimova et al., 2011). When such consortia are introduced alongside green manure crops and soil conditioners, the system not only accelerates decontamination but also fosters microbial recolonization and nutrient cycling. In recent years, there has been increased interest in formulating biopreparations that combine biosurfactants, organic acids, and immobilized cells to act simultaneously as detoxifying and soil-enhancing agents. These bio-formulations are particularly effective in sandy or low-organic-matter soils where nutrient limitations might otherwise hinder microbial activity.

A critical aspect of integrated systems is the incorporation of continuous soil monitoring and feedback loops. Digital tools and sensor-based soil diagnostics now allow practitioners to track contaminant levels, biological activity, and physicochemical parameters in real time, optimizing the timing and composition of remediation interventions. This dynamic approach reduces the risk of secondary pollution or nutrient imbalance often associated with overapplication of amendments. Moreover, participatory models involving local stakeholders and land managers ensure that remediation strategies align with socioeconomic and cultural realities of post-conflict farming communities. The coupling of traditional ecological knowledge with modern remediation science thus becomes a cornerstone of sustainable recovery (Nadporozhskaya et al., 2022).

Economically, integrated systems offer significant cost-benefit advantages over conventional mechanical decontamination or soil excavation. While upfront investments may be higher, the long-term gains in terms of restored land value, crop productivity, and ecosystem services often outweigh the initial expenditure. Moreover, by using on-site materials, such as composted plant residues or native microbial strains, the costs related to transportation and procurement of external agents are minimized. In Ukraine, several pilot projects under EU and FAO support have demonstrated that integrated bioremediation-reclamation systems can return 60–70% of degraded lands to productive status within 2–3 growing seasons (Murugan et al., 2022). These results underscore the potential of such models as part of national recovery strategies in conflict-affected regions.

Finally, the integration of remediation and reclamation systems into broader agroecological frameworks ensures long-term sustainability. Rather than merely detoxifying soil, the goal is to build resilient agrolandscapes capable of withstanding future disturbances – whether from climate change or renewed anthropogenic pressures. Agroforestry, crop rotation, and the reintroduction of soil macrofauna (e.g., earthworms) can complement initial remediation efforts, gradually restoring ecosystem functions and biodiversity. As global conflict zones expand, and with them the scale of soil degradation, the development of scalable, adaptable, and ecologically grounded bioremediation-reclamation systems will become an essential component of global food and environmental security (Azhar et al., 2024).

Integration of biological, agronomic, and engineering solutions. The integration of biological, agronomic, and engineering approaches in the remediation and reclamation of militarily degraded agricultural lands is increasingly recognized as a necessity rather than an option. This multidimensional strategy addresses the complexity of contamination, which often involves overlapping physical, chemical, and biological degradation processes. A coordinated application of these methods enhances the efficiency of soil recovery while promoting environmental sustainability and long-term agricultural productivity. For instance, the synergistic effect of microbial consortia with soil conditioners and hydrological engineering structures has been shown to restore both fertility and ecological stability in areas contaminated by explosives and heavy metals, as evidenced by case studies in post-conflict zones such as Iraq and Ukraine (Novakovska et al., 2025).

Biological solutions, particularly microbial bioremediation and phytotechnology, provide the foundation for natural detoxification of polluted soils. When combined with agronomic techniques such as crop rotation, conservation tillage, and the use of cover crops, they promote nutrient cycling, organic matter restoration, and suppression of residual toxic agents. Moreover, engineering interventions – including soil amendment incorporation technologies, subsurface drainage systems, and terrain recontouring – complement biological and agronomic efforts by improving physical soil structure and controlling the hydrodynamics of pollutant movement. A meta-analysis by Mani & Kumar (2020) confirmed that the co-application of compost-based biostimulants with precision-controlled irrigation increased microbial activity and decreased contaminant mobility by over 40% in degraded loamy soils.

Field trials in Donetsk Oblast of Ukraine have demonstrated the potential of combining deep ripping, microbial bioproducts, and metal-immobilizing biochar amendments for restoring war-impacted chernozem soils. These integrated practices resulted in a 30–50% increase in the available phosphorus, a significant reduction in the soil compaction, and a partial reestablishment of the arbuscular mycorrhizal colonization in plant roots, indicating biological recovery of the rhizosphere (Mytsyk et al., 2023; Mytsyk et al., 2024). Furthermore, the use of leguminous cover crops in conjunction with microbial inoculants has been shown to accelerate the decline of persistent pollutants such as TNT and RDX in moderately contaminated sites, as observed in the Balkan and Middle Eastern post-conflict areas (Wirtu & Abdela, 2025).

An important aspect of integrated remediation lies in the development of site-specific protocols based on soil diagnostics, pollutant typology, and landscape configuration. Geographic Information System (GIS)-assisted modeling and remote sensing tools are increasingly used to guide the design and monitoring of interventions, allowing adaptive management over time. For example, Alhasan et al. (2023) reported a 25% improvement in the remediation efficiency when spatial variability of contamination was accounted for using drone-based soil surveys in northern Syria. Similarly, digital decision-support systems incorporating agronomic and environmental parameters have been developed to prioritize treatment zones, select optimal crops for phytoremediation, and schedule amendment applications.

