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Diagnostics and bioremediation of soils affected by military operations in Ukraine

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Abstract. As a result of the full-scale invasion, extensive areas of agroecosystems suffered from toxic substances, which made the issue of restoring damaged land through the destruction of pollutants relevant. The purpose of this study was to substantiate and systematise diagnostic indicators for characterising soil bioactivity and to develop scientific approaches to bioremediation of damaged land. The study employed the method of analysing existing approaches to solving problems, the method of comparing data on the number of microorganisms of the main ecological and functional groups, which was determined according to the method of sowing soil suspensions on agarified nutrient media. The indices of microbial processes were calculated. Bioremediation measures were performed by introducing microbial biomass and culture fluids into the soil: *Dietzia maris* IMV B-7350, *Rhodococcus erythropolis* IMV B-7351, *Bacilus subtilis* IMV B-7349, *Pseudomonas aureofaciens* IMV B-7558, and *Streptomyces violaceus* IMV Ac-5027. The findings of the study showed that the level of microbiota

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repression in the soil affected by the explosions was exceedingly high compared to the undamaged soil. The most sensitive were phosphate-mobilising, nitrogen-fixing, amylolytic (including streptomycetes) microorganisms. In the soil from the bomb crater, the number of nitrogen-fixing and streptomycetes was 7% and 8% of the control, respectively, oligotrophic and amylolytic – 19.2% and 23.6%; phosphate-mobilising – 26%. In the soil damaged by an anti-tank shell explosion, the number of amylolytic, phosphate-mobilising, nitrogen-fixing, oligotrophic, and streptomycetes bacteria was 1.5%-10% of the control soil. The microbiota was repeatedly analysed 6 months after soil bioremediation. In the soil from the bomb crater, the number of phosphate-mobilising and nitrogen-fixing microorganisms increased and was 1.5-3.8 times greater than in the undamaged control, while the number of streptomycetes increased 12 times compared to the damaged soil. In the soil from the unexploded ordnance crater, the amount of phosphate mobilisers was 2.5 times higher than in the control, while the number of streptomycetes and nitrogen fixers increased 5.9 and 20.5 times, respectively, compared to the damaged soil. After bioremediation measures, the soil samples under study can be classified as either slightly toxic or non-toxic. The practical value of this study lies in the effectiveness of the proposed bioremediation approach, which is crucial for the further development of soil remediation measures in the context of the destruction of the Ukrainian agroecosystem

Keywords: military impact; damage; restoration; biological products; biological activity; soil microbiota

INTRODUCTION

Due to Russia's full-scale aggression, active hostilities are ongoing on the territory of Ukraine, which are a severe stress factor for ecosystems, including soil biological activity. The military impact has led to the destruction of arable land, which is Ukraine's most valuable natural resource. Toxic substances present in the soil, overcoming the barrier of the rhizosphere microbiota, get into plants and agricultural products, and then through trophic chains – into the human body. Determining the level of soil damage and developing biotechnologies for its remediation is an urgent problem.

According to statistics from the World Bank, the Government of Ukraine, and the European Commission, the territories of Luhansk (100%), Kherson (95%), Chernihiv (80%), Zaporizhzhia (74%), Sumy (70%), and Donetsk (64%) regions were the most affected by the Russian full-scale invasion in 2022, while the share of Ukraine's territory affected by occupation, mining, and hostilities in the total area of the country was 31.74% (Nykolyuk *et al.*, 2024). Total losses from soil disturbance are currently estimated at over UAH 980 billion. During a full-scale invasion, many toxic substances, including heavy metals (plumbum, cadmium, aluminium, copper, cobalt), are released into the soil as a result of military equipment, explosions, and combustion. Explosive substances also enter the ground: 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine, nitroglycerin, nitrocellulose, 2,4-dinitrotoluene, and various perchlorate compounds used in rocket and gunpowder (Zaitsev *et al.*, 2022). The explosion of a single ballistic missile produces more than 60 kg of toxic poisonous substances that enter the soil. I. Greaves & P. Hunt (2022) reported that the harmful emissions usually include carbon monoxide, nitrogen dioxide, heavy metals, and solid rocket fuel residues.

