A Portfolio of Nature-based Remediation Methods for a Climate-smart Recovery of Agriculture on Demined Land in Ukraine

Master's thesis in Infrastructure and Environmental Engineering

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Cover: The cover picture shows agricultural farmland in Ukraine before the 2022 invasion.
Photo Source: https://www.dreamstime.com/illustration/ukrainian-farming.html
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Abstract

The continuing war in Ukraine has resulted in widespread pollution of agricultural soils owing to military actions such as the discharge of heavy metals and explosive residues. These toxins pose serious threats to agricultural production, food security, ecosystem functioning, and human health. Because of the large area of contaminated land, traditional remediation methods such as excavation and disposal are often economically and technically challenging. Nature-based solutions (NbS) offer a long-term option for repairing polluted agricultural soils while also promoting climate-smart recovery.

This thesis aims to develop a portfolio of nature-based remediation technologies suited to addressing large-scale soil pollution caused by heavy metals and explosive residues on demined agricultural land in Ukraine. The study focuses on analyzing the chemical remediation potential of NbS, including their methods, benefits, limits, and application under Ukrainian environmental conditions.

A systematic literature review was conducted using the PRISMA approach, and studies were located using the Scopus database. The remediation methods examined included phytoremediation, bioremediation, biosorption, and soil amendments. The studies were chosen based on their pollutant type, remediation performance, relevance to agricultural soils, environmental sustainability, scalability, and Technology Readiness Level (TRL). Laboratory and greenhouse studies were classified as low technology readiness levels (TRL 3-4), while pilot-scale and field investigations were classified as high readiness levels (TRL 5-6) because they are more relevant to practical application.

The findings showed that phytoremediation and soil amendment techniques have significant promise for large-scale agricultural restoration. Phytostabilisation and phytoexclusion were especially effective at reducing contaminant mobility and preventing transfer into the food chain, while phytoextraction showed potential for progressive contaminant removal in moderately polluted regions. Bioremediation has shown promise for explosive-contaminated hotspots via microbial degradation mechanisms. However, biosorption remains limited for agricultural soil applications because most studies are laboratory-based and aqueous.

The research found that no single remediation strategy can address all pollution issues in war-affected agricultural soils. Integrated techniques that include phytoremediation, soil amendments, and bioremediation are the most effective way to achieve long-term restoration. However, doubts persist due to a lack of field-scale research in Ukrainian circumstances, seasonal climatic fluctuation, and discrepancies between laboratory trials and real-world

agricultural situations.

This thesis presents a decision-support portfolio of nature-based remediation options to guide future restoration efforts for polluted agricultural land in Ukraine, as well as a contribution to long-term environmental recovery after the conflict.

Keywords: Ukraine; contaminated agricultural soils; heavy metals; explosive residues; nature-based solutions; soil remediation; phytoremediation; bioremediation; soil amendments; PRISMA;

Statement on the use of AI: Grammarly was utilized as a writing and language editing tool to enhance the content of this thesis, such as grammar, spelling, punctuation, sentence structure, and readability. The author retains responsibility for the scientific content, analysis, interpretation, and conclusions expressed in this thesis.

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1. Introduction

The following sections of this chapter provide an overview of the scope of the report and outline its aim and objectives and limitations.

1.2 Background

Ukraine, a country in Eastern Europe, is one of the world's largest agricultural nations due to its fertile black soil, known as chernozem, and its high organic matter content, both of which are vital to its status as a major producer and exporter of grain and oilseed products. Before the 2022 invasion, half of the land was used for agriculture, given Ukraine's favourable climate conditions. (**Y. Li et al., 2026**). Although Ukraine still has a significant impact on the global food chain, 34% of arable land (ca 6 million hectares) is affected by the war and is inaccessible for sowing, reducing grain exports and the agricultural sector's annual revenue (**Y. Li et al., 2026**). However, due to ongoing full-scale conflicts commencing in February 2022, most soil properties have been significantly affected by intensive military activities, causing physical, chemical, and biological destruction of soils and thereby reducing the land available for agriculture (**Pereira et al., 2022**).

As the full-scale of Russia`s invasion of Ukraine continues, the Ukrainian government and farmers are faced with a major and complex challenge of landmine and explosive remnants of war (ERW) contamination on agricultural land. As a result, Ukraine is now classified as the country with the most mines in the world as of 2023. The exact amount of time required to demine affected areas remains unknown, but with adequate funding, equipment, and trained personnel, the time needed could range from decades to hundreds of years. Furthermore, Ukraine has gone from being classified as “heavily contaminated” to “massively contaminated”, and the full extent of contamination across the country is not yet known, including territories occupied by Russian forces (**Curtis and Welsh et al., 2024**)

Armed conflict has a variety of severe consequences for soil health. Physical disturbances such as trenches, explosions, cratering, and vehicle movements damage soil structure and raise erosion risk. Furthermore, heavy metals, explosive residues, and petroleum derivatives deposited by shell fragments, burned armored vehicles, military equipment and debris, and fuel spills affect soil chemistry, posing long-term environmental and health risks. Recent studies have found increasing levels of pollutants in soil damaged by military operations, along with reduced biological activity and soil quality indices (**Solokha et al., 2023**) (**Bonchkovskyi et al., 2025**). These degradation processes reduce soil fertility, potentially limiting long-term agricultural production without focused restoration of soils’ physical, chemical, and biological properties.

The extent of soil pollution is a challenge Ukraine should not solve on its own. At the rupture site, the concentration of titanium exceeded the threshold limit values (TLV) more than 150 times. Moreover, metals such as vanadium, lead, and cadmium accumulated in the soil from military activities also exceeded the threshold limit values. In addition to this pollution problem, the soil is degraded and compacted, leading to losses of humus and water content, as well as increased wind erosion (**Novakovska et al., 2025**). The war-affected agricultural land requires a need-based remediation method capable of addressing risks posed by soil contamination and evaluating land suitability.

Nature-based solutions (NbS) for soil remediation can mitigate hazards to human health and the environment while enhancing soil health, i.e., the ability of soil to deliver ecosystem services. NbS are actions to protect, sustainably manage, and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits (International Union for Conservation of Nature (**IUCN, 2020**). Moreover, NbS for soil remediation are low-input and cost-effective technologies, inevitable for addressing shallow contamination in soils across large areas (**Chowdhury, 2022**).

The investigation of these solutions is therefore significant from technological, economic, and political perspectives. The quick repair of farmland is also important for Ukraine's economy to get agricultural fields back into productive use for food production to continue. The issue is also significant globally, as the widespread pollution of agricultural land elsewhere necessitates the use of NbS to counteract this environmental concern across large areas while providing both human well-being and biodiversity benefits (**Backman et al., 2025; Song et al., 2019**)

1.3 Aim and objectives

This thesis work aims to develop a portfolio of NbS for soil remediation that offers a sustainable and practical approach to managing large-scale soil contamination caused by metall(oid)s' and explosives' residuals after the military operation, in order to facilitate climate-smart recovery of agriculture on demined land in Ukraine.

The objectives to reach this aim are:

- Perform a systematic literature review to complement studies on NbS that were recently found suitable for Ukraine.
- Describe main mechanisms, strengths and limitations of each NbS suitable for Ukraine's environmental concerns due to war-induced pollution.
- Assess the suitability of the identified complementary NbS for Ukrainian conditions.

1.4 Scope and limitations

1.4.1. Scope

This thesis examines nature-based remediation options to mitigate metal and explosive contamination in post-conflict agricultural soils, with a case study in Ukraine. The research focuses on pollutants often associated with military operations, namely hazardous metals (e.g., lead, cadmium, copper, zinc) and explosive remnants of war (ERW), such as TNT, RDX, and HMX. The study employs a systematic literature review, using the Scopus database to identify relevant peer-reviewed research. The analysis focuses on nature-based remediation techniques, including Phytoremediation (phytoextraction, phytoexclusion, and phytostabilization), Soil amendments (e.g., biochar, compost), Biodegradation, phytodegradation, and rhizoremediation of explosive pollutants.

