ENVIRONMENTAL PROBLEMS

Vol. 10, No. 4, 2025

CHEMICAL SOIL DEGRADATION FROM MILITARY ACTIVITIES: AN INTEGRATED APPROACH TO LAND RECLAMATION

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https://doi.org/10.23939/ep2025.04.344

Received: 04.08.2025

Abstract. Soil degradation due to military operations is a pressing environmental problem today, requiring detailed study and application of environmentally safe protection technology. The study of the impact of military operations on the soil was conducted using the example of the Sumy region. The methods of X-ray fluorescence (elemental composition and content of heavy metals – HM) and liquid chromatography (organic explosives content) were used to analyze the selected soil samples. The assessment of the environmental risk from soil contamination with HM was carried out using the potential environmental risk index. The maximum permissible concentration for HM Cr, Sr, Cu, and Zn was found to be exceeded, as well as samples for Mn in some. The distribution of pollution by the values of environmental risk from soil contamination with HM has the form: Cu > Cr > Sr > Zn > Mn, and a low level of environmental risk was found, which is associated with high concentrations of HM in the control sample. In the studied soil samples, explosive residues (hexogen) were detected at a level from 1.38 mg/kg at the epicenter of the explosion to 2.34 mg/kg at a distance of 5 m from the funnel cut. Natural pathways of hexogen degradation have been established, which formed the basis of proposed approaches to process intensification, in particular the use of biosorbents and bacterial consortia. A comprehensive remediation scheme has been developed for contaminated sites, including the use of technologies based on physical, chemical and biological methods.

Keywords: explosives, heavy metals, land reclamation, soil contamination, soil protection technologies.

1. Introduction

The war in Ukraine has led to significant soil degradation and contamination with various hazardous chemicals. According to data from the Ministry of Environmental Protection and Natural Resources of Ukraine, as of June 2025, the area of contaminated soils was 1.196.475 m², and the area of littered lands was 23.400.382 m² (Land resources, 2025). The deterioration of the useful properties and fertility of the soil, i.e., its degradation, occurs as a result of mechanical, thermal, and chemical loads on the soil during military operations, which leads to the occurrence of all types of degradation: mechanical, physical, chemical, physico-chemical and biological (Baliuk et al., 2024). Chemical soil pollution is one of the manifestations of degradation, which negatively affects both soil properties and soil ecosystems. This type of pollution is a factor of long-term risk to human health because of the consumption of products grown on contaminated soils (Gorecki et al., 2017), and indirectly through secondary pollution of air, surface, and groundwater (Hryhorczuk et al., 2024). In

For citation: Kuzomenska, K., Ablieieva, I., Tischenko, S., Lysytska, A. (2025). Chemical soil degradation from military activities: an integrated approach to land reclamation. *Journal Environmental Problems*, *10*(4), 344–354. DOI: https://doi.org/10.23939/ep2025.04.344

addition, military actions lead to soil compaction, changes in the grain size distribution, mechanical structure, and physicochemical parameters of the soil, in particular, fluctuations in the content of organic carbon and humus are observed after explosions and fires, which is the cause of a decrease in soil fertility (Solokha et al., 2024).

Military actions can lead to chemical contamination of soil through various mechanisms, including the use of munitions, spills of fuel and chemicals, and the location of broken military equipment (Broomandi et al., 2020). In this regard, the pollutants commonly encountered in these scenarios are heavy metals (HM), petroleum hydrocarbons, and explosive materials (Shukla et al., 2023). Soil contamination with petroleum hydrocarbons occurs because of accidental releases from explosions, burning equipment, and spills during refueling, transportation, or storage of fuel for military equipment (Shebanina et al., 2023). The content of HM in the soil in the combat zone from the sites of burned military equipment and the fall of air bombs can reach the following levels (mg/kg): Pb – 103.78, Zn – 55.11, Cd – 23, Cu – 39.39, Ni – 43 (Petrushka et al., 2023). According to the standards of maximum permissible concentrations (MPC) of hazardous substances in soils approved in Ukraine, for this scenario, the MPC is exceeded several times for all HM, mg/kg: Pb – 32, Zn – 23, Cd – 3, Cu – 3, Ni – 4. Based on the preliminary predictive assessments of the ecological risk index for the soil in the combat zone from the sites of burned military equipment in the Sumy region, a moderate level of ecological risk has been established (Skvortsova et al., 2025). However, soil contamination by HM because of military actions depends on many factors and requires analysis for each case before making decisions on land reclamation or conservation measures in accordance with the current legislation of Ukraine.