The use of phosphorus bombs produces phosphoric acids, phosphine, and white phosphorus particles wrapped in oxides that can persist in the soil for years. These toxic substances interact with soil organic matter and its absorption complex, on which fertility depends most of all. The transportation and storage of large quantities of fuels and lubricants can be added to the list of negative military impacts, which become an environmental problem due to large fuel spills that often occur in the middle of agricultural land and cover large areas (Tauqueer *et al.*, 2021). Against the backdrop of anthropogenic factors, global climate change has been added, which acts as a stressor in plant growth and development and prevents high and quality yields. Pollution by toxic substances released into the soil, disruption of genetic horizons after explosions, and changes in organic matter content have a repressive effect on microbiocenosis, which raises reasonable concerns about possible disruptions to ecological balance in agroecosystems (Wang *et al.*, 2024).

Soil functioning is ensured by the interaction of three components: physical, chemical, and biological. As biological components, microorganisms play a vital role in maintaining soil fertility and stabilising biological activity. Soil microbial communities perform crucial ecosystem functions such as regulatory, maintenance, and biosynthetic (Ortiz & Sansinenea, 2022). Managing these functions is a significant biotechnological challenge in modern agrocenoses. Especially significant are the functions of microbial cenoses in soils affected by military operations in Ukraine. X. Wang *et al*. (2024) noted that the bacterial biomass of soil in temperate meadows reaches 1-2 t/ha. The study of the microbiome showed that 1 g of soil contains about 1,000 thsd bp of microbial genomic sequences. The soil of agrocenoses is one of the most diverse anthropogenic environments.

Research was conducted at the D.K. Zabolotnyi Institute of Microbiology and Virology of the National Academy of Sciences of Ukraine to investigate the functioning of microbiocenoses of various soil types, microbial biodiversity, and to identify microorganisms that are indicators of soil ecological status. The study showed the role of agronomically useful rhizosphere and phytosphere bacteria in biological nitrogen fixation, transformation of hardly soluble soil phosphates into a form accessible to plants, provision of plants with biologically active compounds and phytoprotective effect. According to M. Dimova *et al*. (2020), this helps to improve the conditions for plant growth and development, increase their immunity, and improve the quality of agricultural products. According to the findings of F.W. Leal *et al*. (2024), the current problem is to overcome the agrarian crisis by restoring soils damaged by military actions, destroying toxic substances, restoring the biological potential of the native microbiota, increasing plant resistance to adverse biotic and abiotic factors through the biosynthetic potential of microorganisms.

To assess the damage caused to soils and carry out a set of remediation measures, it is necessary to determine the environmental indicators and bioactivity of soils. As of 2024, no comprehensive scientific approaches have been developed to monitor the impact of adverse military factors on the biological properties of soils, including microbiocenosis, nor has the list of indicators to be studied been determined or the relevant methods described. The lack of assessment of the environmental damage and its toxic consequences determined the purpose of the study – to substantiate and systematise biodiagnostic indicators for characterising the condition and biological activity of soils and to develop scientific approaches to bioremediation of land damaged by hostilities. To this end, it was necessary to determine the number of the key agronomically useful groups of microorganisms in damaged soils, calculate the ratio between the main ecological and functional groups of microorganisms, develop bioremediation measures based on the latest microbial biotechnologies and determine their effectiveness.

MATERIALS AND METHODS

Soil sampling for the study was performed according to DSTU GOST 17.4.4.02:2019 (2019). The location of the source of contamination/damage/explosion, test sites, and sampling sites were marked on a map or plan of the damage. For microbiological analysis, 10-20 spot samples were taken from one test site at a depth of 0-20 cm, mixed and formed into a pooled sample, packed in cooler bags and submitted for analysis, and soil samples were stored at 4°C for no more than 24 hours. Samples of military-affected soil from Chernihiv region were examined: soil from a crater after a 250 kg bomb explosion; and a control of undamaged soil from the same location outside the affected area.

Soil from the crater of an exploded anti-tank shell near a burnt-out tank and a control of undamaged soil from this location outside the affected area. The count of microorganisms of the main ecological and functional groups in the studied samples was determined by conventional methods of sowing soil suspension on agarified nutrient media: ammonification – on meat-peptone agar, pedotrophic – on agar with soil extract, amylolytic – on starch-ammonia agar, phosphate-mobilising – on Naum's medium with phenolphthalein sodium phosphate, nitrogen-fixing – on Ashby's selective medium, and oligotrophic – on starvation agar. The counts of microorganisms in the soil were expressed in colony forming units per 1 g of absolutely dry soil (CFU/1 g), considering its moisture content in the initial samples. The replication of the analyses was triplicate. To determine the focus of microbial processes in the soil, the ratio of the number of individual groups of microorganisms (m.o.) – indices of pedotrophicity (PI), oligotrophicity (OI), and mineralisation/immobilisation (MII) – was calculated as follows: PI = number of pedotrophic m.o./number of ammonifying m.o.; PI > 1 indicated soil recovery in the presence of organic matter. The PI > 6 indicated that the soil quality was approaching virgin lands, OI = number of oligotrophic m.o./number of amylolytic m.o. OI > 1 indicated unfavourable degradation processes in the soil, MII = number of amylolytic m.o./number of ammonifying m.o. An MII > 1 indicates the predominance of mineralisation processes over the immobilisation of soil organic matter.