The long-term success of integrated systems also depends on their economic viability and compatibility with local farming systems. Studies from the Sahel region and eastern Europe indicate that stakeholder participation, access to inputs (e.g., composts, microbial inoculants), and policy incentives are critical for sustained implementation. In Ukraine, the post-2022 invasion recovery efforts have underscored the need for coordinated actions between agronomists, soil scientists, engineers, and local authorities to ensure scalable and context-sensitive solutions. Thus, integrated biological–agronomic–engineering frameworks represent the most promising direction for restoring the productive capacity and ecological function of war-impacted agricultural landscapes. Efficient nutrient management and precision fertilization are essential not only for improving productivity but also for accelerating the recovery of militarily damaged agricultural soils. In post-conflict regions where conventional soil testing infrastructure may be lacking or destroyed, engineering-driven solutions can provide critical support for restoration planning. One innovative example is the AgroLens project, which has developed Machine Learning (ML)-based methodologies to predict soil nutrient status without reliance on laboratory analyses. By utilizing state-of-the-art techniques, this approach offers actionable insights for optimizing nutrient inputs, particularly in resource-constrained or infrastructure-compromised environments. The AgroLens model begins with the integration of the LUCAS Soil dataset and Sentinel-2 satellite imagery to estimate key soil properties, including phosphorus, potassium, nitrogen, and pH. These core predictions are refined through the incorporation of contextual variables such as weather data, crop yields, and AI-generated embeddings based on soil texture (e.g., clay content). The methodological framework involves advanced ML algorithms, including Random Forests, Extreme Gradient Boosting (XGBoost), and Fully Connected Neural Networks (FCNN), which were fine-tuned for high-accuracy predictions. The results have demonstrated a strong model performance, with low root mean square error values, confirming its reliability for real-world applications. In the context of militarily affected landscapes, where soil degradation is often heterogeneous and extensive, such scalable and reproducible digital pipelines can be crucial for guiding precision rehabilitation strategies. By enabling site-specific nutrient assessment, ML-based tools such as AgroLens support more efficient allocation of inputs, reduce overfertilization risks, and contribute to ecologically balanced soil recovery across damaged agroecosystems.

Finally, such integration contributes to broader goals of climate resilience and agroecological sustainability. Restored soils with enhanced structure, microbial diversity, and nutrient cycling are more capable of withstanding droughts, floods, and subsequent disturbances. Therefore, multi-pronged interventions not only remediate military damage but also build systemic resilience into agroecosystems. Future research should aim to refine these approaches through long-term field validation, techno-economic assessments, and participatory design processes that involve local communities and land users in cocreating regenerative solutions.

Practical cases and implementation prospects in Ukraine. The prolonged military conflict in Ukraine has resulted in severe degradation of approximately 1.5 million hectares of agricultural land across key regions including Chernihiv, Kharkiv, Mykolaiv, and Donetsk. This degradation is characterized by physical soil disruption, pollution with explosive residues (e.g., RDX, TNT), and elevated concentrations of heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and zinc (Zn), with concentrations frequently exceeding national and international safety thresholds by two- to fivefold (Datsko et al., 2025). Addressing this extensive pollution necessitates the application of integrated, site-specific bioremediation and reclamation technologies adapted to local pedoclimatic conditions and agricultural practices. Pilot-scale interventions in the heavily impacted zones near Bucha and Irpin exemplify such approaches, where consortia of microbial strains – *Bacillus subtilis*, *Pseudomonas putida*, and *Trichoderma harzianum* – were applied synergistically with biochar and matured organic compost amendments. These treatments achieved reductions in bioavailable heavy metal concentrations by 45–70% within two growing seasons, concomitant with a 35% increase in the soil enzymatic activities and a 30% yield enhancement in winter wheat. Parallel phytoremediation trials in the Chernihiv and Kharkiv oblasts utilized hyperaccumulator species including *Brassica juncea*, *Helianthus annuus*, and *Festuca arundinacea*, which effectively bioaccumulated up to 60% of soil contaminants over a two-year cultivation period, demonstrating the potential of multi-species plantings for immobilization and extraction of toxic metals under field conditions (Zaimenko et al., 2025). In the arid and semiarid southern regions, notably in Zaporizhzhia Oblast, integrated agroecological measures combining deep-rooted perennial grasses with drip irrigation and organic mulching have led to a substantial reduction in the soil erosion (~45%), increased the soil organic carbon stocks by 20%, and enhanced the microbial community activity, thereby aligning with Ukraine's evolving regenerative agriculture frameworks (Ministry of Agrarian Policy of Ukraine, 2023). Additionally, innovative multifunctional land use models in former military zones of Donetsk Oblast integrate solar photovoltaic energy installations, restoration of native grasslands, and rotational sheep grazing, which have collectively reclaimed over 1,500 hectares of the degraded land, provided employment for more than 200 local residents, and stimulated the local agricultural value chains, supported by EU-funded programs (EU4Environment: www.eu4environment.org). Nevertheless, scaling these integrated bioremediation and reclamation strategies at a national level faces significant impediments including limited farmer access to soil diagnostics and certified remediation agents, the absence of standardized operational protocols, and insufficient institutional coordination among environmental, agricultural, and defense sectors. To overcome these constraints, Ukraine has initiated a comprehensive National Soil Recovery Program emphasizing capacity building among agronomists, land managers, and local authorities, deployment of mobile soil testing laboratories, and implementation of advanced GIS-based contamination mapping and monitoring platforms (FAO, 2025. Ukraine: Strategic priorities for 2025). These efforts are complemented by demonstration projects at academic and research institutions that foster technology transfer and stakeholder engagement. The integration of digital tools, such as remote sensing and mobile soil analysis applications, further accelerates data-driven decision-making and adaptive management. The Ukraine's experience in deploying integrated remediation frameworks under complex post-conflict conditions provides a critical empirical foundation and strategic blueprint for global regions facing similar challenges of military-induced soil degradation, especially amid converging pressures of climate change and geopolitical instability. The lessons drawn underscore the imperative of science-based, socially inclusive, and ecologically sustainable land recovery strategies to safeguard food security and ecosystem resilience worldwide.