The geographical focus is on post-demining agricultural land in Ukraine, specifically regions affected by recent military conflict. However, owing to the restricted availability of site-specific studies, the research further integrates findings from secondary sources, such as previous theses conducted at Chalmers University of Technology (**Menson et al., 2023; Backman et al., 2025**), and literature to bolster the universality of remediation strategies. The research advances an evaluative decision-support portfolio to analyze remediation solutions against criteria including efficacy, practicality, scalability, environmental impact, and appropriateness for agricultural reuse. The master's thesis project is conducted as a requirement for the Master's Program in Infrastructure and Environmental Engineering at Chalmers University of Technology.

1.4.2. Limitations

The study has some limitations, even though it contains some important information about nature-based remediation methods and their applications.

- It only uses secondary data from published literature from Scopus and previous theses, and does not include field tests or primary data, which might change the results.

- The emphasis on Ukraine is constrained by the lack of peer-reviewed research addressing pollution in its agricultural soils, particularly with explosive residues, which compels dependence on worldwide literature that may not correctly represent local realities.

- It is hard to evaluate integrated remediation techniques well because post-conflict pollution is so complicated, with metals and explosive remnants living together.

- Nature-based remedies also sometimes take a long time to show results, and this study looks at their effectiveness based on what has been written about them instead of long-term testing, which makes it unclear how they will be used.

2. Theoretical background

This chapter provides information about contaminant interaction and describes remediation mechanisms, as well as strengths and limitations for nature-based solutions (NbS) which are suitable for Ukraine's environmental concerns.

2.1 Risks: Source- Pathway-Receptor Linkages

Contaminated agricultural soil containing metals and explosives originating from military activities such as bombs, mines, burning buildings, fuel leakage, and the detonation of grenades, tanks, and other military equipment poses a potential risk to the environment and public health. These post-war activities result from the leaching of toxic metals and explosive compounds into the soil. **(Bonchkovskyi et al., 2025; Alloway, 2013)**. The contaminants associated with military activities in soil, surface water, and groundwater are recalcitrant in nature and have a negative impact on human health and the environment due to their toxicity effect. The method of assessing risk at a contaminated site can differ significantly depending on human health risk or ecological risk. **(Broomandi et al., 2020)**.

In general, risks at a contaminated site can be assessed through the source-pathways-receptor (S-P-R) concept, which can also be referred to as ‘contaminant linkages'. As reported by

(**Swartjes, 2011**; **Drenning, 2021**, not all contaminated sites are associated with risk, but risk should be considered when there is a source (contaminant), a receptor such as humans, animals, or surface and groundwater, and an exposure pathway connecting both the source and the receptor. There are several transfer pathways through which the receptor can generally be exposed to soil contamination, in which humans as a receptor hold significant importance in the assessment of risk management. Some exposure pathways identified by (**Swartjes, 2011**; **Drenning, 2021** are as follows: direct contact with contaminated soil through ingestion of polluted soil, inhalation of dust or vapor, and dermal contact, 2) through consumption of food from polluted sites (vegetables, poultry, meat, fish etc.), and intake of drinking water originating from contaminated sites.

Sometimes, risk may be classified as high or low based on the contaminant concentration that reaches the receptor, which can either be the environment or people. In some circumstances, low risk can be dangerous when a person is exposed to persistent contaminants whose concentration increases over a considerable period (**Swartjes, 2011**). Figure 2-1 shows the source-pathways- receptor risks flow chart.

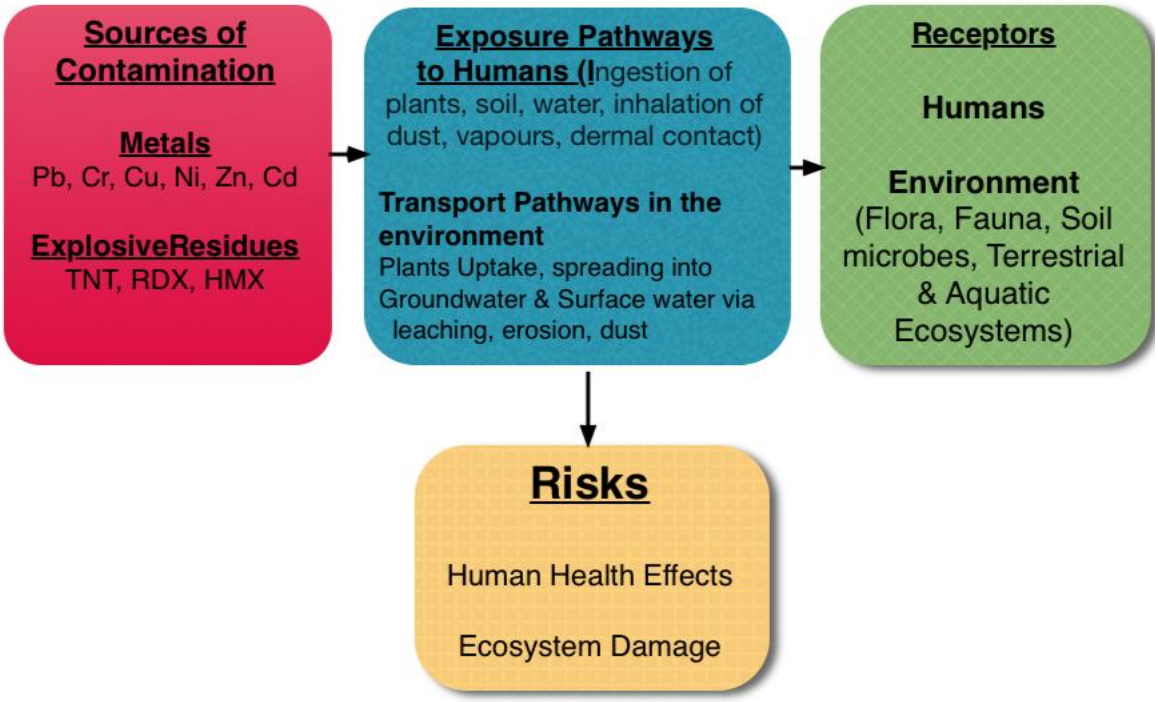


Figure 2-1: illustrates the source-pathways-receptor risks flow chart

2.2 Pathways of metals and explosives in soil

Heavy metal (HM) pollution in soil is a global concern, posing a serious threat to agricultural production. Excessive increase of HM concentration in soil not only affects human health but also has a detrimental effect on crop production and safety, and the soil ecosystem. The immobilization and pathways of HM in the soil setting are heavily dependent on their interactions with solid soil components, including clay minerals, organic matter, and subsequently microorganisms. (**Q. Li et al., 2022**; **Jayakumar et al., 2021**)

Metals such as Pb, Cd, and As can persist in ecosystems due to a variety of environmental factors that control their mobility. These metals link with humic material and are firmly bound to soil clay minerals, restricting their short-term mobility. The mobility and stability of these pollutants are influenced by sorption-desorption processes as well as soil pH, organic matter content, redox conditions, and clay concentration. The transport pathways of HM in soil include advection, diffusion, dispersion, preferential flow, and colloid-facilitated transport (**Mustapha et al., 2026a**; **Ramos-Romero et al., 2026**; **Rammal et al., 2025**).

There are many ways through which contaminants are transported to the soil. Agricultural land can be affected by military activities, resulting in contamination by both heavy metals and explosives. TNT, RDX, and HMX, which are high-energy ring compounds and are therefore considered potent explosives and energy sources. (**Corredor et al., 2024a**). For example, TNT is a nitroaromatic compound having both hydrophobic and hydrophilic properties, preventing it from being fully sorbed to organic particles in the soil and sediment. This compound has low vapor pressure and a low Henry's Law constant, which makes it produce nitro-reduction products such as 2,4-diamino-6-nitrotoluene.

In contrast to metals, explosives are degradable. TNT degradation pathways in soils occur through the metabolic pathways of microbes under aerobic or anaerobic conditions **(M. I. Khan et al., 2013**). Compared to TNT, RDX is more complex and more resistant due to its aromatic ring, which includes cleavable nitro groups, boosting its stability and energy when deflagrated. The toxicity of this compound can lead to microbial proliferation, metabolic alterations, and environmental stress in the soil (Ibid.). RDX can be broken down into 4-nitro-2,4-diazabutanal (NDAB) through the processes of aerobic degradation and alkaline oxidation.