To develop the key approaches to bioremediation of the affected soils, laboratory experiments were conducted with the introduction of microbial biomass and culture fluid of microorganisms into the soil, i.e., bioaugmentation of soil samples with biological products: a complex biological preparation (BP 1) based on microorganisms – destructors of toxic substances: *Dietzia maris* IMV B-7350, *Rhodococcus erythropolis* IMV B-7351, *Bacilus subtilis* IMV B-7349, *Pseudomonas aureofaciens* IMV B-7558 and a biological preparation (BP 2) based on the biomass and culture fluid of *Streptomyces violaceus* strain IMV Ac-5027, which is characterised by high phosphate-mobilising and cellulosolytic activity and antagonistic effect against phytopathogens (Ukraine Patent No. 107240, 2006; Iutynska, *et al*., 2017). Both biological preparations were mixed in the following volumes: 1-2 l of BP 1 diluted in water and 0.5-1 l of BP 2 per 1 ha. The microbial preparations were used to stimulate soil microbiota and activate the destruction of chemical pollutants, after which the microbiological characteristics and the level of soil damage were reassessed.

As the most sensitive microorganisms to stress factors, it was proposed to use the number of nitrogen-fixing, phosphate-mobilising bacteria, and streptomycetes as bioindicators. It was proposed to determine the level of damage (repression, R) of the soil microbiota by military actions (toxic substances, thermal explosion, etc.) by the percentage of the above groups of microorganisms in relation to the control undamaged soil according to Equation 1:

$$R = B : O \times 100\%, \qquad (1)$$

where *P* is the level of repression of the bioindicator group of microorganisms; *B* is the number of microorganisms of the bioindicator group from the affected area; *O* is the number of microorganisms of the bioindicator group outside the affected area, control. That is, the lower the percentage of diagnostic groups of microorganisms in the soil, the higher the level of damage. Accordingly, the levels of damage gradation were used and proposed (Table 1).

Table 1. Gradation of soil damage levels

Damage level	Repression coefficient value	Repression level characteristics
I	under 20%	Critical damage
II	21-30%	High damage
III	31-40%	Average damage
IV	41-70%	Weak damage
V	over 71%	Fluctuations in the number of microorganisms within statistically acceptable limits

Source: created by the authors

The distribution of soil microbiota damage levels by gradations allows determining both the condition of the original samples of the affected soil and the effectiveness of remediation measures. The comparative method was applied to determine changes in the microbial communities of the affected soils after remediation.

RESULTS AND DISCUSSION

Explosives are known to adversely affect soil microbiota. The widespread use of 2,4,6-trinitrotoluene, the primary component of explosives, pollutes the environment and causes severe harm to human health. For example, TNT in soils inhibits nitrogen fixation, dehydrogenase, and other microbial activity even at low levels of contamination of 10 mg/g (Lamba *et al.*, 2024). It was found that the impact of shell explosions had a considerable negative effect on the counts of microorganisms of the main ecological and functional groups (Table 2).

Table 2. Counts of microorganisms in the soil damaged after explosions and after bioremediation, mn CFU/1 g of absolutely dry soil