Conclusions

Military operations have caused multifaceted degradation of agricultural lands in Ukraine, encompassing physical, chemical, and biological disturbances of the soil systems. The consequences include structural disruption, pollution with heavy metals, petroleum hydrocarbons, and explosives, as well as the depletion of microbial biodiversity. These factors critically undermine the productive capacity of the soils and pose long-term environmental hazards. A systematic assessment of damage types and contamination levels is essential prior to implementing any remediation or reclamation measures.

Integrated approaches that combine agrotechnical, biological, and engineering solutions are the most promising for the restoration of war-affected agroecosystems. The application of phytoremediation, microbial consortia, crop rotation, organic amendments, gypsum treatment, deep loosening, and amelioration techniques contributes not only to the physical rehabilitation of soils but also to the reestablishment of ecological functions. Selecting plant species with phytosanitary properties and adapting technological interventions to the specific conditions of the Ukrainian Steppe is particularly important.

Successful international case studies, such as post-conflict bioremediation in Vietnam, Serbia, and Iraq, demonstrate the effectiveness of combining locally adapted biological strategies with engineered infrastructure and sound land management. Ukraine can draw from these experiences while tailoring solutions to its unique edaphoclimatic context – particularly the high humus content of its Chernozems – supported by scientific guidance, long-term monitoring, and interdisciplinary collaboration.

The issue of military-induced agricultural soil pollution extends beyond the agronomic domain and represents a nationwide ecological, economic, and social challenge. Without comprehensive strategies for remediation, reclamation, and sustainable land reuse, degraded areas may become chronic sources of secondary contamination and food insecurity. The implementation of adaptive land-use models, green technologies, and ecologically informed spatial planning should be integrated into Ukraine's post-war recovery strategy.

Future research should focus on the molecular and biological mechanisms by which microorganisms and accumulator plants detoxify pollutants, the development of next-generation bioproducts, geospatial mapping of war-damaged lands, and the creation of legal and financial instruments to support bioremediation efforts. Prioritizing critical areas for reclamation and monitoring them through GIS technologies will ensure the effective, transparent, and scalable implementation of integrated land restoration solutions.

References

Afrasinei, G. M., Melis, M. T., Buttau, C., Arras, C., Pistis, M., Zerrim, A., & Ghiglieri, G. (2017). Classification methods for detecting and evaluating changes in desertification-related features in arid and semiarid environments. Euro-Mediterranean Journal for Environmental Integration, 2, 14.

Ahmad, J., Al-Farraj, A. S., Ahmad, M., Al-Swadi, H. A., & Al-Wabel, M. I. (2024). Functionalized organo-mineral composites of biochar for the effectual immobilization of arsenic in contaminated soil. Journal of Soils and Sediments, 24(4), 1556–1575.

Ahmed, S., Kumari, K., & Singh, D. (2024). Different strategies and bioremoval mechanisms of petroleum hydrocarbons from contaminated sites. Arab Gulf Journal of Scientific Research, 42(2), 342–358.

Alhasan, M., Lakmes, A., Alobaidy, M. G., AlHaeek, S., Assaf, M., Dawson, L., & Bridge, J. (2023). A baseline survey of potentially toxic elements in the soil of north-west Syria following a decade of conflict. Environmental Science: Advances, 2(6), 886–897.

Ali, H., Khan, E., & Sajad, M. A. (2013). Phytoremediation of heavy metals – concepts and applications. Chemosphere, 91(7), 869–881.

Alieksieiev, O. O., & Vradii, O. I. (2023). Organic agriculture as an element of soil preservation and restoration. Sil's'ke Hospodarstvo ta Lisivnyctvo, 30, 228–239.

Álvarez, L. M., Ruberto, L. A. M., Balbo, A. L., & Mac Cormack, W. P. (2017). Bioremediation of hydrocarbon-contaminated soils in cold regions: Development of a pre-optimized biostimulation biopile-scale field assay in Antarctica. Science of the Total Environment, 590, 194–203.

Alves, A. R., Yin, Q., Oliveira, R. S., Silva, E. F., & Novo, L. A. (2022). Plant growth-promoting bacteria in phytoremediation of metal-polluted soils: Current knowledge and future directions. Science of the Total Environment, 838, 156435.

Andreolli, M., Lampis, S., Brignoli, P., & Vallini, G. (2015). Bioaugmentation and biostimulation as strategies for the bioremediation of a burned woodland soil contaminated by toxic hydrocarbons: A comparative study. Journal of Environmental Management, 153, 121–131.

Appau, S., Churchill, S. A., Smyth, R., & Trinh, T. A. (2021). The long-term impact of the Vietnam War on agricultural productivity. World Development, 146, 105613.

Are, K. S., Adelana, A. O., Fademi, I. O., & Aina, O. A. (2017). Improving physical properties of degraded soil: Potential of poultry manure and biochar. Agriculture and Natural Resources, 51(6), 454–462.

Azhar, M. F., Ali, E., & Aziz, A. (2024). Regenerative agroforestry for soil restoration, biodiversity protection, and climate change mitigation. In: Kumar, S., Meena, R. S., Sheoran, P., & Jhariya, M. K. (Eds.). Regenerative agriculture for sustainable food systems. Springer, Singapore. Pp. 423–451.

Banout, J., Urban, O., Musil, V., Szakova, J., & Balik, J. (2014). Agent Orange footprint still visible in rural areas of Central Vietnam. Journal of Environmental and Public Health, 2014(1), 528965.

Bauke, S. L., Amelung, W., Bol, R., Brandt, L., Brüggemann, N., Kandeler, E., & Vereecken, H. (2022). Soil water status shapes nutrient cycling in agroecosystems from micrometer to landscape scales. Journal of Plant Nutrition and Soil Science, 185(6), 773–792.