HMX, on the other hand, when degraded, produces highly toxic nitrogen compounds such as (n-hdroxymethyl-methylene-dinitramine and methylene-dinitroamine). These compounds disrupt genes involved in amino acid biosynthesis and several metabolic pathways, which are very crucial for withstanding abiotic stress and reducing toxicity (**Corredor et al., 2024a**). The transport of explosives is largely dependent on factors such as the main processes of dissolution, volatilization, and adsorption, and some factors, like the main processes of photolysis, reduction, hydrolysis, and biological degradation, are factors responsible for the transformation of explosive compounds **(Broomandi et al., 2020)**.

2.3. Bioavailability of metals and explosives

Bioavailability is the proportion of a contaminant that crosses the cell membrane and is strongly influenced by its binding strength to the solid matrix in soil **(Swartjes, 2011)**. This binding can intensify over time through a process termed aging. When pollutants penetrate soil, they remain attached and become enclosed within organic matter in micropores, rendering them less available for uptake by an organism. The duration of this aging process varies across compounds and soil types, yet it is often shorter than the degradation period of pollutants. Understanding this process is essential for assessing the duration of pollutant release and its bioavailability, as well as determining when its concentrations are sufficiently low to mitigate risk. (**Backman et al., 2025**).

Bound pollutants remain bioinactive until liberated, and diminished bioavailability may result in elevated amounts subsequently, hindering extraction and degradation remediation mechanisms, but, at the same time, reducing the risk of contaminants entering a system of an organism. However, a high correlation can be observed for uptake by e.g. earthworms **(Enell et al., 2025)**. Furthermore, the bioavailability of heavy metals and organic compounds is a major concern due to their exposure pathways to humans and increasing health risks. The bioavailability of these pollutants is influenced by a variety of parameters, including climate conditions, transfer processes, sequestration and speciation, redox potential, and plants, animals, and microbes' responses to seasonal cycles (**Hlihor et al., 2017**).

The amount of metals available in porewater can be taken up by the receptor organisms in the soil. Plants can accumulate metals in their tissue only if they are bioavailable in soil, which depends on how long the metals remain in the soil and on their interactions with other solid components in the growth medium. Plants alter the soil by providing physicochemical and biodegradable elements that can increase metal mobility and thus their availability in soils (**S. Khan et al., 2023**). The main factors influencing heavy metal speciation and potential bioavailability are their ability to bind to soil solids, their presence in ionic states in soil fluids, and their adsorption onto the surfaces of soil clay minerals, organic matter, microbes, and their associated complexes. Furthermore, precipitation and chelation with different minerals and organic matter molecules are significant and necessary for metal speciation and their potential bioavailability (**Q. Li et al., 2022**).

According to **Fernandez-Lopez et al., 2022**, the bioavailability of organic pollutants is an important topic for research on nature-based remediation, but it is rarely mentioned in association with military activities. The concept of bioavailability regarding risk assessment and monitoring is critical because it evaluates how much contaminant in a polluted soil is available for an organism's uptake, which causes harm to human health and the environment. Although there are beneficial experiences associated with the adoption of bioavailability in risk assessment of metal-contaminated soils and sediments, there is, in contrast, limited studies available for organic compounds, e.g. PAH (**Arp et al, 2015**) and DDT (**Enel et al., 2025**).

2.4. Nature-based solutions

Nature-based Solutions (NbS) are characterized as "actions aimed at protecting, sustainably managing, and restoring natural or modified ecosystems, which effectively and adaptively address societal challenges while concurrently delivering benefits for human well-being and biodiversity" (**Fernandez-Lopez et al., 2022**). In this thesis, the focus is on evaluating a remediation technology for Ukrainian agricultural soils and sediments contaminated by organic and inorganic contaminants from military activities, for a compilation of suitable nature-based solutions capable of remediating the soils in a climate-smart way for sustainable contaminated land management. These solutions are collectively called "Nature-based remediation options" in this thesis. Figure 2-4 shows a set of nature-based remediation options for managing metals and explosive residues in soils.

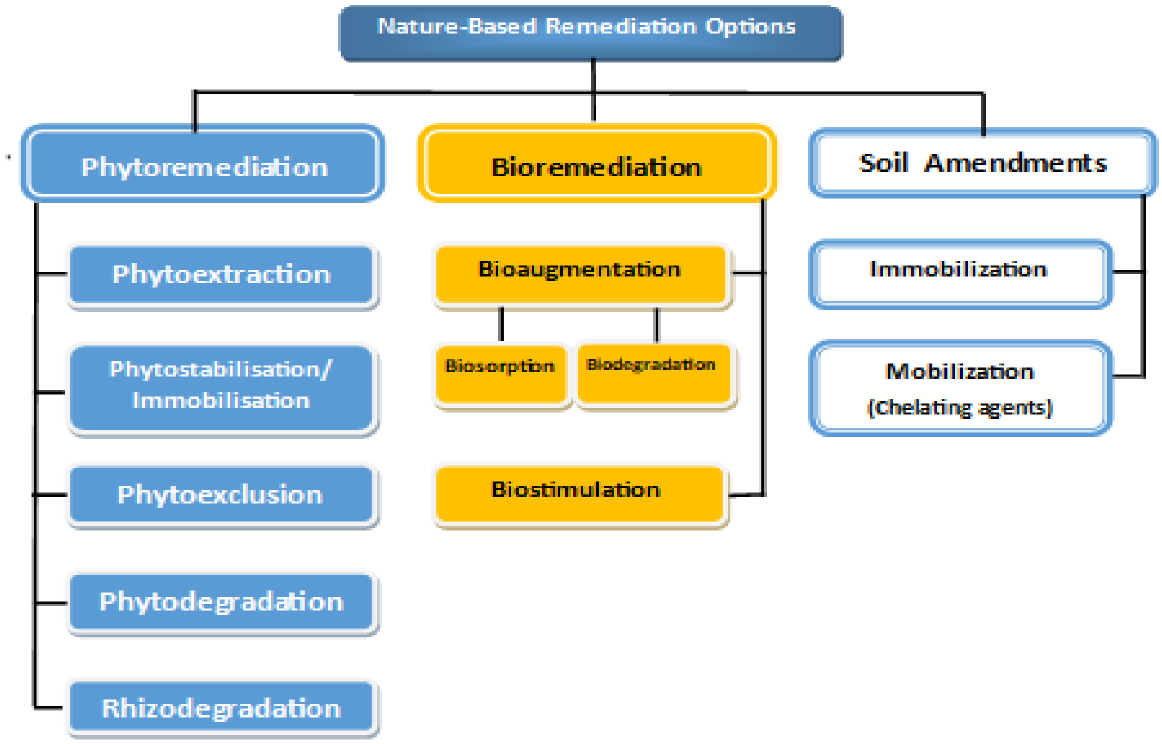


Figure 2-4. Nature-based remediation options for metals and explosives.

Table 2-4. Definitions of nature-based remediation methods used to remediate agricultural soil contaminated from military activities. Sources: (**Cundy et al., 2016; Drenning, 2021**; **Backman et al., 2025**.)

Method	**Definitions**
Phytoextration (metals)	The process that uses plants and microorganisms to accumulate and remove contaminants through harvesting the aboveground biomass with accumulated soil contaminants.
Phytostabilisation (both metals and organics)	Plants are involved in reducing the bioavailability and movement of contaminants through immobilization in their root systems or rhizosphere soil of living or dead biomass.
Phytoexclusion (metals)	The use of excluder plants that exclude uptake of soil contaminants into their aboveground biomass.
Phytodegradation (organics)	The process involves using plants and associated microorganisms, such as rhizosphere and endophytic bacteria, to uptake, store, and degrade organic pollutants within plant tissues.
Rhizodegradation (organics)	The process through which organic pollutants are degraded using plant roots and the associated rhizosphere microorganisms.
Immobilisation/ Stabilisation with soil amendments (both metals and organics)	Use of soil amendments for immobilising contaminants in soil and thus reducing their bioavailability.
Mobilisation with soil amendments (both metals and organics)	Use of chelating agents for mobilising contaminants in soil and thus increasing their bioavailability for increased degradation or uptake.