Experimental variant	Ammonifying	Pedotrophic	Nitrogen-fixing	Phosphate-mobilising	Oligotrophic	Amylolytic	
						Total	Incl. streptomycetes
Soil from a bomb crater							
Source sample	12.4 ± 1.2	74.6 ± 2.9	3.8 ± 0.7	2.6 ± 0.5	6.4 ± 0.8	6.5 ± 0.8	1.3 ± 0.4
After bioremediation	100 ± 3.3	154 ± 4.3	68.8 ± 2.8	37.8 ± 2.1	67 ± 2.7	118.4 ± 3.6	15.6 ± 1.3
Control intact	14.6 ± 1.2	42.7 ± 2.2	47.4 ± 2.2	2.9 ± 0.6	33.3 ± 1.9	27.5 ± 1.7	19.8 ± 1.5
Soil from an exploded ordnance crater							
Source sample	3.5 ± 0.6	17.0 ± 1.4	2.0 ± 0.3	0.8 ± 0.2	1.2 ± 0.4	0.4 ± 0.2	0.19 ± 0.1
After bioremediation	188.5 ± 4.6	28.5 ± 1.8	41.0 ± 2.1	25.0 ± 1.7	38.4 ± 2.1	32.4 ± 1.8	11.2 ± 1.1
Control intact	14.6 ± 1.3	42.7 ± 2.2	47.4 ± 2.2	9.9 ± 1.0	33.3 ± 1.9	27.5 ± 1.7	19.8 ± 1.4

Source: compiled by the authors

In the soil of the bomb crater, the count of bacteria decreased and was as follows relative to the control: nitrogen-fixing bacteria and streptomycetes, 7% and 8%, respectively, oligotrophic and amylolytic bacteria, 19.2% and 23.6%; phosphate-mobilising bacteria, 26%; the number of pedotrophic and ammonifying microorganisms changed insignificantly. In the soil affected by the explosion of an anti-tank shell, a catastrophic inhibition of the development of amylolytic, phosphate-mobilising, nitrogen-fixing, oligotrophic bacteria, and streptomycetes was recorded; their number was 1.5-10% of the control variant. The number of ammonifying and pedotrophic microorganisms, which was 23.9% and 39.8% of the control values, decreased. According to the findings of the study, the data obtained revealed that the sensitivity of microorganisms to these factors and their ecological functions in the soil were considered to determine bioindicator groups that characterise the impact of explosives. Nitrogen-fixing, phosphate-mobilising bacteria, and streptomycetes were the most sensitive to these stress factors, which shows the sensitivity of these microorganisms to chemical polythenes and high-temperature combustion.

It was argued that nitrogen-fixing bacteria play a major role in optimising the nitrogen regime of soils due to their ability to fix biological nitrogen by binding molecular atmospheric nitrogen into ammonium compounds available to plants (Sharma *et al.*, 2023). Nitrogen is an essential chemical element responsible for photosynthesis and chlorophyll content, synthesis of plastic substances, and overall crop productivity. It was noted that phosphate-mobilising bacteria are a significant ecological and functional group, capable of decomposing hard-to-reach organophosphates using phosphatases. Inorganic phosphates, through the production of organic acids and their conversion into plant-absorbable forms of phosphorus, mobilised it by releasing phosphorus from insoluble and fixed forms in the soil. This resulted in increased availability for plants, changes in the pH of the environment, and the production of chelating substances (Ammar *et al.*, 2023).

It was found that amylolytic microorganisms perform hydrolytic decomposition of carbohydrate components (oligo-, polysaccharides, and starch) contained in plant residues and soil organic matter. These processes result in the transformation of residual carbohydrates, which are subsequently involved in the formation of the aliphatic part of the molecules of humus and humic compounds, thereby increasing soil fertility (Putri & Nakagawa, 2020). Among amylolytic agents, it is important to determine the count of streptomycetes, as this is a common group of mycelial bacteria that perform active functions in the mineralisation and transformation of organic matter due to their ability to synthesise a wide range of enzymes and other biologically active compounds, and play a vital role in the formation of productive microbial-plant systems and increase soil suppression of phytopathogens (Loboda *et al.*, 2024).

According to Table 1, the level of damage to microorganisms of bioindicator groups in the soil of the bomb crater averaged 13.7%; in the soil from the exploded munition crater – 7.3%. These values belonged to the 1st critical level of damage, which indicated an urgent need for reclamation measures. Earlier, the effectiveness of the destruction of toxic organochlorine compounds and the cleanup of contaminated soils using selected microorganisms-destructors was shown (Levchuk *et al.,* 2022). Microorganisms can decompose explosives such as trinitrotoluene. For the bioremediation of the affected soil, microbial preparations based on *D. maris* IMV B-7350, *R. erythropolis* IMV B-7351, *B. subtilis* IMV B-7349, *P. aureofaciens* IMV B-7558, and a metabolic biopreparation based on *S. violaceus* IMV Ac-5027 were used in the samples.