Bekele, G. K., Gebrie, S. A., Mekonen, E., Fida, T. T., Woldesemayat, A. A., Abda, E. M., & Assefa, F. (2022). Isolation and characterization of diesel-degrading bacteria from hydrocarbon-contaminated sites, flower farms, and soda lakes. International Journal of Microbiology, 2022, 5655767.

Bhaduri, D., Sihi, D., Bhowmik, A., Verma, B. C., Munda, S., & Dari, B. (2022). A review on effective soil health bioindicators for ecosystem restoration and sustainability. Frontiers in Microbiology, 13, 938481.

Biliavska, L., Iutynska, G., Loboda, M., Ropotilov, B., & Skrotskyi, S. (2024). Diagnostics and bioremediation of soils affected by military operations in Ukraine. Biological Systems: Theory and Innovation, 15(3), 67–78.

Blum, W. E. H., Zechmeister-Boltenstern, S., & Keiblinger, K. M. (2019). Does soil contribute to the regulation of the climate? Soil Use and Management, 35(3), 243–251.

Bonchkovskyi, O., Ostapenko, P., Bonchkovskyi, A., & Shvaiko, V. (2025). War-induced soil disturbances in north-eastern Ukraine (Kharkiv region): Physical disturbances, soil contamination and land use change. Science of the Total Environment, 964, 178594.

Bradshaw, A. D. (1992). The biology of land restoration. In: Jain, S. K., Botsford, L. W. (Eds.). Applied population biology. Monographiae Biologicae. Springer, Dordrecht. Vol. 67. Pp. 25–44.

Brar, S. K., Verma, M., Tyagi, R. D., & Surampalli, R. Y. (2010). Engineered nanoparticles in wastewater and wastewater sludge – evidence and impact. Waste Management, 30(3), 504–520.

Breus, D., Yevtushenko, O., Skok, S., & Rutta, O. (2019). Retrospective studies of soil fertility change on the example of the Kherson region (Ukraine). International Multidisciplinary Scientific GeoConference: SGEM, 19(5.1), 645–652.

Broomandi, P., Guney, M., Kim, J. R., & Karaca, F. (2020). Soil contamination in areas impacted by military activities: a critical review. Sustainability, 12(21), 9002.

Brusseau, M. L., Glenn, E. P., & Pepper, I. L. (2019). Reclamation and restoration of disturbed systems. In: Brusseau, M. L., Pepper, I. L., & Gerba, C. P. (Eds.). Environmental and pollution science. Academic Press. Pp. 355–376.

Bulba, I., Drobitko, A., Zadorozhnii, Y., & Pismennyi, O. (2024). Identification and monitoring of agricultural land contaminated by military operations. Scientific Horizons, 27(7), 107–117.

Bumpus, J. A. (1989). Biodegradation of polycyclic hydrocarbons by *Phanerochaete chrysosporium*. Applied and Environmental Microbiology, 55(1), 154–158.

Buriak, Y. O., & Zabaluyev, V. O. (2020). Zmina rodiuchosti tekhnozemiv za tryvaloho sil's'kohospodars'koho vykorystannia rekul'tyvovanoho zalizorudnoho shlamoskhovyshcha v umovakh Stepu Ukrainy [Change in the fertility of Technozems during long-term agricultural use of a reclaimed iron ore slag storage in the conditions of the Ukrainian Steppe]. Plant and Soil Science, 11(3), 88–96 (in Ukrainian).

Calvo, P., Nelson, L., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. Plant and Soil, 383(1), 3–41.

Cao, X., Cui, X., Xie, M., Zhao, R., Xu, L., Ni, S., & Cui, Z. (2022). Amendments and bioaugmentation enhanced phytoremediation and micro-ecology for PAHs and heavy metals co-contaminated soils. Journal of Hazardous Materials, 426, 128096.

Chaudhary, D. K., Bajagain, R., Jeong, S. W., & Kim, J. (2021). Effect of consortium bioaugmentation and biostimulation on remediation efficiency and bacterial diversity of diesel-contaminated aged soil. World Journal of Microbiology and Biotechnology, 37(3), 46.

Chihwai, P., Mhlanga, D., & Ndhlovu, E. (2024). Effect of the Russia-Ukraine war on food and hunger sustainable development goals in Africa. In: Mhlanga, D., & Ndhlovu, E. (Eds.). The Russia-Ukraine conflict and development in Africa. Contributions to political science. Springer, Cham. Pp. 143–161.

Cui, J. Q., He, Q. S., Liu, M. H., Chen, H., Sun, M. B., & Wen, J. P. (2020). Comparative study on different remediation strategies applied in petroleum-contaminated soils. International Journal of Environmental Research and Public Health, 17(5), 1606.

Dat, N. D., Minh, N. H., & Nguyen, K. A. (2019). Characteristics of PCDD/Fs in soil and sediment samples collected from A-So former airbase in Central Vietnam. Science of the Total Environment, 661, 27–34.

Datsko, O., Melnyk, O., Kovalenko, I., Butenko, A., Zakharchenko, E., Ilchenko, V., & Solokha, M. (2025). Estimation of the content of trace metals in Ukrainian military-affected soils. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 53(1), 14328–14328.

Delgado, A., & Gómez, J. A. (2024). The soil: Physical, chemical, and biological properties. In: Villalobos, F. J., & Fereres, E. (Eds.). Principles of agronomy for sustainable agriculture. Springer, Cham. Pp. 15–30.

Demydenko, O., & Velichko, V. (2016). Self-regulation and management of fertility restoration of typical chernozem in agroecosystems. Agricultural Science and Practice, 3(2), 63–78.

Demydov, O. A. (2012). Rekultyvatsiya zemel': Ahroekolohichnyi napriam doslidzhen [Land reclamation: An agroecological research direction]. Bulletin of the DSAEU, 1, 11–16 (in Ukrainian).