Bioremediation (both metals and organics)	A generic term used to describe use of microbes for remediation purposes.
Bioremediation by means of bioaugmentation	Introducing new microbes to soils for remediation purposes. Biodegradation (organics): use of bacteria and fungi to degrade various organic pollutants in soils. Biosorption (metals): use of bacteria, fungi, algae, and yeast are used to immobilize various metals in soils.
Bioremediation by means of biostimulation	Stimulating the indigenous microbes in soils using fertilizers or other soil amendments that improve nutrient and water availability in soils. Increased biological activity can lead to higher rates of biodegradation.

2.5. Nature-Based remediation mechanisms for metals

2.5.1. Phytoextraction

Phytoextraction, which can also be called phytoaccumulation, phytoabsorption, or, phytosequestration, is one of the methods of phytoremediation that describes the ability of plants to absorb, accumulate, translocate, and concentrate inorganic soil contaminants from the root system to the shoots and leaves. (**Abdel-Shafy & Mansour, 2018**). The phytoextraction mechanism, as suggested by **Drenning (2021)**, is the ability of plants to function as ''bio-pumps'' to enhance the successful removal of contaminants from the soil and sometimes from the groundwater. These contaminants are stored in the plant's aboveground biomass, which requires harvesting and disposal. This can generate substantial amounts of waste. Compared to soil excavation, the disposing costs of the biomass harvested can still be considered a cheaper alternative.

Phytoextraction mechanism requires three important procedures, which include i) the evaluation and selection of plant species suitable for the contaminated site, ii) harvesting of pollutant-absorbing plants/biomass from the site, and iii) disposing of the harvested plant/biomass for post-treatment through the processes of incineration, landfilling, and composting (**Menson et al., 2023**). Phytoextraction is a technique mainly used in the remediation of soil and sediments contaminated by heavy metals such as (Cadmium (Cd), Nickel (Ni), Cooper (Cu), Zinc (Zn), Lead (Pb) and also (Selenium (Se), Cobalt (Co), and Arsenic (As). This technique favors hyperaccumulator species capable of absorbing and retaining significant quantities of heavy metals in their aerial parts, capable of storing adequate concentrations of metals in their tissues (i.e., 0.01–1% of dry weight) (**Abdel-Shafy & Mansour**, 2018; **Asante-Badu et al., 2020**). According to several researchers (**Drenning, 2021; Mench et al., 2010; Abdel-Shafy & Mansour, 2018)**, some hyperaccumulating plants, such as *Populus Sp or Salix, sunflower, Brassica Sp, maize, wheat*) are suitable for removing heavy metals. (eg. Pb, Zn, Cu, Ni, and Cd). These plants can remove heavy metals 100 times more than non-hyperaccumulating plants. They are essential for effective phytoextraction or hyperaccumulation. However, phytoextraction is a very long process (decades, sometimes hundreds of years). It is mainly suitable as a polishing technique for stripping low-concentration bioavailable metals in soils (**Drenning, 2021**).

2.5.2. Mechanisms of Phytoextraction

The mechanism of phytoextraction is the use of plants as cation pumps, absorbing heavy metal cations, and salts from agricultural or other land use type of soils by taking up of metals available to plants in soil porewater. This process involves planting hyperaccumulating plants in soil polluted with heavy metals, along with certain agricultural practices to enhance plant growth. (**Asante-Badu et al., 2020**). Figure 2-4-2 explains the mechanism of phytoextraction.

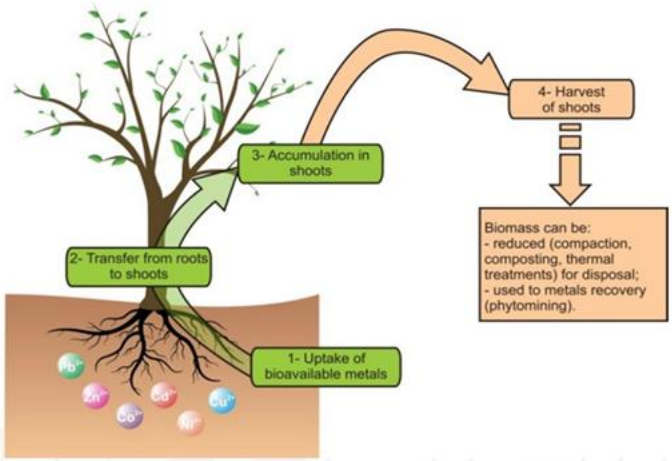


Figure 2-5-2. Phytoextraction of metal removal from the soil. Source: (**Menson et al., 2023**) in (**Favas et al., 2014**)

2.5.3. Strengths of Phytoextraction

The strengths or advantages of phytoextraction proposed by (**Menson et al.** (**2023**) include:

- Phytoextraction can accumulate and translocate metals and radionuclides in chemically mobile forms that are extremely dangerous to human health and the ecosystem.
- This method is particularly suitable for stripping low-concentration bioavailable metals in soils.
- Plants use nutrients from the soil the phytoextraction process, thus enhancing plant growth.

2.5.4. Limitations

There are some critical concerns or limitations to consider when choosing a phytoextraction method for remediation (**Menson et al., 2023**)

- The process of phytoextraction requires a very long-time frame (from decades to hundreds of years) to achieve its remediation goals successfully. The phytoextraction cannot be applied to wetlands.
- The selected plants for phytoextraction require harvesting and the disposal of the harvested biomass safely to avoid environmental pollution. This process can generate considerable amounts of (sometimes hazardous) waste.
- Management of harvested biomass can be associated with considerable costs.
- Plants with accumulated heavy metal in their aboveground biomass can pose secondary poisoning effects to ecosystems. If accidentally consumed may pose serious human health problems.
- Requires long-term monitoring.

2.6. Phytostabilization

Phytostabilization, also known as phytoimmobilization, is an in-situ method of controlling the movement of contaminants. It is a contrary method to phytoextraction in which specific plant species, often combined with immobilizing soil amendments, are used to restrict the movement of contaminants in the soil and thus reduce their bioavailability, thereby mitigating negative impacts on human health and the environment. **(Drenning, 2021; Cundy et al., 2016; Mench et al., 2010)**. The main objective of phytostabilization is to reduce the mobility of contaminants (metals/loid)s and other persistent organic compounds, such as PAHs, DDT, and PCBs, through rhizodegradation. (**Drenning 2021**). Phytostabilization relies on the use of plants and associate microbes for several reasons: i) plants and associate microbes are used for the long period to ensure the immobilization of contaminants found within the soil matrices are absorb and accumulate in the roots through mechanical, biochemical and physical stabilization of the soil that prevents or reduces the transport of contaminant within the soil, the groundwater and surface water and re-entrainment or resuspension of contaminated particulates for direct inhalation or ingestion by humans. **(Mench et al., 2010**; **Cundy et al., 2016; Drenning, 2021**); and ii) plants and microbial consortia are used to enhance the stability and metabolic activity of the heterotrophic microbial community, and thus promote plant growth and play a role in contaminant stabilization, and reduce dispersion and water migration of contaminants in the soil through the process of evapotranspiration. Plants and their roots prevent water erosion and store contaminants. However, root channels are solely responsible for the pathways through which leaching, product decomposition, speciation, and contaminant movement change. (**Mench et al., 2010**). The use of phytostabilization is sometimes due to the inability of phytoextraction to decontaminate the phytotoxicity of topsoil, the longer time required to achieve remediation goals, or plants' uptake of contaminants may pose a risk to animals, or no alternative method is appropriate due to cost and site characteristics (**Mench et al., 2010**; **Gerhardt et al., 2017**).