The ecological problem of soil and water contamination with persistent and toxic explosives is urgent for military training sites, former military demolition ranges, and current military sites. A Web of Science and Scopus database search identified that most of the research related to explosives' fate in the environment, human health, and the efficiency of different remediation approaches were concentrated in the USA, Canada, UK, Korea, China, and India (Corredor, 2024; Mystrioti and Papassiopi, 2024). This problem became urgent for Ukraine since the current war and consequences from the bombing, hostilities, and explosion on land sites, including agricultural soils.

One of the most common energy-rich components of insensitive munitions is hexahydro-1,3,5-trinitro-1,3,5-triazine (Royal Demolition Explosive, RDX, or hexogen). It is released as particles on the soil surface when explosives undergo low-order or incomplete detonation. The behavior and fate of RDX in ecosystems and the environment are determined primarily by its properties as xenobiotic, but this process can be affected by various stress factors (Lance et al., 2020). The known degradation pathways of RDX determine the choice of a specific soil remediation method and technology, among which the use of biochar is effective (Sharma et al., 2023). However, the reclamation of lands degraded and contaminated as a result of military actions is a complex task, which is associated with multilateral impacts on soil and ecosystems, as well as the combined effects of several chemical substances.

It is worth emphasizing that in the case of agricultural use of a land plot that is in a war zone, further cultivation of plants becomes impossible, which hinders the supply of food, leads to significant losses and undermines the country's food security (Onopriienko et al., 2025). At the same time, the restoration and cleaning of such territories require multilateral research and in-depth analysis. The issue of developing scientifically based engineering, technological and remedial measures to ensure the environmental safety of the population, prevent the migration of pollutants through food chains and, accordingly, reduce the risk to human health is relevant today.

The main aim of this paper is to establish the regularities of chemical soil degradation, which will allow developing comprehensive solutions for the restoration and cleaning of soils degraded and contaminated as a result of military operations. To achieve this aim, the following research tasks were set:

1) to analyze the nature of the impact of military operations on soil using the example of the Sumy region;

2) to assess the level of environmental risk from chemical soil contamination;

3) to propose a comprehensive scheme for the reclamation of land degraded as a result of military actions.

2. Materials and Methods

The research was conducted in the Sumy region, Ukraine, in the places where air bombs fell in September 2024 at the agricultural land. The fall of air bomb KAB-500 resulted in a crater with an approximate diameter of 8–10 m, and a depth of 8 m. Soil samples were taken in the same month 10 days after the explosion according to the developed methodology considering international standards for soil sampling (ISO 18400), which provided for the study of the spatial impact of the blast wave on soils within the formed funnel. The sampling scheme is shown in Fig. 1.

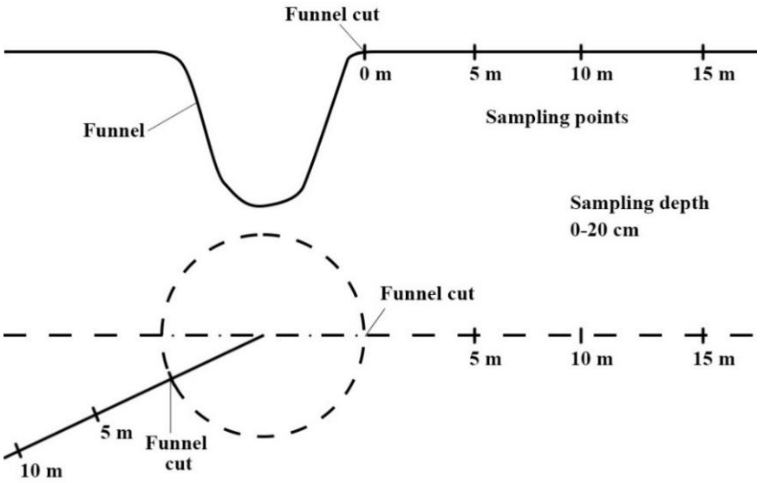


Fig. 1. Scheme of soil sampling in areas affected by military operations

To ensure representativeness of the results, three replicates were taken for each sample, including for control (uncontaminated soil outside the impact area) taken 25 m from the crater in a direction that minimized the direct of the explosion products. The control point was chosen based on similar relief, soil type, and land use. There were 5 chosen points (sites) for the investigation of the soil after explosion, including 1 point at the epicenter of the explosion, 1 on the funnel cut and 3 at 5, 10 and 15 m from the funnel cut, consequently. Therefore, the total number of samples taken by soil counted 18 samples considering 5 investigated sites and 1 control site as well as 3 replicates for each site.