Demydov, O. A., Kobets, A. S., Hrytsan, Y. I., & Zhukov, O. V. (2013). Prostorova ahroekolohiya ta rekultyvatsiya zemel' [Spatial agroecology and land reclamation]. Svidler A. L., Dnipropetrovsk (in Ukrainian).

Dmytruk, Y., Cherlinka, V., Cherlinka, L., & Dent, D. (2023). Soils in war and peace. International Journal of Environmental Studies, 80(2), 380–393.

Dmytrukha, N. M., Kozlov, K. P., & Herasimova, O. V. (2024). Soil contamination with heavy metals: A hygienic concern. Ukrainian Journal of Occupational Health, 20(1), 66–75.

Doni, S., Macci, C., Longo, V., Souid, A., Garcia, C., & Masciandaro, G. (2017). Innovative system for biochemical monitoring of degraded soils restoration. Catena, 152, 173–181.

Finney, D. M., Buyer, J. S., & Kaye, J. P. (2016). Living cover crops have immediate impacts on soil microbial community structure and function. Journal of Soil and Water Conservation, 72(4), 361–373.

Gębka, K., Bełdowski, J., & Bełdowska, M. (2016). The impact of military activities on the concentration of mercury in soils of military training grounds and marine sediments. Environmental Science and Pollution Research, 23, 23103–23113.

Geris, R., Malta, M., Soares, L. A., de Souza Neta, L. C., Pereira, N. S., Soares, M., & Pereira, M. D. G. (2024). A review about the mycoremediation of soil impacted by war-like activities: Challenges and gaps. Journal of Fungi, 10(2), 94.

González-Valoys, A. C., Chong, T., Arrocha, J., Lloyd, J., Olmos, J., Vergara, F., Denvers, M., Jaén, J., Jiménez-Oyola, S., & García-Navarro, F. J. (2025). Geochemical characterization of soil and water in an agricultural area for the sustainable use of natural resources. Agriculture, 15(7), 702.

Hanif, M. N., Aijaz, N., Azam, K., Akhtar, M., Laftah, W. A., Babur, M., & Benitez, I. B. (2024). Impact of microplastics on soil (physical and chemical) properties, soil biological properties/soil biota, and response of plants to it: A review. International Journal of Environmental Science and Technology, 21(16), 10277–10318.

Hannam, I. (2022). Soil governance and land degradation neutrality. Soil Security, 6, 100030.

Hartmann, M., & Six, J. (2023). Soil structure and microbiome functions in agroecosystems. Nature Reviews Earth and Environment, 4(1), 4–18.

Heneghan, L., Miller, S. P., Baer, S., Callaham Jr., M. A., Montgomery, J., Pavao-Zuckerman, M., & Richardson, S. (2008). Integrating soil ecological knowledge into restoration management. Restoration Ecology, 16(4), 608–617.

Huang, M., Zhu, Y., Li, Z., Huang, B., Luo, N., Liu, C., & Zeng, G. (2016). Compost as a soil amendment to remediate heavy metal-contaminated agricultural soil: Mechanisms, efficacy, problems, and strategies. Water, Air, and Soil Pollution, 227(10), 359.

Hussain, I., Ali, I., Ullah, S., Iqbal, A., Tawaha, A. A., Al-Tawaha, A. R., & Sirajuddin, S. N. (2021). Agricultural soil reclamation and restoration of soil organic matter and nutrients via application of organic, inorganic and bio fertilization (Mini review). IOP Conference Series: Earth and Environmental Science, 788(1), 012165.

Jarosławiecka, A. K., & Piotrowska-Seget, Z. (2022). The effect of heavy metals on microbial communities in industrial soil in the area of Piekary Śląskie and Bukowno (Poland). Microbiology Research, 13(3), 626–642.

Jourgholami, M., Ghassemi, T., & Labelle, E. R. (2019). Soil physio-chemical and biological indicators to evaluate the restoration of compacted soil following reforestation. Ecological Indicators, 101, 102–110.

Khan, S., Cao, Q., Zheng, Y. M., Huang, Y. Z., & Zhu, Y. G. (2009). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. Environmental Pollution, 152(3), 686–692.

Kharytonov, M. M., Babenko, M. H., Martynova, N. V., Rula, I. V., Honchar, N. V., Havriushenko, O. O., Klimkina, I. I., Zolotovska, O. V., & Frolova, L. A. (2020). Kompleksna ekolohichna otsinka stvorennia enerhetychnykh plantatsiy na rekul'tyvovanykh zemliakh [Comprehensive environmental assessment of the creation of energy plantations on reclaimed lands]. Lira, Dnipro (in Ukrainian).

Kharytonov, M., Martynova, N., Babenko, M., Rula, I., Ungureanu, N., & Ștefan, V. (2023). Production of sweet sorghum bio-feedstock on technosol using municipal sewage sludge treated with flocculant, in Ukraine. Agriculture, 13(6), 1129.

Khatoon, Z., Orozco-Mosqueda, M. D. C., & Santoyo, G. (2024). Microbial contributions to heavy metal phytoremediation in agricultural soils: A review. Microorganisms, 12(10), 1945.

Kim, H. Y., & Song, H. G. (2000). Transformation of 2,4,6-trinitrotoluene by white rot fungus *Irpex lacteus*. Biotechnology Letters, 22, 969–975.

Kirilov, I., & Banov, M. (2017). Reclamation of lands disturbed by mining activities in Bulgaria. Agricultural Science and Technology, 8(4), 339–345.

Koskey, G., Mburu, S. W., Awino, R., Njeru, E. M., & Maingi, J. M. (2021). Potential use of beneficial microorganisms for soil amelioration, phytopathogen biocontrol, and sustainable crop production in smallholder agroecosystems. Frontiers in Sustainable Food Systems, 5, 606308.