2.6.1. Mechanism of phytostabilization

The mechanism of phytostabilization involves absorption, accumulation of contaminants within the roots, precipitation and immobilization in the Rhizosphere, Complexation with organic matter, root uptake and sequestration, reduction of soil erosion and dust generation, and microbial interaction in the rhizosphere. (**Ali et al., 2013; Rascio & Navari-Izzo, 2011**). Through accumulation and absorption by roots, the bioavailability of contaminants is reduced, rendering them insoluble, immobile, and less harmful in natural and agricultural environments. So, they settle or ooze out of the soil around the roots and root zones. Phytostabilization is an in-situ method that involves incorporating harmful compounds into root cell wall lignin, thereby transforming them into non-toxic molecules that reduce contaminant levels in natural and agricultural environments. This process allows metals to precipitate as insoluble forms in response to root exudates, thereby integrating them into the soil matrix. **(Asante-Badu et al., 2020).**

According to **Ali et al. (2013), Asante-Badu et al. (2020**), and **Abdel-Shafy & Mansour (2018)**, the major goal is to prevent contaminants from moving, becoming soluble, or spreading in the soil. Some genus species that are grown for this purpose include Alyssum, Haumaniastrum, Eragrostis, Gladiolus, and Ascolepis. This study focuses on identifying a remediation method to remove pollutants from agricultural soil and diminish their bioavailability. Through accumulation and absorption by the roots, the contaminants become insoluble, immobile, and less harmful. So, they settle or ooze out of the soil around the roots and root zone. Phreatophytic trees with fibrous roots are often used to manage water flow and prevent soil erosion. These trees are also used to take in heavy metals such as Cd, Pb, Zn, Cu, As, U, and Se. They are also used to remove organic substances that do not break down and do not dissolve in water, e.g. W *Salix caprea,* and Poplars (*Populus spp*.) (**Dickinson et al., 2009**). Figure 2-6-1 explains the mechanism of Phytostabilisation.

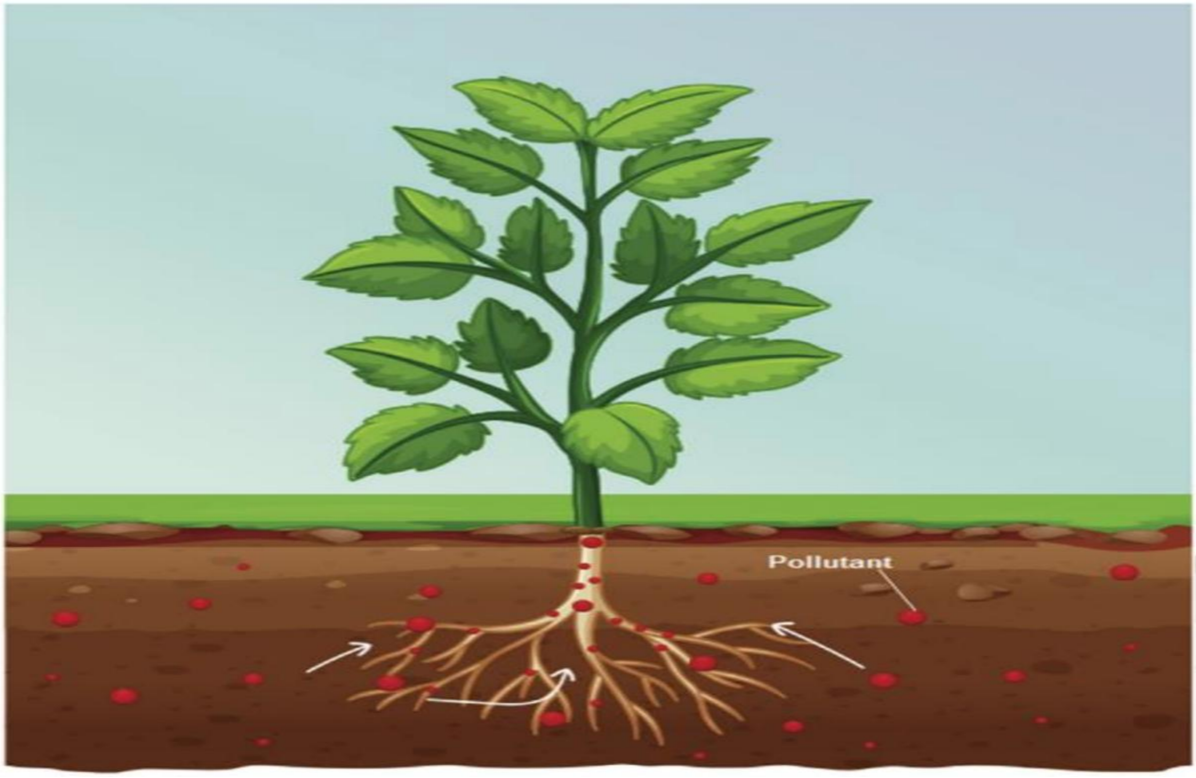


Figure 2-6-1. explains the mechanism of phytostabilization of heavy metals: Source: (Menson et al., 2023) in (Tonelli et al., 2022)

2.6.2. Strengths of phytostabilization

Advantages of phytostabilization include the following (**Menson et al., 2023**)

- In-situ treatment phytostabilization controls the mobility of contaminants without changing their position.
- Through Phytostabilization mechanism, organic matter from plant residues deposited in the soil can restore the fertility and structure of the soil and enhance the ecosystem.
- This mechanism is an in-situ method and does not require waste disposal from the contaminated site to enhance treatment.
- It is a relatively fast method, especially when combined with soil amendments that help to immobilize contaminants in the soil.

2.6.3. Limitations

Despite the advantages of the method, some limitations require mentioning. (**Menson et al., 2023**)

- Phytostabilization plants require the use of fertilizers and sometimes immobilizing amendments to achieve remediation goals.
- The main objective of phytostabilization is to achieve a risk-free site and not a contamination-free site by controlling the mobility and bioavailability of the contaminants but not removing them.

- Constant maintenance is needed for plants to restrict the mobility of the contaminants continuously and to ensure the contaminants' capture does not get released.
- Translocation must be avoided for the phytostabilisation mechanism to succeed in its objective of containing contaminants below ground.
- Plants' roots may result in creating a pathway for the leaching of the contaminants.
- Requires long-term monitoring.

2.6. Phytoexclusion

Phytoexclusion can be considered as a soil-plant barrier restricting contaminants' translocation to the aboveground biomass or aboveground edible parts of crops. It is a phytoremediation method that involves the use of many plants serving as a barrier to exclude contaminants such as heavy metals or other types of contaminants by restricting or binding them to the root surface or preventing uptake in shoots, leaves, or grains. This method has a high efficiency in reducing the toxicity risks of many insoluble elements, except for some elements such as Mo, Se, Cd, and Co. These elements resist the ability of plants to exclude them from their tissues due to their low phytotoxicity in concentrations similar to agricultural soil pollution **(Haller & Jonsson, 2020**). Cd posed a serious threat to plant germination and growth, which makes certain plants capable of preventing Cd uptake valuable, especially for agriculture in which contaminant translocation to the edible aboveground biomass is a risk **(Drenning, 2021; Haller and Jonsson,** 2020). Crops capable of preventing Cd uptake or excluding other toxic elements in a contaminated agricultural soil are, for example, corn (Zea mays), cereals, and vegetables. These crops, including cultivars like wheat (Triticum spp.), barley (Hordeum vulgare), rice (Oryza sativa), potato (Solanum tuberosum), and soybean (Glycine max), according to **Drenning 2021**, **TANG et al., 2012**, **and Haller and Jonsson,** 2020**),** have proven to have the capacity to prevent toxic metals, particularly Cd, from reaching the food chain. These cultivars play a major role in the prevention of contaminant transfer to the food chain, and it should be regarded as a safe option to produce safe edible crops in an agricultural soil contaminated with heavy metals. (**Drenning, 2021**). Phytoexclusion can be enhanced by immobilizing soil contaminants by means of soil amendments (e.g. some types of biochar). (**Backman et al., 2025**).

2.6.1. Mechanism of phytoexclusion

The phytoexclusion mechanism can be described as the use of plants to restrict their movement to roots, thereby preventing excessive uptake and translocation of elements and contaminants to edible parts and preventing them from reaching the food chain (**Cundy et al., 2015; Tang et al., 2012**). This method involves the selection and use of plant cultivars capable of low metal accumulation in their edible parts in order to reduce the human health risk associated with ingestion of plants contaminated with heavy metals.. Phytoexclusion requires screening to determine low heavy metal accumulation cultivars (LACs) of cadmium (Cd), lead (Pb), and other metals such as barley, wheat, soybean, rice, Chinese cabbage, and pakchoi. Even though some studies have been conducted to evaluate LACs screening and identification methods, there is still a lot of research needed to minimize the uncertainty associated with LACs identification criteria, occurrence mechanisms, and application strategies. Crops identified to have acceptable yield performance with lower HM accumulation in their edible parts are referred to as LACs. These LACs possess features such as i) the concentration of accumulated HM must not exceed the food safety guideline values for each targeted HM; ii) the control varieties must be less than the crop yield; and iii) both the yield and the concentration of HM in the food chain must be stable across several contaminated sites and seasons (**L. Wang et al., 2021**).