Transportation, storage of soil samples and sample preparation for chemical analysis were carried out in accordance with the standard DSTU 7948:2015 Soil quality. Conducting analyses. General requirements. Air-dried soil samples were subjected to chemical analysis. Elemental analysis of soil samples was determined by the X-ray fluorescence method on an energy dispersive X-ray fluorescence spectrometer EDX-7000/8100 (Shimadzu). Sample preparation included drying samples to constant mass at a temperature of 105 °C, and pressing tablets with a force of 4 tons (tablet diameter 1 cm) with a thickness of 3–4 mm. Before pressing, the soil samples were ground in an agate mortar with a pestle, then sieved through a sieve with a mesh size of 0.28 mm. Grass particles, pebbles, and small metal fragments remained on the sieve. The analysis was performed in air with a, 5 mm collimator, a rhodium X-ray tube, and X-ray test energy settings: in the range from Na to Sc voltage 15 kV, current automatic, detector dead time 30 %, and recording duration 60 s. In the range from Ti to U, in air, collimator 5 mm, voltage 50 kV, current automatic, dead time 30 %, recording duration 60 s. Sample holder polypropylene film. The content of each element in the studied soil samples was converted from % to concentration (g/kg) per 1 kg of soil. The detection limit for the EDX 7000 X-ray fluorescence spectrometer for heavy metals is 10 ppm, for light metals – 1000 ppm for pressed samples using filters.

The content of organic substances of explosive nature in soil samples was determined by liquid chromatography using the EPA 8330 method (U.S. EPA 2006 “Method 8330B (SW-846): Nitroaromatics, Nitramines, and Nitrate Esters by High Performance Liquid Chromatography (HPLC)”, section for extraction from solid samples. The analysis was performed on a liquid chromatograph LC-2060C (Shimadzu). The detection limit for hexogen for the selected analysis method, considering the configuration of the liquid chromatograph, is 1 ppm (1 mg/kg). The peak height of the test substance should be at least 5 times higher than the background noise.

The ecological risk assessment was performed using the potential ecological risk index (RI) according to equation (1):

$$RI = \sum_{i=1}^{n} ER = \sum_{i=1}^{n} T_r^i \cdot \frac{C_i}{C_b}, \qquad (1)$$

where *RI* is the potential ecological risk index; *ER* is the ecological risk factor for the i^{th} HM; T_r^i is the toxic response factor for the i^{th} HM (Mn, Sr, and Zn – 1; Cr – 2; Cu – 5); C_i is the actual concentration of the i^{th} HM in the soil, mg/kg; C_b is the background concentrations of the i^{th} HM in the soil, mg/kg.

The assessment of the level of environmental risk was carried out based on the obtained values of the potential environmental risk index according to the classification described in Table 1 (Jahandari & Abbasnejad, 2024).

Table 1

Classification of environmental risk levels by factor and index values

Ecological risk factor (ER)	Degree of ecological risk	Potential ecological risk index (RI)	Degree of ecological risk
ER < 40	Low	RI ≤ 150	Low
40 ≤ ER < 80	Moderate	150 < RI ≤ 300	Moderate
80 ≤ ER < 160	Considerable	300 < RI ≤ 600	High
160 ≤ ER < 320	Serious	RI > 600	Severe
ER ≥ 320	Severe pollution	–	–

Statistical analysis was performed using IBM SPSS Statistics and Microsoft Excel. ANOVA analysis of variance was used to compare values in samples. The dispersion of data on the concentrations of HM in the studied soil samples relative to their mean value was determined using the standard deviation function at 95% confidence interval (CI).

3. Results and Discussion

3.1. Analysis of chemical soil contamination due to military operations

Based on the X-ray fluorescence analysis of the samples of contaminated soil after the explosion, the content of the main elements was determined (Fig. 2).

Probably, the predominant compounds are aluminosilicates and silicon compounds. Accordingly, it is possible to assume the natural sorption properties of soil rocks, which will positively affect the immobilization of heavy metals and organic pollutants and slow down their extraction into soil solutions. Along with this, it is worth noting the fluctuations of elements in soil samples compared to the control. Closer to the epicenter of the funnel, the concentration of iron and calcium increases, while the silicon content decreases. These trends can be hypothesized by several mechanisms, both geochemical and physical, such as high-temperature melting, redistribution of soil layers and minerals, and input of weapon-derived materials. Mentioned above processes lead to significant changes in soil composition, including the mixing of genetic horizons and formation of new soil layers (Menshov et al., 2024). High-temperature melting causes the transformation of mineral phases resulted in the increasing of iron and calcium content through the formation of new minerals (Rodrigues et al., 2012). Physical redistribution can elevate both Fe and Ca (from subsurface sources) while diluting the relative Si content (Illienko et al., 2025). The increased content of iron in the soil after explosions indicates the input of weapon-derived materials, which can alter the soil's magnetic properties and mineral content (Menshov et al., 2024). Such processes lead to soil erosion, which requires the use of appropriate restoration technologies.