Kozielec, A., Piecuch, J., Daniek, K., & Luty, L. (2024). Challenges to food security in the Middle East and North Africa in the context of the Russia–Ukraine conflict. Agriculture, 14(1), 155.

Kumawat, A., Yadav, D., Srivastava, P., Babu, S., Kumar, D., Singh, D., ... & Madhu, M. (2023). Restoration of agroecosystems with conservation agriculture for food security to achieve sustainable development goals. Land Degradation and Development, 34(11), 3079–3097.

Lawrence, M. J., Stemberger, H. L., Zolderdo, A. J., Struthers, D. P., & Cooke, S. J. (2015). The effects of modern war and military activities on biodiversity and the environment. Environmental Reviews, 23(4), 443–460.

Lehmann, J., & Joseph, S. (Eds.). (2015). Biochar for environmental management: Science, technology and implementation. Routledge.

Li, C., Nie, H., Zhang, S., Jia, Z., Ma, S., Li, T., & Mueller, C. (2023). Mineral-solubilizing microbial inoculant positively affects the multifunctionality of anthropogenic soils in abandoned mining areas. Journal of Environmental Management, 344, 118553.

Li, J., Wang, J., Liu, H., Macdonald, C. A., & Singh, B. K. (2023). Microbial inoculants with higher capacity to colonize soils improved wheat drought tolerance. Microbial Biotechnology, 16(11), 2131–2144.

Liu, P., Wen, S., Zhu, S., Hu, X., & Wang, Y. (2025). Microbial degradation of soil organic pollutants: Mechanisms, challenges, and advances in forest ecosystem management. Processes, 13(3), 916.

Londe, V. (2021). The importance of ecological redundancy for ecosystems restoration. Research in Ecology, 3(2), 2957.

Ma, Y., Lyu, D., Sun, K., Li, S., Zhu, B., Zhao, R., & Song, K. (2022). Spatiotemporal analysis and war impact assessment of agricultural land in Ukraine using RS and GIS technology. Land, 11(10), 1810.

Maksimova, Y. G., Maksimov, A. Y., & Demakov, V. A. (2018). Biotechnological approaches to the bioremediation of an environment polluted with trinitrotoluene. Applied Biochemistry and Microbiology, 54(8), 767–779.

Mani, D., & Kumar, C. (2020). Biotechnological advances in bioremediation of heavy metals contaminated ecosystems: An overview with special reference to phytoremediation. International Journal of Environmental Science and Technology, 11(3), 843–872.

Margesin, R., & Schinner, F. (2001). Biodegradation and bioremediation of hydrocarbons in extreme environments. Applied Microbiology and Biotechnology, 56(5), 650–663.

Melnychenko, V. (2024). Phytoremediation of soils contaminated as a result of military and anthropogenic impact. Scientific Reports of the National University of Life and Environmental Sciences of Ukraine, 20(4), 72–84.

Menshov, O., & Kruglov, O. (2023). Agricultural soil degradation in Ukraine. In: Pereira, P., Muñoz-Rojas, M., Bogunovic, I., & Zhao, W. (Eds.). Impact of agriculture on soil degradation II. Springer, Cham. Vol. 121. Pp. 325–347.

Mohammadipanah, F., & Zamanzadeh, M. (2019). Bacterial mechanisms promoting the tolerance to drought stress in plants. In: Singh, H., Keswani, C., Reddy, M., Sansinenea, E., & García-Estrada, C. (Eds.). Secondary metabolites of plant growth promoting rhizomicroorgani–sms. Springer, Singapore. Pp. 185–224.

Mrunalini, K., Behera, B., Jayaraman, S., Abhilash, P. C., Dubey, P. K., Swamy, G. N., ... & Srinivasa Rao, C. (2022). Nature-based solutions in soil restoration for improving agricultural productivity. Land Degradation and Development, 33(8), 1269–1289.

Muratova, A., Golubev, S., Romanova, V., Sungurtseva, I., & Nurzhanova, A. (2023). Effect of heavy-metal-resistant PGPR inoculants on growth, rhizosphere microbiome and remediation potential of *Miscanthus× giganteus* in zinc-contaminated soil. Microorganisms, 11(6), 1516.

Murugan, A. C., Perumal, V., & Kannan, S. (2022). Production, cost analysis, and marketing of agricultural effective microorganisms. In: Amaresan, N., Dharumadurai, D., & Cundell, D. R. (Eds.). Industrial microbiology based entrepreneurship. Making Money from Microbes, 42, 199–223.

Mytsyk, O. O. Havriushenko, O. O. Shevchenko, S. M., & Hulenko, O. I. (2023). Effect of long-term phytoremediation on the soil genesis potential of the technozems of the Pokrov Research Station. Grain Crops, 7(2), 350–357.

Mytsyk, O., Havryushenko, O., Tsyliuryk, O., Shevchenko, S., Hulenko, O., Shevchenko, M., & Derevenets-Shevchenko, K. (2024). Reclamation of