2.6.2. Strengths of phytoexclusion

Some advantages of this method are reported by **Haller and Jonsson (2020)**

- It is a relatively fast method, especially when it is combined with soil amendments that immobilize contaminants in soils.
- Enables immediate return of contaminated agricultural land into beneficial productive use.

2.6.3. Limitations

Despite its advantages, phytoexclusion has some limitations to consider, according to **Haller and Jonsson (2020**), listed below.

- Limited knowledge of crops with the ability to exclude contaminants.
- Ineffective cultivars taking up some contaminants from soil containing mixed pollutants.
- Requires long-term monitoring.

2.7. Soil amendments for immobilization

Soil amendment is an agronomic practice that falls directly under soil management. It involves using organic or inorganic amendments to improve efficiency by either reducing the mobility and toxicity of soil contaminants or increasing metal bioavailability in the soil. The method uses plant uptake to enhance soil quality, especially in poor soils, and to improve soil physical properties (soil density and structure), as well as water infiltration and soil water storage capacity. (**Drenning, 2021; Gerhardt et al., 2017**). Contaminated sites often have poor soil quality, physical compaction, low organic matter content, low dissolved oxygen, and low conductivity, all of which require various amendments such as biochar, compost, microbial agents, plant exudates, and chelating agents to improve soil texture and enhance plant growth by modifying soil properties, increasing the amount of nutrients available to plants, and reducing the bioavailability of contaminants. (**Tamma et al., 2025**; **Gerhardt et al., 2017**). The use of fertilizer is necessary for soil low in nutrients to ensure plant growth. Nutrients such as nitrogen and phosphorus are needed to ensure that petroleum hydrocarbons (PHCs) are degraded into microbial biomass. However, insufficient nutrients (Nitrogen and Phosphorus) may limit PHC degradation due to competition from plants and microorganisms for nutrients in the rhizosphere. To enhance the rate of PHC degradation, additional nutrients are required (**Gerhardt et al., 2017**). Other amendments can be used to fertilize the soil, including biochar, compost, chemical fertilizers, straw mulch, and tannery sludge. According to **Tamma et al. (2025**), biochar is effective in decreasing metal toxicity to plants while also preserving metal bioavailability for uptake. It also improves soil structure and retains nutrients more effectively. Compost created from organic waste promotes microbial diversity and nutrient cycling. These two amendments play an important role in long-term plant development. Several microbial agents, including plant growth-promoting bacteria (PGPB) and mycorrhizal fungi, help plants resist metal stress by enhancing metal uptake and activating metal tolerance mechanisms. Furthermore, plant exudates, particularly root exudates, can affect soil pH and redox potential, boosting metal availability for plant absorption while promoting beneficial microbial interactions. Several studies have explored the role of soil amendments in improving phytoremediation, as indicated in Figure 2-7 below.

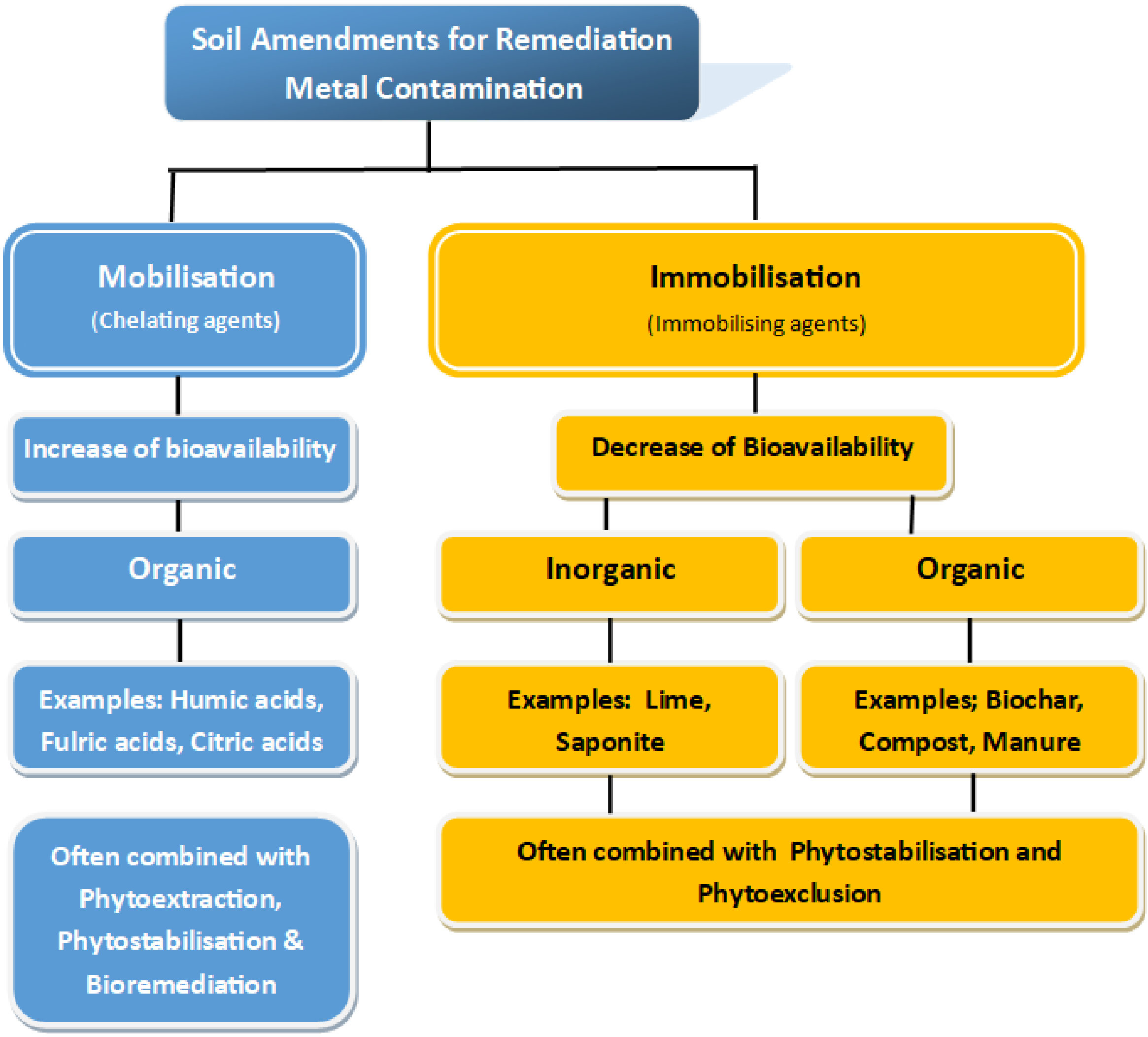


Figure 2-7. shows soil Amendments classification for heavy metal removal.

2.7.1. Mechanism of immobilization

Immobilization strategies may be used to remediate soil based on PTE type, soil physicochemical properties, and the availability of resources such as soil amendments. The specific process depends on the amendment type, soil conditions (pH, redox potential, and organic matter), and the specific metal species. It is relevant to consider these three important factors before deciding on immobilization remediation approaches. These factors are: 1) the nature of individual PTEs, 2) exposure routes and deleterious consequences, and 3) interactions between soil amendments and PTEs. Immobilization approaches use various soil additives to restrict PTE movement, minimize PTE bioavailability to plants, animals, and people, and reduce leaching into groundwater. Ex situ or in situ immobilization is frequently achieved by introducing appropriate soil amendments into polluted soils. Several soil additives have been tested for PTE immobilization. Organic additions such as biochar produced promising results, as did inorganic amendments such as phosphates, clay minerals, metal oxides, and liming materials. The use of low-cost soil additives to immobilize PTEs is a promising approach to achieving ecologically friendly, cost-effective rehabilitation, but it is not always feasible under certain conditions, as various soil amendments may adversely affect PTEs and phytoavailability, as documented by several researchers. **(Palansooriya et al., 2020 Beigmohammadi et al., 2024; Rinklebe & Shaheen, 2015)**.

