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# PHYTOREMEDIATION AS A FRUGAL MECHANISM FOR RECOVERY OF TRANSFORMED SOIL AS A RESULT OF COMBAT OPERATIONS

**Svitlana Kovtun-Vodyanytska<sup>1</sup>, Dzhamal Rakhmetov<sup>2</sup>**

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**1.** PhD of Biological Sciences, Senior Researcher*M. M. Gryshko National Botanical Garden of the NAS of Ukraine, Kyiv, UKRAINE***ORCID ID: 0000-0002-2367-461X****2.** Corresponding Member of the National Academy of Sciences of Ukraine, Professor*M. M. Gryshko National Botanical Garden of the NAS of Ukraine, Kyiv, UKRAINE***ORCID ID: 0000-0001-7260-3263**

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## INTRODUCTION

In war zones, both active and inactive, natural ecosystems suffer significant damage. The use or testing of weapons, the dropping of bombs, shooting, etc., lead to contamination of air, water, and soil with various explosives and heavy metals. The problem of complex soil pollution as a result of military operations is extremely relevant for Ukraine. The use of various weapons in the Russian-Ukrainian war, which has been ongoing since 2014, has led to significant soil changes. These changes include changes in the physical and mechanical properties of the soil, its structure, chemical balance, nutrient cycling, the presence and composition of microorganisms, and water-holding capacity, which have also impacted groundwater. Therefore, the search for mechanisms, methods, and techniques for soil improvement and post-war recovery is highly relevant for the Ukrainian people.

## MAIN PART

Combat operations involve the use of various types of weapons and military equipment, which leads to:

- chemical pollution – combustion gases, residual unburned particles, exhaust gases, lubricants, heavy metals, petroleum products, tungsten, tungsten carbide, and heavy alloys;
- physical pollution – thermal, acoustic, vibration, and light;
- mechanical pollution – shrapnel, shells, casings, soil erosion from explosions, movement, and storage, as well as compaction.

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All of this has very negative consequences and long-term effects. For example, artillery shells contain carbon monoxide, carbon dioxide, brown gas, nitrous oxide, nitrogen dioxide, formaldehyde, and cyanide vapors, while ammunition contains lead, TNT, mercury, and arsenic. The detonation of high-explosive and armor-piercing shells releases heavy metals, fuels, and chemical agents. Depending on the type of ammunition, each shell contains 7-35% explosive [16].

During explosions, soil horizons and their sequence are destroyed, which changes the water-air regime. Damage to armored vehicles and tanks leads to the release of gasoline, diesel fuel, and gas into the soil [4]. The constant release of heavy metals into the soil creates zones of increased toxicity, within which the nature of the spontaneous migration of soil substances and some geochemical parameters change. Up to 30-40% of heavy metals and their derivatives also migrate from the soil to groundwater [8].

The most common secondary explosives and heavy metals that pollute soil include TNT (2,4,6-trinitrotoluene), hexogen, octogen, and lead, cadmium, mercury, zinc. TNT is extremely toxic to animals and moderately toxic to plants [18]. In soil, TNT decomposes and forms toxic compounds, causing significant environment damage [10]. Exposure to TNT causes liver damage and significant changes in the hematopoietic system, leading to anemia [19]. It negatively affects on red blood cells, liver function, and the lens of the eye. There are known cases of death from toxic hepatitis and aplastic anemia caused by the harmful effects of TNT [6]. TNT can penetrate the human body through the skin. When heated, it releases toxic fumes and accumulates in most soils. The presence of TNT in sandy soil, which is characterized by a minimal amount of organic matter, increases the risk of its migration to surface waters. According to experts from the Environmental Protection Agency (USA EPA), the TNT concentration level in soil at which land plots should be assessed for chemical contamination is  $1.3 \times 10^{-2}$  µg/kg. TNT content in water is classified according to the degree of its danger to humans as follows: for a carcinogenic risk, the concentration should be  $3 \times 10^{-2}$  µg/kg per day; the risk to human health from consuming one unit of drinking water is  $9 \times 10^{-7}$  µg/L; the minimum risk level (MRL) for oral exposure is 0.0005 µg/kg per day over an average 24-hour period [5].