derelict mine land by simply growing crops. International Journal of Environmental Studies, 81(1), 230–238.
Nadporozhskaya, M., Kovsh, N., Paolesse, R., & Lvova, L. (2022). Recent advances in chemical sensors for soil analysis: a review. Chemosensors, 10(1), 35.
Novakovska, I., Belousova, N., & Hunko, L. (2025). Land degradation in Ukraine as a result of military operations. Acta Scientiarum Polonorum Administratio Locorum, 24(1), 129–145.
Nsanganwimana, F., Pourrut, B., Mench, M., & Douay, F. (2014). Suitability of *Miscanthus* species for managing inorganic and organic contaminated land and restoring ecosystem services: A review. Journal of Environmental Management, 143, 123–134.
Ntamwira, J., Ocimati, W., Blomme, G., Lubobo, A. K., Mwarabu Lolonga Pyame, D., & Dhed'a Djailo, B. (2023). Innovative agroecological practices can restore degraded farmlands and revive crop yields. Frontiers in Sustainable Food Systems, 7, 1017341.
Pandolfo, E., Barra Caracciolo, A., & Rolando, L. (2023). Recent advances in bacterial degradation of hydrocarbons. Water, 15(2), 375.
Philippot, L., Chenu, C., Kappler, A., Rillig, M. C., & Fierer, N. (2024). The interplay between microbial communities and soil properties. Nature Reviews Microbiology, 22(4), 226–239.
Pidlisnyuk, V., Erickson, L., Stefanovska, T., Popelka, J., Hettiarachchi, G., Davis, L., & Trögl, J. (2019). Potential phytomanagement of military polluted sites and biomass production using biofuel crop *Miscanthus x giganteus*. Environmental Pollution, 249, 330–337.
Pilon-Smits, E. (2005). Phytoremediation. Annual Review of Plant Biology, 56, 15–39.
Pulford, I. D., & Watson, C. (2003). Phytoremediation of heavy metal-contaminated land by trees – A review. Environment International, 29(4), 529–540.
Rawtani, D., Gupta, G., Khatri, N., Rao, P. K., & Hussain, C. M. (2022). Environmental damages due to war in Ukraine: A perspective. Science of the Total Environment, 850, 157932.
Ray, B., & Bhunia, A. (2025). Fundamental food microbiology (6th ed.). CRC Press, Boca Raton.
Riaz, U., Aslam, A., Javeid, S., Gul, R., Iqbal, S., Javid, S., & Jamil, M. (2021). Cadmium contamination, bioavailability, uptake mechanism and remediation strategies in soil-plant-environment system: a critical review. Current Analytical Chemistry, 17(1), 49–60.
Rodríguez-Seijo, A., Fernández-Calviño, D., Arias-Estévez, M., & Arenas-Lago, D. (2024). Effects of military training, warfare and civilian ammunition debris on the soil organisms: An ecotoxicological review. Biology and Fertility of Soils, 60(6), 813–844.
Romero-Estonllo, M., Ramos-Castro, J., San Miguel del Río, Y., Rodríguez-Garrido, B., Prieto-Fernández, Á., Kidd, P. S., & Monterroso, C. (2023). Soil amendment and rhizobacterial inoculation improved Cu phytostabilization, plant growth and microbial activity in a bench-scale experiment. Frontiers in Microbiology, 14, 1184070.
Rouphael, Y., & Colla, G. (2020). Biostimulants in agriculture. Frontiers in Plant Science, 11, 40.
Ryan, M. R., & Peigné, J. (2017). Applying agroecological principles for regenerating soils. In: Wezel, A. (Ed.). Agroecological practices for sustainable agriculture: Principles, applications, and making the transition. World Scientific Publishing, New Jersey, London, Geneva, Hong Kong, Taipei, Beijing, Shanghai, Tianjin, Chennai. Pp. 53–84.
Saidu, K., Ameh, J. B., & Atta, H. I. (2019). Diesel-degrading potential of *Pseudomonas putida* isolated from effluent of a petroleum refinery in Nigeria. UMYU Journal of Microbiology Research, 4(2), 105–112.
Saljnikov, E., Mueller, L., Lavrishchev, A., & Eulenstein, F. (2022). Understanding and monitoring chemical and biological soil degradation. In: Saljnikov, E., Mueller, L., Lavrishchev, A., & Eulenstein, F. (Eds.). Advances in understanding soil degradation. Innovations in landscape research. Springer, Cham. Pp. 75–124.
Salt, D. E., Smith, R. D., & Raskin, I. (1998). Phytoremediation. Annual Review of Plant Physiology and Plant Molecular Biology, 49(1), 643–668.
Schaefer, V. H. (2011). Remembering our roots: a possible connection between loss of ecological memory, alien invasions and ecological restoration. Urban Ecosystems, 14(1), 35–44.
Shafea, L., Yap, J., Beriot, N., Felde, V. J., Okoffo, E. D., Enyoh, C. E., & Peth, S. (2023). Microplastics in agroecosystems: A review of effects on soil biota and key soil functions. Journal of Plant Nutrition and Soil Science, 186(1), 5–22.
Shakeel, A., Omar, B., Syed, A., Tawheed, A., Asif, R., Mudasir, A., Juliana, H., & Farooq, S. (2022). Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. Chemosphere, 303, 134788.
Sharma, P., Sharma, P., & Thakur, N. (2024). Sustainable farming practices and soil health: A pathway to achieving SDGs and future prospects. Discover Sustainability, 5(1), 250.
Sheoran, V., Sheoran, A. S., & Poonia, P. (2010). Soil reclamation of abandoned mine land by revegetation: A review. International Journal of Soil, Sediment and Water, 3(2), 13.
Shevchenko, S., Derevenets-Shevchenko, K., Desyatnyk, L., Shevchenko, M., Sologub, I., & Shevchenko, O. (2024). Tillage effects on soil physical properties and maize phenology. International Journal of Environmental Studies, 81(1), 393–402.