6 months after the application of the biological products, the soil microbiota was repeatedly analysed, focusing on the counts of biodiagnostic groups of microorganisms, according to Table 2. In the soil from the bomb crater, the number of phosphate-mobilising and nitrogen-fixing microorganisms increased and was 1.5-3.8 times greater than in the undamaged control. The number of streptomycetes also increased by 12 times compared to the damaged soil and amounted to 79% of the number in the undamaged control sample. In the soil from the unexploded ordnance crater after bioaugmentation, the number of phosphate-mobilising microorganisms exceeded the value in the undamaged control sample by 2.5 times, the number of streptomycetes and nitrogen fixers increased by 5.9 and 20.5 times, respectively, compared to the damaged soil, and amounted to 57% and 86% of the undamaged control. The study showed that as a result of the application of biological products, the samples can be classified as slightly toxic or non-toxic. The calculation of ecological and physiological indices helped to determine the focus of biochemical processes in the soil and the activity of the microbiota involved in the overall process of decomposition-synthesis of organic matter (Table 3).

Table 3. Ecological indices of microbial communities

Experiment variant	Pedotrophicity index	Oligotrophicity index	Mineralisation-immobilisation index
Soil from a bomb crater			
Source sample	6.0	1.0	0.52
After bioremediation	1.5	0.6	1.18
Control intact	2.9	1.2	2.0
Soil from an exploded ordnance crater			
Source sample	4.9	3.0	0.1
After bioremediation	0.2	1.2	0.2
Control intact	2.9	1.2	2.0

Source: calculated by the authors

The pedotrophicity index shows the activity of transformation of water-soluble humus fractions. The oligotrophicity index shows the activity of the oligotrophic part of the soil microbiocenosis; an increase in this index may generally indicate a slowdown in the destruction of organic matter and a decrease in the content of nutrients in the soil. The mineralisation-immobilisation index shows how actively the processes of decomposition of soil organic matter are taking place (increase in the coefficient) or, conversely, the incorporation of organic matter into biological assimilation and a decrease in its mobility (decrease in the coefficient) (Demyanyuk *et* *al.*, 2020). Under the conditions of this experiment, the initial samples of the damaged soil were characterised by the highest pedotrophicity indices, which, combined with high oligotrophicity indices, showed the danger of humus compounds destruction. After bioremediation, both indices decreased simultaneously with an increase in the immobilisation index, which indirectly indicated positive changes in the focus of biochemical processes involved in the preservation of soil organic matter. The positive effect of bioaugmentation can also be explained by the fact that the use of microbial preparations, apart from introducing beneficial microorganisms into the soil, provides it with biologically active substances synthesised by introduced producers, which activates the native microbiota.

The experience of the First and Second World Wars, the hostilities in Vietnam and Myanmar, and the civil war in Yugoslavia showed that military operations cause severe damage to soils, disturbing the topsoil and subsoil layers, and polluting with toxic heavy metals and explosives (Appau *et al.*, 2021; Shukla *et al.*, 2023). The self-restoration of damaged soils is extremely slow, and even today, European soils where hostilities were fought in the First World War contain toxic heavy metals in levels hundreds of times greater than the permissible levels. Thus, there is a necessity for bioremediation measures. This is especially true for Ukraine's fertile soils. Analysts emphasise that the Russian-Ukrainian war has far-reaching adverse effects on the interconnected systems of food production, energy supply, and the overall ecosystem (Chowdhury *et al.*, 2023).

The use of microorganisms to clean soils from heavy metals, pesticides, and industrial pollution is an effective and environmentally safe measure, since the relevant microorganisms present in contaminated soils are resistant to and capable of degrading pollutants (Tufail *et al.*, 2022, Sarker *et al.*, 2023). This approach is quite reasonable and effective, which has been proven by the findings of studies on the isolation of active organochlorine degraders from a toxic waste landfill near the city of Kalush. Microbial bioremediation using selected active microbial degraders has been successfully used to remediate soil from pesticides, organic contaminants, explosives, and radioactive residues (Gupta *et al.*, 2020).

The successful use of microorganisms for explosives remediation is known, specifically the use of micromycetes for mycoremediation. The biotransformation of explosives in soil by the fungus *Phanerochaete chrysosporium* near an army ammunition depot (USA, Oregon) was effective, and strains of *Mucor* sp. T1-1 and *Aspergillus niger* N2-2 degraded trinitrotoluene by 70-100% in dark and red soils (USA, Georgia, USA) (Geris *et al.*, 2024). However, micromycetes require the development of special biotechnologies for cultivation under industrial conditions to produce the necessary volumes of biomass sufficient for practical use. Furthermore, some species of aspergillus fungi recommended for remediation may not meet toxicological and hygienic requirements, as bacterial strains are more promising.