2.7.2. Strengths of immobilization

In-situ soil amendment using the immobilization method has several advantages according to (**Palansooriya et al., 2020**), listed below:

- In situ immobilization can be considered a cost-effective method compared to ex-situ, and it is ideal for large-scale agricultural cleanup.
- It is effective in soil quality improvement, such as soil health, increasing the soil water-holding capacity, and restoring microbial diversity.
- It is a relatively rapid remediation method. Agricultural land can immediately be returned into beneficial productive use after application of soil amendment immediately immobilizing soil contaminants and thus lowering the bioavailability of PTEs and reducing plant uptake.

2.7.3. Limitations

Despite several advantages, the immobilization method has limitations that restrict its global use, as reported by several researchers.

- Requires long-term monitoring.
- Could require repeated applications over time to maintain immobilization of contaminants in soils.

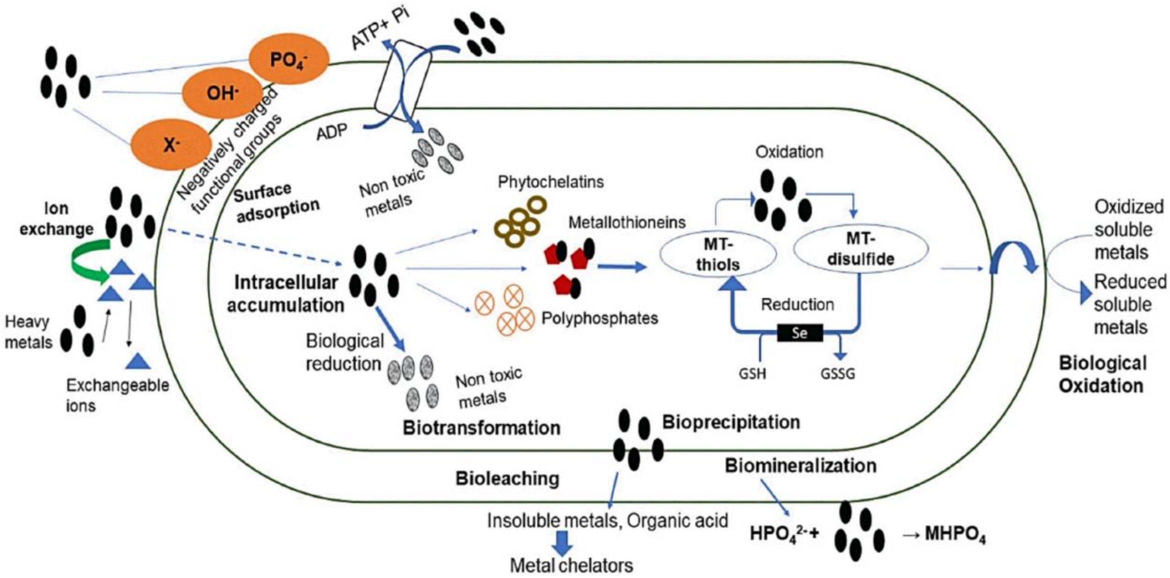
2.8. Bioremediation by means of biosorption (immobilization by microbes)

Bioremediation by means of biosorption is a natural process that uses microorganisms, such as algae, fungi, and bacteria, to immobilize different contaminants. It is effective in the removal of various heavy metal ions from aqueous solutions, including copper, lead, mercury, cadmium, and nickel (**Plazinski, 2013**). Biosorption can also be defined as an eco-friendly alternative technology with a physicochemical process in which metal ions precipitate to the surface of a biosorbent, enter the cells or form organic complexes, which are likely to be either yeast, algae, bacteria, or fungi.

2.8.1. Mechanism of biosorption

This method is regarded by many as an effective mechanism with the ability to remove even the lower concentrations of metals in porewater, as well as recover them (**Shrestha et al., 2021**). This physicochemical process utilizes the mechanisms of absorption (on the cell surface), adsorption (into a cell), ion exchange and surface complexation with a cell, and precipitation (on the cell surface), in which living and dead biomass are occupied. The physicochemical biosorption mechanism, including the bioavailability of contaminants, as well as the chemical speciation and accumulation or transformation by metabolism-dependent properties, may all be affected by the living organism's metabolic process. Organic contaminants like phenolic compounds or dyes, and inorganic contaminants, for example, heavy metals, can be removed using the biosorption method (**Plazinski, 2013; Hlihor et al., 2017**). pH is one of the factors that significantly influence metal ion sorption, which is one of the characteristic features of the biosorption process. The increase in pH may result in immobilization and a positive metal binding efficacy, subject to the metal being in the cationic form. A much higher pH (usually pH>8) may decrease the availability of metals and their uptake into a cell. (**Plazinski, 2013**). Note, As and Cr become more available at higher pH, in contrast to other metals (**Swartjes, 2011**).

Factors such as the status of biomass, including types of biomaterials, chemical properties of metal solution, and also pH and temperature, e may significantly affect the mechanism of biosorption of heavy metals such as Cu, Ni, and Zn, which are classified as essential heavy metals, as well as the non-essential heavy metals like cadmium, mercury, arsenic, and lead. The biosorption technique sometimes uses dead biomass instead of living biomass, due to its many advantages; thus, it is known as the passive method. The biosorption process outperforms several other approaches for removing contaminants such as heavy metals from aqueous solutions, particularly when dealing with low concentrations. However, in bioaccumulation, live biomass is used to remove heavy metals. So, it's known as the active technique. (**Dutta & Dutta, 2024**).



Oval shapes represents the heavy metals; MT- represents as Metallothioneins; Se-Compound is amplifier of thionin-reduction; GSH-Glutathione; GSSG-Glutathione disulfide

Figure 2-8-1. Various mechanisms of microbial remediation of heavy metal-contaminated soil. Source: (***Jeyakumar et al. 2023 in Mohamed et al., 2025***).

The concept of sorption is not exact, implying that the mechanisms involved in biosorption are difficult to quantify, particularly outside of small laboratory systems. Biological materials are complicated, with several systems acting under certain circumstances. Biomass comprises a variety of structural components that can interact with metal species, depending on physicochemical parameters. Biosorption, defined as a physicochemical process unrelated to metabolism, may entail processes such as adsorption, ion exchange, and complexation/coordination, allowing for quick and reversible biosorption similar to conventional ion exchange resins. Ion exchange replaces one ion in a solid with another from a solution. This idea is basic, but it can be difficult to apply in practice because it involves several processes that affect sorption and desorption, including precipitation. This phenomenon is found with actinides like uranium on non-living fungi (**Gadd, 2009**)

2.8.2. Strengths of biosorption

Advantages of biosorption technology discussed by **Plazinski et al., 2013** and **Shrestha et al., 2021** are listed below.

- The biosorption technique has a low operational cost with high sorption ability.
- It is mostly in comparison with the ion exchange method.
- The operational process is simple with no additional nutrient requirements.
- The biosorbents are regenerated with low Chemical Oxygen Demand (COD)

2.8.3. Limitations

This method has some limitations to consider despite its several advantages as reported by **Shrestha et al., 2021**.

- High dependence on pH, including temperature and type of biosorbents used.
- Requires very high energy for operation and maintenance processes.
- Requires long-term monitoring.
- Could require repeated applications to maintain immobilization of soil contaminants over time.