The studied soil samples contained heavy metals (HM), including manganese (Mn), chromium (Cr), stable strontium (Sr), copper (Cu), and zinc (Zn), which are potentially toxic elements (PTEs), which constitute one group of chemicals typical of the consequences of military operations.

Nickel (Ni) was also identified for samples No. 0 and No. 2 but was not plotted because there was no data on its concentration in the control sample. According to the obtained results, the MPC was exceeded for manganese for sample No. 0 and the control sample. Control sample was taken from the top layer of soil in an agricultural field where aerial bombs occurred, that's why the increased content of heavy metals can be explained by their entry into the top layers of soil along with fertilizers that are applied annually. Also, approximately 1 km from this field is a local road, which can also act as a source of pollution. The following distribution of contamination by HM concentrations can be identified: for samples No. 0 (in the epicenter of the explosion) and No. 1 (on the funnel cut) – Mn > Cr > Sr > Cu > Zn; for sample No. 2 (at a distance of 5 m from the funnel cut) – Mn > Cu > Cr > Sr > Zn; for sample No. 3 (at a distance of 10 m from the funnel cut) – Mn > Cu > Sr > Zn > Cr; for sample No. 4 (at a distance of 15 m from the funnel cut) – Mn > Cu > Sr > Cr > Zn. The predominant PTEs for investigated soil samples are copper, chromium, and strontium. It is obvious that the content of HM in the soil after military operations will depend on the type of impact, in particular, it is possible to assume different patterns of their content and distribution for the places of air bombs and places of crashed and burned military equipment.

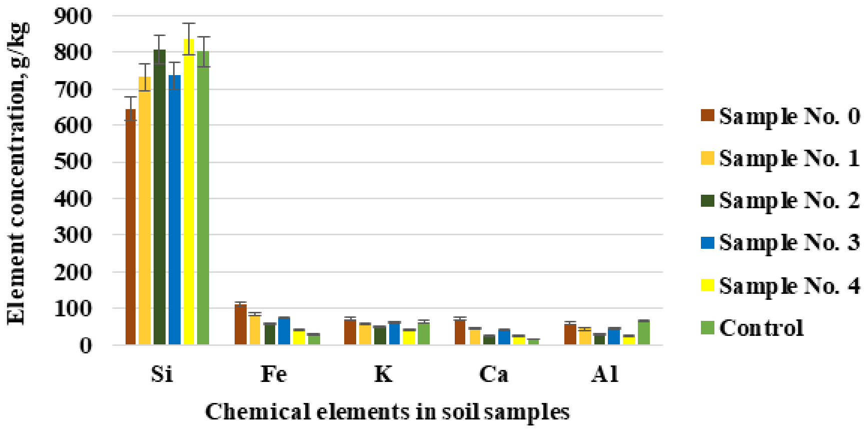
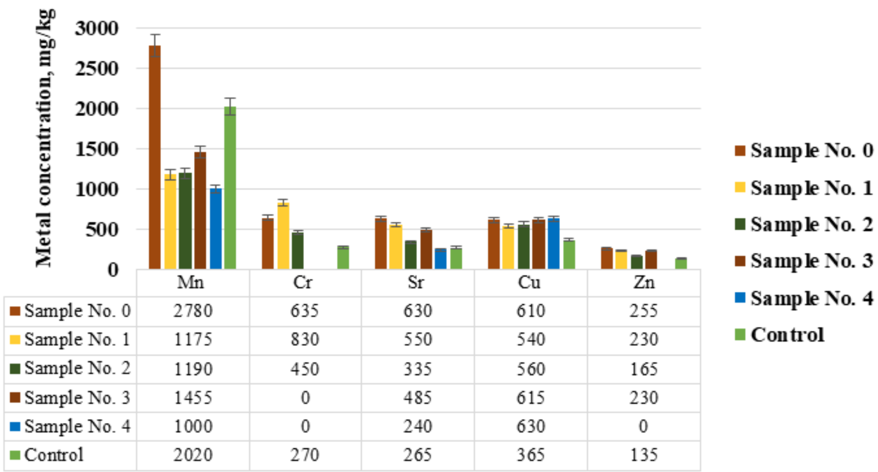


Fig. 2. Content of major elements in soil samples



	Mn	Cr	Sr	Cu	Zn
Sample No. 0	2780	635	630	610	255
Sample No. 1	1175	830	550	540	230
Sample No. 2	1190	450	335	560	165
Sample No. 3	1455	0	485	615	230
Sample No. 4	1000	0	240	630	0
Control	2020	270	265	365	135

Fig. 3. Heavy metal content in soil samples

In the places of explosion of air bombs or missiles, the average content of lead, zinc, cadmium, copper and nickel is lower compared to soil samples taken from the places of crashed military equipment, according to the results obtained for soils in the combat zone in the Sumy region. At the same time, the lowest lead content was found in the places where air bombs fell (Zaitsev et al., 2022). It is worth noting that lead and cadmium, which belong to Hazard Class I and whose compounds are quite toxic to living organisms and humans, were not detected in the soil samples studied by X-ray fluorescence methods. However, as a result of studies of soil samples from the places of rocket explosions in Lviv by the ICP-OES method, these elements were detected and the following order of concentrations of the total content of HM was established: Cd > Cu > Pb > Cr > Zn > Ni (Petrushka et al., 2024b).