Heavy metals that pollute soil during military operations include lead, cadmium, mercury, zinc, and others. Mixtures of lead and cadmium are significantly more toxic than other heavy metals. Depending on the degree of potential adverse effects on living organisms and the environment, heavy metals are divided into three classes: highly hazardous – arsenic, cadmium, mercury, selenium, lead, zinc, and fluorine; hazardous – boron, cobalt, nickel, molybdenum, antimony, and chromium; and low-hazard-barium, vanadium, manganese, and strontium [8].

Lead exists as insoluble forms  $PbCO_3$  or  $PbS(NO_4)_2$  and has low mobility in soil. These forms can be converted from insoluble to soluble by soil acidification [3; 9]. Mercury is a heavy metal used in weapons, primarily in detonators to accelerate the detonation of explosives. Its harmful effects on the human body include damage to nerve cells and can cause birth defects in unborn children. Lead also has a similar effect on the fetus, potentially causing miscarriage [18].

Experts distinguish several levels of damage to land as a result of military action. The degree of contamination depends on the number of explosions, the depth of detonation, and the release of certain explosives used in munitions. Possible restoration tools for low- or moderate-level damage include remediation measures, particularly through biological remediation technologies such as phytoremediation. If damage is catastrophic, with 75-100% of the area severely impacted, the optimal mitigation method is conservation and expected natural recovery [20].

Today, phytoremediation is a natural biotechnological method that provides a basis for the remediation of contaminated sites. It is an environmentally friendly and less expensive alternative to physical and chemical methods [2].

The term «phytoremediation» is based on two languages: the Greek «phyton» (plant) and the Latin «remediare» (recovery, correction, removal of evil), meaning the assistance of plant organisms in the cleansing and restoration of soils.

Remediation of soils contaminated with metals and explosives mainly focuses on the removal, stabilization, or detoxification of pollutants. This approach is environmentally friendly, sustainable, safe, non-invasive, and effective in recovering contaminated soils, while also being low-cost and causing minimal environmental disruption. It is often referred to as «green remediation» or «botanical remediation» [9; 12].

Phytoremediation is an effective, green, and environmentally friendly method, the success of which is determined by the selection of an appropriate plant species. Removing metal contaminants not only cleanses the soil, but also affects planet's biota, which are interconnected through the food chain [15].

Successful phytoremediation requires consideration of natural factors such as soil type, pH, moisture, and climate, as well as the factors affecting the selected site. This ensures the selection appropriate plant species and their sustainable integration into the local ecosystem [12].

Initial pilot experiments in laboratory and field conditions are assessing plant tolerance and the ability to accumulate certain elements for further large-scale studies [1].

The process of heavy metal accumulation in plants involves several stages. Initially, metals are absorbed by the root surface and enter the cells passively or



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actively. Subsequently, in the root cells, the metals form complexes with so-called chelators – organic substances that combine with metal ions to form stable complex compounds called chelates, which are sequestered in cell walls or vacuoles and have higher bioavailability. In other words, metals in the accumulating plant undergo a process of mobilization, absorption, transport, and sequestration. Organic chelators include acetic, malic, citric, and oxalic acids, which undergo organic decomposition, making them environmentally friendly. Throughout this chain of processes, the high mobility of chelators in the soil must be taken into account, as this can lead to excessive metal absorption and phytotoxicity [1].

Phytoremediation uses plants that are able to grow in polluted environment and influence biological, chemical, and physical processes, triggering effective remediation. Currently, approximately 400 taxa of metal-accumulating plants are known, capable of concentrating hundreds and thousands of times higher amounts of metals in their tissues than other plants, thereby accelerating soil remediation. The largest number of potential plants for phytoremediation belong to the families Brassicaceae, Poaceae, Lamiaceae, Asteraceae, Geraniaceae, Fabaceae, Violaceae, and Cyperaceae. The plant species selected for phytoremediation must meet certain characteristics, namely: have an increased metabolism, high level of reclamation, high tolerance to waterlogging, resistance to soil pH and salinity, as well as the ability to immobilize various metal pollutants [7; 11; 13-15, 17].

### CONCLUSION

Thus, the post-war recovery of Ukrainian soils, negatively transformed by military action, is a highly pressing issue. It already requires a well-developed theoretical and methodological basis for practical implementation. The economic efficiency and environmental friendliness of phytoremediation give hope for the remediation of some soils through the use of plants and their ability to accumulate harmful substances and heavy metals. Analysis of global research on this topic and practical testing will help determine optimal measures to improve soil condition and maximize their recovery.

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