Among prokaryotic microorganisms, particularly non-spore-forming bacteria, explosive destructors are also being searched for to bioremediate militarily disturbed soils. For example, 41 strains of bacteria, 14 strains of microscopic fungi, and 3 strains of yeast were isolated from soil from explosive testing sites, and their ability to degrade TNT was established in experiments where degrading microorganisms used these toxicants as the sole source of carbon (C) and nitrogen (N) (Kvesitadze & Khatisashvili, 2023). These microorganisms were characterised by the presence of a highly active enzyme, nitroreductase, which catalyses the primary conversion reactions of TNT and hexogen, reducing their toxicity and increasing the water solubility of explosives (Tauqueer *et al.*, 2021). The experiments of these researchers showed that the native soil microflora is capable of decomposing TNT by 30% under optimum humidity and temperature conditions, while the introduction of microbial degraders further increases the level of destruction by another 25-30%. The greatest effect was achieved with the introduction of *Pseudomonas* sp. TNT-44 and *Rhodococcus* sp. TNT-74 strains into the soil, which contributed to the 70-75% remediation. However, the researchers do not provide data on how the state of the soil microbiota changed under the influence of these measures. The complete mineralisation of explosives, primarily TNT, through bacterial degradation as an effective method of remediation of contaminated areas is of great research interest. Biological treatment of contaminated soil is an effective and economical method of complete mineralisation of TNT and reduction of the total amount of intermediate products formed at the following stages (Serrano-González *et al*., 2018; Xu *et al*., 2021). Several bioremediation technologies are used to remove or stabilise contaminants from a contaminated environment by applying bioremediation at the site of contamination – so-called *in situ* bioremediation – or by transferring contaminated material (e.g., soil) to a remote treatment facility – *ex situ* methodology. *In situ* processes include biosparging, biostimulation, bioaugmentation, bioventilation, natural attenuation, bioleaching, bioremediation, phytoremediation, while *ex situ* methods include bioburial, composting, agriculture, biofilters, and bioreactors. Among the above methods, according to the findings of the present study, the most affordable and low-cost is bioaugmentation, which is characterised by the use of microorganisms that are environmentally friendly, have pronounced biodegrading activity, are resistant to high concentrations of pollutant, and do not have undesirable side effects (Bala *et al*., 2022).

The bioaugmentation of soils contaminated with polychlorinated dibenzo-p-dioxins and dibenzofurans using the micromycetes *Stropharia rugosoannulata* or *Phanerochaete velutina* can reach 62-64% of the initial concentration of pollutants (Kvesitadze & Khatisashvili, 2023). Thus, microorganisms are considered as one of the biological agents that perform remediation (Bala *et al*., 2022). However, despite the general approaches, the use of bioaugmentation requires correction considering the specifics and degree of contamination, characteristics of the native microbiota, and soil and climatic conditions. That is why this study was conducted, which showed the positive effect of the bioaugmentation used in the study – the introduction of a consortium of microorganisms that decompose contaminants and reduce their adverse effects on biota: it activated native soil microorganisms and facilitated the purification process. Based on the data obtained, it was argued that the introduced microorganisms initiate degradation processes, which are subsequently performed not only by the introduced strains, but also by the native microbiota. The involvement of soil microbiocenoses in the remediation of contaminated soils has not been sufficiently covered in the literature and requires more extensive research. The effectiveness of the applied biological products in the study was confirmed by the improvement of biodiagnostic indicators of soil biota.