The obtained data on the content of HM are higher compared to the study conducted in the Kharkiv region at the sites of destroyed equipment and ammunition detonation (Solokha et al., 2024). The highest concentrations were recorded for lead, zinc, and cadmium for samples from the bottom of the destroyed T72B3 tank, while the impact of contamination of destroyed vehicles (tanks) on the soil had the following distribution: Pb > Zn > Cd > Cu. It is also worth noting the higher background concentrations of these elements, respectively, the average content of HM after military operations will depend not only on the type of military operations as described above, but also on other factors, in particular: the initial background content, type of rock, type of soil, and physicochemical properties of the soil. In this regard, conducting a chemical analysis of soil samples should be a mandatory component before conducting land reclamation, the results of which will influence the choice of the appropriate soil remediation technology.

In addition to PTEs, the content of energy-rich materials, which are explosives, was determined in the soil samples. According to the results of liquid chromatography, it was found that in the control sample (clean soil), no traces of explosives were detected, and for the contaminated soil, the presence of hexogen, which belongs to the group of high-power explosives and has a high specific energy and detonation rate (Table 2), was noted.

Table 2

Hexogen concentration in soil samples from explosion sites

Sample No.	Concentration, mg/kg (mean ± SD)	Description of sampling location
0	1.38 ± 0.1	At the epicenter of the explosion
1	1.99 ± 0.2	On the funnel cut
2	2.34 ± 0.3	At a distance of 5 m from the funnel cut
3	2.26 ± 0.25	At a distance of 10 m from the funnel cut
4	2.00 ± 0.15	At a distance of 15 m from the funnel cut

The determined concentrations are consistent with the average RDX content in surface and deep soil samples affected by military activities, which has a wide range, in particular for US military bases (<0.003–1130 mg/kg), Canada (1.4–6000 mg/kg), and Korea (0.08–51.2 mg/kg) according to the survey of soil contamination in areas affected by military activities (Broomandi et al., 2020).

In Ukraine, the content of explosives in soil is not regulated – the relevant regulations do not contain information on the MPC of RDX in soil. However, the US Environmental Protection Agency (EPA) calculated the level of soil contamination for residential premises (SSL) at 5.6 mg/kg and the industrial SSL at 24 mg/kg. At the same time, the previous recommendations on soil quality for the environment (Bordeleau et al., 2008) set the limit values for soil contamination with hexogen at 4.7 mg/kg. Accordingly, the recorded values of the RDX content in the studied soil samples do not exceed the values in the recommendations, however, the entry of these substances because of an explosion causes pollution not only of the soil, but also of the atmospheric air, and depends on several factors.

3.2. Environmental risk assessment

Based on the calculated potential ecological risk index RI (Table 3), the level of ecological risk was determined as low for all soil samples (RI = 18.74, 17.92, 14.08, 12.69 and 10.03 for samples of No. 0, 1, 2, 3, and 4, respectively). Such results are explained by the high values of HM concentrations in the control sample, since the methodology involves comparison with background concentrations.

Table 3

Results of the environmental risk assessment

Potential ecological risk for soil samples (±standard deviation)					
Ecological risk factor (ER)	Sample No. 0	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4
ER(Mn)	1.38±0.33	0.58±0.00	0.59±0.06	0.72±0.25	0.50±0.01
ER(Cr)	4.71±1.62	6.15±0.00	3.33±0.00	0.00±0.00	0.00±0.00
ER(Sr)	2.39±0.28	2.08±0.01	1.26±0.16	1.83±0.07	0.91±0.02
ER(Cu)	8.37±1.13	7.41±0.92	7.68±0.15	8.44±0.84	8.63±0.17
ER(Zn)	1.90±0.15	1.71±0.09	1.23±0.22	1.71±0.09	0.00±0.00
Potential ecological risk index (RI)	18.74±2.85	17.92±1.02	14.08±0.16	12.69±1.25	10.03±0.18

The distribution of environmental risk values for HM is as follows: for samples No. 0 (at the epicenter of the explosion), No. 1 (at the funnel cut) and No. 2 (at a distance of 5 m from the funnel cut) – Cu > Cr > Sr > Zn > Mn; for sample No. 3 (at a distance of 10 m from the funnel cut) – Cu > Sr > Zn > Mn > Cr; for sample No. 4 (at a distance of 15 m from the funnel cut) – Cu > Sr > Mn > Cr > Zn.