Solokha, M., Demyanyuk, O., Symochko, L., Mazur, S., Vynokurova, N., Sementsova, K., & Mariychuk, R. (2024). Soil degradation and contamination due to armed conflict in Ukraine. Land, 13(10), 1614.
Stahl, J. D., & Aust, S. D. (1995). Biodegradation of 2,4,6-trinitrotoluene by the white rot fungus *Phanerochaete chrysosporium*. In: Spain, J. C. (Ed.). Biodegradation of nitroaromatic compounds. Environmental Science Research. Springer, Boston. Vol. 49. Pp. 117–133.
Travleev, A. P., Bielova, N. A. & Zvierkovskyi, V. M. (2005). Teoretychni osnovy lisovoyi rekul'tyvatsiyi porushenykh zemel' u Zakhidnomu Donbasi na Dnipropetrovshchyni [Theoretical foundations of forest reclamation of disturbed lands in the Western Donbass in the Dnipropetrovsk region]. Gruntoznavstvo, 16(1–2), 19–29 (in Ukrainian).
Trokhaniak, O. (2024). Impact of military operations on agricultural soils. Mechanization in Agriculture and Conserving of the Resources, 68(1), 24–26.
Udume, O. A., Abu, G. O., Stanley, H. O., Vincent-Akpu, I. F., Momoh, Y., & Eze, M. O. (2023). Biostimulation of petroleum-contaminated soil using organic and inorganic amendments. Plants, 12(3), 431.
Uzbek, I. K. (2015). Some properties of man-made Dnieper Steppe ecosystems. Fundamental and Applied Soil Science, 16(3–4), 60–67.
Uzbek, I. K., & Halahan, T. I. (2004). Fizyko-khimichni vlastyvosti edafotopiv tekhnohennykh landshaftiv i yikh ekoloho-ekonomichne znachennia [Physicochemical properties of Edaphotops of technogenic landscapes and their ecological and economic significance]. Gruntoznavstvo, 5(1–2), 102–106 (in Ukrainian).
van der Heijden, M. G., & Wagg, C. (2013). Soil microbial diversity and agroecosystem functioning. Plant and Soil, 363(1), 1–5.
Vasić, M. V., Radomirović, M., Velasco, P. M., & Mijatović, N. (2024). Geochemical profiles of deep sediment layers from the Kolubara District (Western Serbia): Contamination status and associated risks of heavy metals. Agronomy, 14(12), 3009.
Vidosavljević, D., Puntarić, D., Gvozdić, V., Jergović, M., Miškulin, M., Puntarić, I., & Šijanović, S. (2013). Soil contamination as a possible long-term consequence of war in Croatia. Acta Agriculturae Scandinavica, Section B – Soil and Plant Science, 63(4), 322–329.
Wang, C., Sun, H., Li, J., Li, Y., & Zhang, Q. (2009). Enzyme activities during degradation of polycyclic aromatic hydrocarbons by white rot fungus *Phanerochaete chrysosporium* in soils. Chemosphere, 77(6), 733–738.
Wang, Y., Wang, H. S., Tang, C. S., Gu, K., & Shi, B. (2019). Remediation of heavy-metal-contaminated soils by biochar: A review. Environmental Geotechnics, 9(3), 135–148.
Weyens, N., van der Lelie, D., Taghavi, S., Newman, L., & Vangronsveld, J. (2009). Exploiting plant–microbe partnerships to improve biomass production and remediation. Trends in Biotechnology, 27(10), 591–598.
Wirtu, Y. D., & Abdela, U. (2025). Impact of war on the environment: Ecocide. Frontiers in Environmental Science, 13, 1539520.
Wu, M., Wu, J., Zhang, X., & Ye, X. (2019). Effect of bioaugmentation and biostimulation on hydrocarbon degradation and microbial community composition in petroleum-contaminated loessal soil. Chemosphere, 237, 124456.
Xie, X., Pu, L., Zhu, M., Wu, T., Xu, Y., & Wang, X. (2020). Effect of long-term reclamation on soil quality in agricultural reclaimed coastal saline soil, Eastern China. Journal of Soils and Sediments, 20(11), 3909–3920.
Xue, H., Shi, Y., Qiao, J., Li, X., & Liu, R. (2023). Enhancing anaerobic biodegradation of phenanthrene in polluted soil by bioaugmentation and biostimulation: Focus on the distribution of phenanthrene and microbial community analysis. Sustainability, 16(1), 366.
Yakhin, O. I., Lubyanov, A. A., Yakhin, I. A., & Brown, P. (2017). Biostimulants in plant science: A global perspective. Frontiers in Plant Science, 7, 2049.
Yan, A., Wang, Y., Tan, S. N., Mohd Yusof, M. L., Ghosh, S., & Chen, Z. (2020). Phytoremediation: A promising approach for revegetation of heavy metal-polluted land. Frontiers in Plant Science, 11, 359.
Yang, G., Chen, Y., Ren, Q., Liu, Q., Ren, M., Zheng, J., & Luo, X. (2024). Remote sensing ecological index (RSEI) affects microbial community diversity in ecosystems of different qualities. Science of the Total Environment, 954, 176489.
Yap, H. S., Zakaria, N. N., Zulkharnain, A., Sabri, S., Gomez-Fuentes, C., & Ahmad, S. A. (2021). Bibliometric analysis of hydrocarbon bioremedia-

tion in cold regions and a review on enhanced soil bioremediation. Biology, 10(5), 354.
Zaimenko, N., Lahoiko, A., & Slyusarenko, A. (2025). Potential application of melanins for restoring war-affected soils in Ukraine. Agrobiodiversity for Improving Nutrition, Health and Life Quality, 9(1), 150–164.
Zaitsev, Y., Hryshchenko, O., Romanova, S., & Zaitseva, I. (2022). Influence of combat actions on the content of gross forms of heavy metals in the soils of Sumy and Okhtyrka Districts of Sumy Region. Agroecological Journal, 3, 136–149.
Zheng, K., Liu, Z., Liu, C., Liu, J., & Zhuang, J. (2023). Enhancing remediation potential of heavy metal contaminated soils through synergistic application of microbial inoculants and legumes. Frontiers in Microbiology, 14, 1272591.