CONCLUSIONS

Considering the extensive destruction of arable land in Ukraine as a result of military impact and the necessity of determining the state of their damage, diagnostic indicators for characterising soil microbiota were substantiated and systematised. Summarising the diagnostics of the state of microbial communities of the soil affected by military actions, the counts of the main ecological and functional groups were determined. In the epicentre of the explosion, compared to relative controls outside the affected area, a sharp decrease in the count of prokaryotes involved in the transformation of nitrogen, phosphorus, and soil organic matter was found. In monitoring the military impact on microbiocenoses, it was proposed to use the number of the most sensitive groups – nitrogen-fixing and phosphate-mobilising bacteria and streptomycetes – as biodiagnostic indicators, and to calculate the indices of mineralisation/immobilisation, oligotrophicity, and pedotrophicity, which characterise the focus of microbial processes. Gradations of five levels of damage (from critical to weak) to the soil microbiota were developed, based on the determination of the repression of each of the bioindicator groups of microorganisms. The prospects of using the bioaugmentation method of biological products based on bacteria capable of degrading toxic substances and increasing the adaptive potential of plants to stress factors were proved. These measures showed a substantial activation of soil microbial communities, which was confirmed by an increase in the count of agronomically useful groups of microorganisms. Based on the findings, it was concluded that the bioremediation measure is effective for restoring microbial communities in the soil damaged by military operations.

The prospect of this study and further case studies is to include microbiological monitoring in the state system of environmental monitoring of militarily disturbed soils. Further development of measures to restore the affected soils involves identifying those microbial agents that form the most active microbial-plant systems in complex biological products, considering the specifics and degree of soil damage, as well as identifying resistant crops for use in integrated phyto-microbial bioremediation. A necessary stage of integrated research is the correction of the soil nutritional regime and its humus state. The body of such research will serve as a basis for developing measures to restore soils damaged by military operations in production conditions.

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CONFLICT OF INTEREST

None.

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Діагностика і біоремедіація ґрунтів, постраждалих внаслідок воєнних дій в Україні

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Анотація. Внаслідок повномасштабного вторгнення значні площі агроекосистем постраждали через пошкодження токсичними речовинами, що зробило актуальним питання відновлення ушкоджених земель шляхом деструкції полютантів. Метою дослідження було обґрунтувати і систематизувати діагностичні показники для характеристики біоактивності ґрунтів та розробити наукові підходи до біоремедіації пошкоджених земель. Використано метод аналізу існуючих підходів для вирішення задач, метод порівняння даних чисельності мікроорганізмів основних еколого-функціональних груп, яку було визначено за методикою посіву ґрунтових суспензій на агаризовані поживні середовища. Розраховано індекси спрямованості мікробних процесів. Біоремедіаційні заходи вносили в ґрунт мікробну біомасу і культуральні рідини: *Dietzia maris* IMB B-7350, *Rhodococcus erythropolis* IMB B-7351, *Bacilus subtilis* IMB B-7349, *Pseudomonas aureofaciens* IMB B-7558 і *Streptomyces violaceus* IMB Ac-5027. Отримані результати дослідження показали, що рівень репресії мікробіоти у ґрунті, постраждалому після вибухів, був надзвичайно високим, порівняно з неушкодженим. Найбільш чутливими були фосфатмобілізувальні, азотфіксувальні, амілолітичні (у т.ч. стрептоміцети) мікроорганізми. У ґрунті з вирви від бомби чисельність азотфіксаторів і стрептоміцетів становила 7 % і 8 % відповідно від контролю, оліготрофних і амілолітичних – 19,2 % і 23,6 %; фосфатмобілізувальних – 26 %. У ґрунті, пошкодженому від вибуху протитанкового снаряду чисельність амілолітиків, фосфатмобілізаторів, азотфіксаторів, оліготрофів і стрептоміцетів становила 1,5 %-10 % від контрольного ґрунту. Через 6 місяців після біоремедіації ґрунту проведено повторний аналіз мікробіоти. У ґрунті із вирви від бомби кількість фосфатмобілізувальних і азотфіксувальних мікроорганізмів зросла і була вищою, ніж у неушкодженому контролі у 1,5-3,8 рази, чисельність стрептоміцетів підвищилась у 12 разів порівняно з ушкодженим ґрунтом. У ґрунті із воронки розірваного боєприпасу кількість фосфатмобілізаторів була у 2,5 рази більшою порівняно з контролем, чисельність стрептоміцетів і азотфіксаторів зросла у 5,9 і 20,5 разів відповідно порівняно з ушкодженим ґрунтом. Після біоремедіаційних заходів, досліджувані зразки ґрунту можна віднести до слаботоксичних, або нетоксичних. Практична цінність роботи полягає в ефективності запропонованого біоремедіаційного підходу, який є важливим для подальшої розробки комплексу заходів з відновлення грунтів в умовах руйнування агроекосистеми України

Ключові слова: мілітарний вплив; пошкодження; відновлення; біопрепарати; біологічна активність; ґрунтова мікробіота