As can be seen, the obtained distribution of the manifested environmental risk for HM differs from the distribution of the values of their actual content in the justification samples, which allows establishing the degree of their danger based on the use of the toxic response factor, which is higher for the copper and chromium. In addition, in accordance with the methodology for calculating the ecological risk factor, the values of background concentrations for HM were used, which were taken as the values of these concentrations in the control sample. Since the manganese content in the control sample was high, the calculated ecological risk factor was determined to be lower compared to other HMs.

The authors Petrushka et al. (2024a) during research in Lviv established the following pattern of the level of ecological risk for heavy metals: Cr > Zn > Cd > Cu > Pb. This distribution differs from ours, which is associated with a higher content of zinc and copper compared to the background, and the absence of cadmium and lead in the studied soil samples. Our previous study in the soil of the combat zone from the sites of destroyed military equipment in the Sumy region showed the following distribution of ecological risk values: Cd > Pb > Cu > Ni > Zn (Skvortsova et al., 2025).

Thus, the results obtained emphasize the importance of conducting an environmental risk assessment of soil contamination by munitions in the military zone, which will allow determining the patterns of chemical soil degradation and developing appropriate technological solutions. However, the degree of soil degradation due to explosions, accompanied by the formation of funnels (craters), is determined primarily by the power of the explosion and soil properties. The size of the funnel and, accordingly, the mass of destroyed soil substances and the mass of pollutants in the dust-gas cloud from the explosion depend on the mass of the explosives in the ammunition. Therefore, the explosion of several FAB-500, and FAB-1500 air bombs causes more damage than hundreds of shells over a certain period and leads to a cumulative effect of soil degradation and atmospheric pollution with substances from the explosion products (Bilyi et al., 2025). These factors will also affect the specifics of soil remediation.

3.3. Development of a comprehensive scheme for the reclamation of degraded lands

According to the results of the studies of soil samples at the explosion site, it was established that the main pollutants are HM and hexogen (RDX). Technologies for cleaning soil from HM based on the mechanisms of sorption, immobilization and complexation are quite widespread and deeply investigated. However, the combined contamination of soil with HM and explosives as a result of military operations requires the development of complex technological solutions. As noted above, hexogen is highly toxic, therefore, the mechanisms of explosive degradation have been analyzed in more detail, which is the basis for the development of soil protection technologies. The chemical and physical parameters of RDX affect its toxicodynamic and toxicokinetic characteristics. According to Lapointe et al. (Lapointe et al., 2017), the fate of RDX is determined by its dissolution, solubility and sorption, as well as the pathways of its degradation.

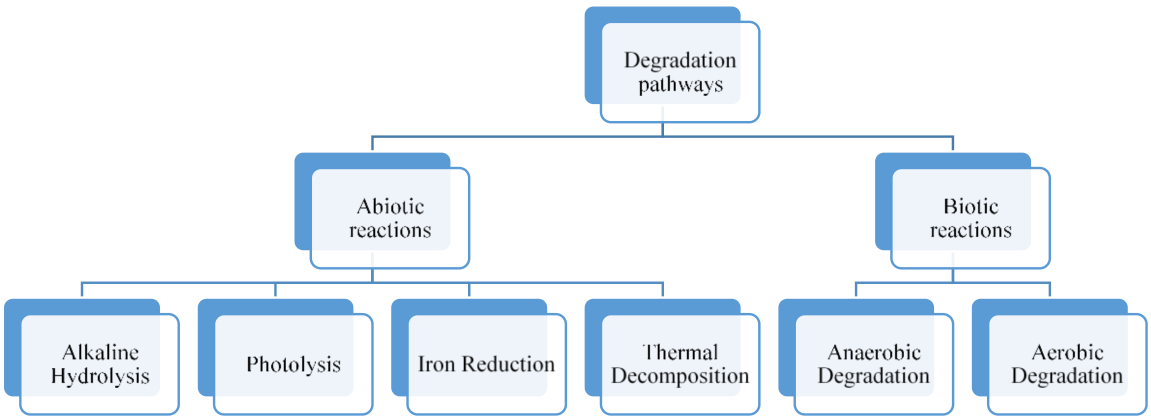


Fig. 4. Overview of the degradation pathways of hexogen in the environment (Lapointe et al., 2017)

In the case of explosions on agricultural lands, hexogen moves from the soil to plants and accumulates in the plant part by 75–95 % (Via and Zinnert, 2015). This means the initial circulation of hexogen in the ecosystem and makes it possible to poison humans through food chains. Based on a literature review on possible degradation pathways of RDX in soil, it was found that RDX can undergo transformations under the influence of abiotic and biotic reactions, as shown in Fig. 4. Understanding these mechanisms is important for the justification of appropriate methods and technologies. Lapointe et al. (Lapointe et al., 2020) suggested that denitrification should be the first step in the degradation pathway, since 4-nitro-2,4-diazabutanal (NDAB) and methylenedinitramine (MEDINA) were identified as RDX degradation products.

The most relevant environmental issue arising from the associated degradation process is the level of toxicity and bioavailability of RDX degradation products. Various approaches to remediation have been developed for contaminated sites, including the use of technologies based on physical, chemical and biological methods. The stages of remediation of land contaminated as a result of military operations are shown in Fig. 5.

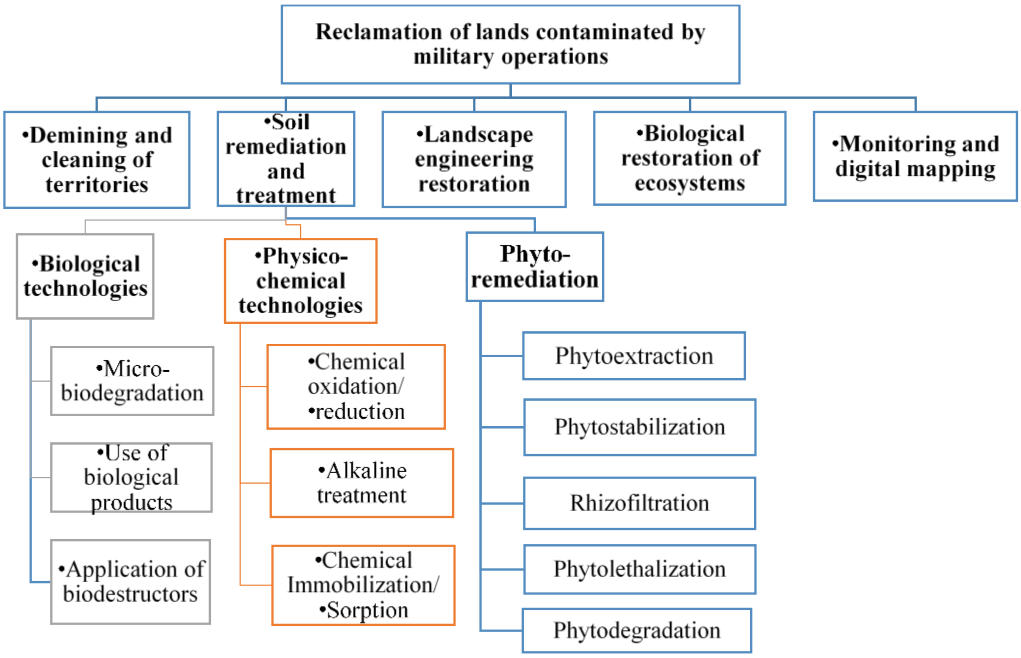


Fig. 5. System of measures for the reclamation of lands degraded as a result of military operations

After demining and clearing the area, remediation and soil treatment are required to neutralize chemical contaminants, which can be implemented by several technologies. Physical technologies involve the use of high temperatures, ultrasound and other physical effects to treat contaminated soil, but such methods are most often used for soil extraction (ex-situ). Some chemicals can be used to treat contaminated soils by chemical methods. However, these methods often lead to phase transfer of the explosive contaminant rather than its mineralization, which leads to secondary contamination. For example, Oh et al. (2015) investigated the effect of zero-valent iron (Fe(0)) on the removal of explosives as a recovery process, which did not have a significant positive effect due to the high toxicity of the recovery products. In contrast, degradation of explosives using subcritical water and Fenton oxidation using Fe(0) significantly reduced their toxicity. However, the presence of heavy metals such as Pb after explosions and detonation processes can reduce the recovery rate and increase the toxicity of by-products. Modified Fenton oxidation based on calcium peroxide (CaO_2) has been found to be an effective approach for hexogen degradation in the case of CaO_2 concentrations of at least 1 M (Lapointe et al., 2020) and low initial hexogen concentrations in the soil.

Bioremediation as a biological technology represents a sustainable alternative to the above-mentioned approaches. This technique consists of bioaugmentation (addition of microorganisms with specific enzymatic systems to the contaminated environment) and biostimulation (addition of specific products rich in nutrients necessary for the metabolism of organisms involved in the decomposition of pollutants).

Various organic additives are used to enhance microbial activity or to promote the immobilization of explosives.

The biodegradation of RDX can be enhanced by the addition of carbon-rich additives, which destructive microorganisms use as an energy source and involve in their own metabolism. Waste glycerin and cheese whey showed high efficiency in RDX degradation and were found to be promising organic additives for soil bioremediation after explosive contamination using soil columns to simulate scale-up conditions (Jugnia et al., 2017), but further investigation of the influencing factors is needed. Waste glycerin stimulated microbial activity under anaerobic conditions in soil, converting organic carbon to acetate and propionate, which are intermediates in anaerobic processes (Jugnia et al., 2018).

Microbial biodegradation of RDX is realized by adding bacterial consortia with appropriate enzymatic systems, for example, bacterial communities of *Sphingomonadaceae* and *Actinobacteriota* can degrade RDX under combined remediation with grass (*Vetiveria ziznioides*) and effective microflora (Yang et al., 2022). In addition, soil microorganisms, including *Rhodanobacter, Granulicella* and *Pseudomonas*, play a crucial role in the changes in the metabolic network. Microorganisms capable of degrading explosives, such as *Sphingomonadaceae*, *Actinobacteria* and *Gammaproteobacteria*, dominate the soil niche, showing a significant increase in their relative abundance (Yang et al., 2021). *Klebsiella asachharohila* strain 12853, isolated from explosive contamination sites, removed 75.7 % of RDX (135 μM) from an aquatic environment within 240 hours. The degradation of RDX was rapid and highly efficient, with its conversion to non-toxic metabolites (NDAB and MEDINA) identified by LCMS and nitrite analysis (Khan et al., 2021).

The use of biopreparations and biodestructors can positively influence phytoremediation, since the above-mentioned strains of bacteria and fungi are able to intensify the process of plant growth and sorption of pollutants. However, plant health and survival depend on numerous stress factors, such as RDX concentration, soil type, water availability, and plant type (Lance et al., 2020). The study of these factors will allow us to identify important relationships and more resistant plants available for phytoremediation.

A promising direction in the implementation of soil cleaning technologies from HM and explosives is the use of biochar. Such a product of pyrolysis of organic matter has a significant specific surface area and numerous surface functional groups. The appropriate physicochemical properties of biochar ensure soil remediation through mechanisms of sorption (π-π electron donor-acceptor interactions and hydrophobic interactions) and chemical transformation (direct transformation, redox mediators and activation of the oxidation process) of pollutants (Dong et al., 2024). Thus, the problem of using biochar for the remediation of soils degraded as a result of military operations and, accordingly, contaminated simultaneously with munitions and explosives is the subject of further research.

4. Conclusions

Based on the conducted research, it was found that as a result of military operations, soils undergo all types of degradation: mechanical, physical, chemical, physicochemical and biological. Thermal impact from explosions and mechanical load from the shock wave led to erosion and a decrease in soil fertility due to a decrease in humus and organic carbon reserves. Soil samples from explosion sites in the Sumy region had a lower silicon value compared to the control, which indicates destruction of silicon-containing minerals under the influence of the shock wave from detonation, and the selective erosional removal of lighter fine mineral particles from the crater area.

Military operations lead to chemical contamination of the soil, in particular, in the studied area, an excess of the MPC was detected for the following elements: Cr, Sr, Cu, and Zn, as well as in some samples for Mn. However, according to the results of the environmental risk assessment, a low level was established, which is associated with high concentrations of these elements in the control sample. The distribution of pollution by heavy metal concentrations takes the following form: Mn > Cr > Cu > Sr > Zn, and by the values of the ecological risk from soil contamination of the HM: Cu > Cr > Sr > Zn > Mn. In the studied soil samples, explosive residues (hexogen) were found at a level from 1.38 mg/kg at the epicenter of the explosion to 2.34 mg/kg at a distance of 5 m from the funnel cut.

A comprehensive scheme for the reclamation of lands degraded because of military operations is proposed, which includes the following stages: demining and cleaning of territories; sanitation and soil treatment; engineering restoration of the landscape; phytoremediation; biological restoration of ecosystems; monitoring and digital mapping. Particular attention is paid to technologies for cleaning the soil from heavy metals and explosives using chemical and biological methods. It has been established that the addition of biological preparations and biodestructors in combination with immobilized bacteria allows for intensifying the reduction of the explosive's concentration in the soil.

Acknowledgements

The authors performed part of the scientific work within the framework of the project "Implementation of the tasks of the perspective plan for the development of the scientific direction "Technical Sciences" of Sumy State University" (state registration number 0121U112684), as well as within the scope of the planned research work of the Department of Ecology and Environmental Protection Technologies of Sumy State University on the topic "Reduction of technogenic load on the environment from oil production facilities: prospects for the use of biotechnology" (state registration number 0121U114460) in accordance with the scientific and technical program of the Ministry of Education and Science of Ukraine.

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