2.9. Nature-based remediation mechanisms for explosives

2.9.1. Bioremediation by means of biodegradation (transformation/degradation)

When a compound is degraded, it can be considered to have broken down into small elements, harmless metabolites (**Menson et al., 2023**). Bioremediation by means of biodegradation is a natural process that uses microorganisms, such as bacteria, fungi, or yeast, to break down toxic organic compounds into less toxic substances. This process is suitable for degrading organic contaminants such as explosives and petroleum products in soil (**F. I. Khan et al., 2004**). As reported by **(Kao et al., 2016**; **Park et al., 2003**). Biodegradation is an environmentally friendly technology used for the remediation of organic contaminants such as TNT, RDX and HMX, which can be degraded by microbial biotransformation or degradation. This method is generally proven worldwide because of its efficiency in degrading environmental pollutants, cost-effectiveness, and its application can be carried out in-situ remediation. Degradation of organic contaminants by microorganisms provides an advantageous equilibrium between remediation effectiveness and environmental safety by facilitating the microbial degradation process of persistent explosive compounds without the introduction of additional harmful substances into the ecosystem. Through this process, RDX, HMX, and TNT can be metabolized or transformed by a variety of microbial taxa in both aerobic and anaerobic circumstances. However, based on factors such as the environmental circumstances, the chemical structure of the compounds, and the diversity of the microbial community, the degradation rates and pathways might vary greatly (**Ben Laish et al., 2025**)

*Bioaugmentation (introducing new microbes to soils)*Bioaugmentation, according to (**Kalsi et al., 2021**), (**Srivastava et al., 2022**) can be considered as an effective remediation method for contaminated sites. This method involves the use of a specific type of microorganism to enhance the remediation process. These specific microorganisms can generally be indigenous (natural) microorganisms from the soil, new consortia introduced to soils or genetically modified to speed up the cleanup process, but this method has a fundamental challenge of transporting these microorganisms into the intended contaminated sites and ensuring the survival of the injected strain or consortia. Furthermore, bioaugmentation with microbes for biodegradation can improve the natural attenuation process in soils, and it is well-documented to have been successful in the degradation of sites contaminated with explosive residues such as TNT. Despite the success history of this method, many researchers have suggested that bioaugmentation is much more effective when combined with biostimulation to enhance TNT degradation and bioremediation efficiency, due to the high cost required to grow competent microorganisms and their weak ability when competing against indigenous microorganisms, compared with biostimulation (**Habineza et al., 2016**)

Biostimulation (stimulated indigenous bacteria in soils)

Biostimulation, also known as enhanced biodegradation, is the process of boosting microbial breakdown of diverse goods by adding nutrients to optimize in situ or on-site environmental conditions. This idea is also used to demonstrate the use of electron donors, electron acceptors, or nutritional components to improve naturally occurring microbial communities (**Mokrani et al., 2024**). According to **(Habineza et al., 2016; Mokrani et al., 2024)** the use of this remediation option is dictated by the ineffectiveness of passive bioremediation where nutrients and electron acceptors are limited. Biostimulation is a popular bioremediation approach that stimulate indigenous bacteria by providing a favorable environment and driving them to use the recalcitrant as a carbon and energy source. This approach offers oxygen, nutrients, moisture, temperature, redox potential, and pH [7, 30, 40, 49, 82], making it the most often used bioremediation procedure and foundational soil remediation technology. It has been used for many years and considerably improves the microbiological breakdown of TNT. Biostimulation also promotes herbicide breakdown in soil by increasing organic changes and nutrient availability. Fertilization with phosphorus (P) and nitrogen (N) components is the most widely used technology for remediating a variety of pollutants, including hydrocarbons, petroleum, polyurethane sulfates, polyesters, herbicides, and pesticides. The employment of microorganisms in bioremediation is critical because they transform contaminants into harmless chemicals. The efficacy of this degrading process is largely dependent on bacterial reproduction and development, stressing the significance of microbial health in the biostimulation strategy (**Mokrani et al., 2024**).

2.9.2. Mechanisms of biodegradation:

The mechanism of biodegradation involves the use of microorganisms to degrade or break down persistent organic pollutants (POP) into smaller elements, making them harmless and reducing their effects in the environment. This process of POP degradation is most dependent on a unique biological reaction carried out by certain species of bacteria and fungi, which use two distinct processes (metabolic and enzymatic) to utilize complex chemicals as carbon and energy sources (**Mokrani et al., 2024**). The ability of microorganisms to remove pollutants from the environment can be classified into two major categories, which include immobilization and mobilization. Methods such as bioaugmentation, and biostimulation are processes of mobilization, while immobilization process involves bioaccumulation, biosorption, complexion, and precipitation (**Ayilara & Babalola, 2023**). The mechanism of biodegradation involves the use of microorganisms to degrade or break down persistent organic pollutants (POP) into smaller elements, making them harmless. The same mechanism of biodegradation can be carried out by introduced bacteria in the case of bioaugmentation and by stimulated indigenous microbes in soils in the case of biostimulation.

2.9.3. Strengths of biodegradation

- There are some advantages or strengths of this method according to (**Mokrani et al., 2024**)Transforming hazardous substances into less toxic forms with their consequent mineralization.
- It is an eco-friendly in-situ remediation method that uses natural biological processes with less environmental impact.
- A relatively fast process under well-designed conditions.
- Usually a cost-effective remediation method.
- Does not entail waste generation.

2.9.4. Limitations of biodegradation

There are some critical concerns or limitations to consider when choosing a biodegradation method for remediation

- It can be a time-consuming and resource-intensive process.
- Requires long-term monitoring.
- Highly dependent on environmental conditions and cannot completely degrade some heavy metals and organic contaminants.
- Unknown effectiveness under co-contamination conidiations (e.g. both metals and explosives).

2.10. Phytodegradation

Phytodegradation, also known as phytotransformation, is the use of plants to take up and break down contaminants through microbial activity or enzymes produced within plant cells. (**Drenning, 2021; Pandey et al., 2021; Gerhardt et al., 2017**). Plants generate enzymes to facilitate the breakdown process, which include: i) nitroreductase (responsible for the degradation, or the breaking down of explosives or other nitroaromatic chemicals.), ii) dehalogenase (enzyme is tasked with the responsibility of breaking down chlorinated solvents, and pesticides), iii) peroxidase (breakdown of phenolic compounds) iv) nitrilase (degradation of cyanated aromatic compounds), and v) phosphatase (engaged in the decomposition or degradation of organophosphate pesticides) (**Menson et al., 2023; Abdel-Shafy & Mansour, 2018; Asante-Badu et al., 2020**).

Phytodegradation is an effective way to clean up sites contaminated with organic substances, including explosives, herbicides, chlorinated solvents, and PAHs. Some plants, such as Canna, can digest organic pollutants, making them harmless. In addition, microorganisms in the plant roots can metabolize these contaminants in soil or water. However, the metabolism of complex pollutants by plant tissues might not completely degrade them, giving rise to the term "phytotransformation," which refers to the modification of chemical structures without complete disintegration (**Abdel-Shafy & Mansour, 2018**). Phytodegradation is applicable for remediating contaminated surface water; however, its primary application is contaminated soil, sludge, sediments, and groundwater. The primary pollutants addressed in phytodegradation are organic substances; however, they are also employed to remediate inorganic nutrients, such as nitrates, which are absorbed by plants and transformed into nitrogen and proteins.

2.10.1. Mechanism of phytodegradation

The mechanism of phytodegradation involves plant uptake of contaminants and their metabolic processing within plant tissues. The enzyme systems break down complex organic contaminants into smaller molecules, which are then used as building blocks in plant tissues, thereby accelerating plant growth. The process may occur within or outside the cell, with the help of certain secretory enzymes that catalyze and accelerate chemical reactions. Biodegradation of contaminants such as chlorinated hydrocarbons, pesticides, and explosives can be done with this method. Plants alter the soil around them by producing root exudates that attract numerous microbes in the rhizosphere, including bacteria, yeast, and fungi. These microbial species promote several beneficial interactions with plants and expedite the biodegradation of xenobiotics. **(Pandey et al., 2021; Menson et al., 2023)** Plants' ability to enhance the successful uptake of contaminants is entirely due to contaminant bioavailability and a good uptake ratio, with hydrophobic organic chemicals (octanol-water partition coefficients, log Kow values ranging from 0.5 to 3.5, **(Drenning 2021)**. Phytodegradation is more suitable for moderately hydrophobic organic compounds, and organics that are excessively hydrophilic (log Kow < 0.5) cannot flow across membranes and are not absorbed by plants. Hydrophobic compounds (log Kow > 3.0) are tightly bonded to root surfaces, making them difficult to move inside the plant. There are several factors involved in determining the successful uptake of contaminants by plants, and these factors are the classification of plants.

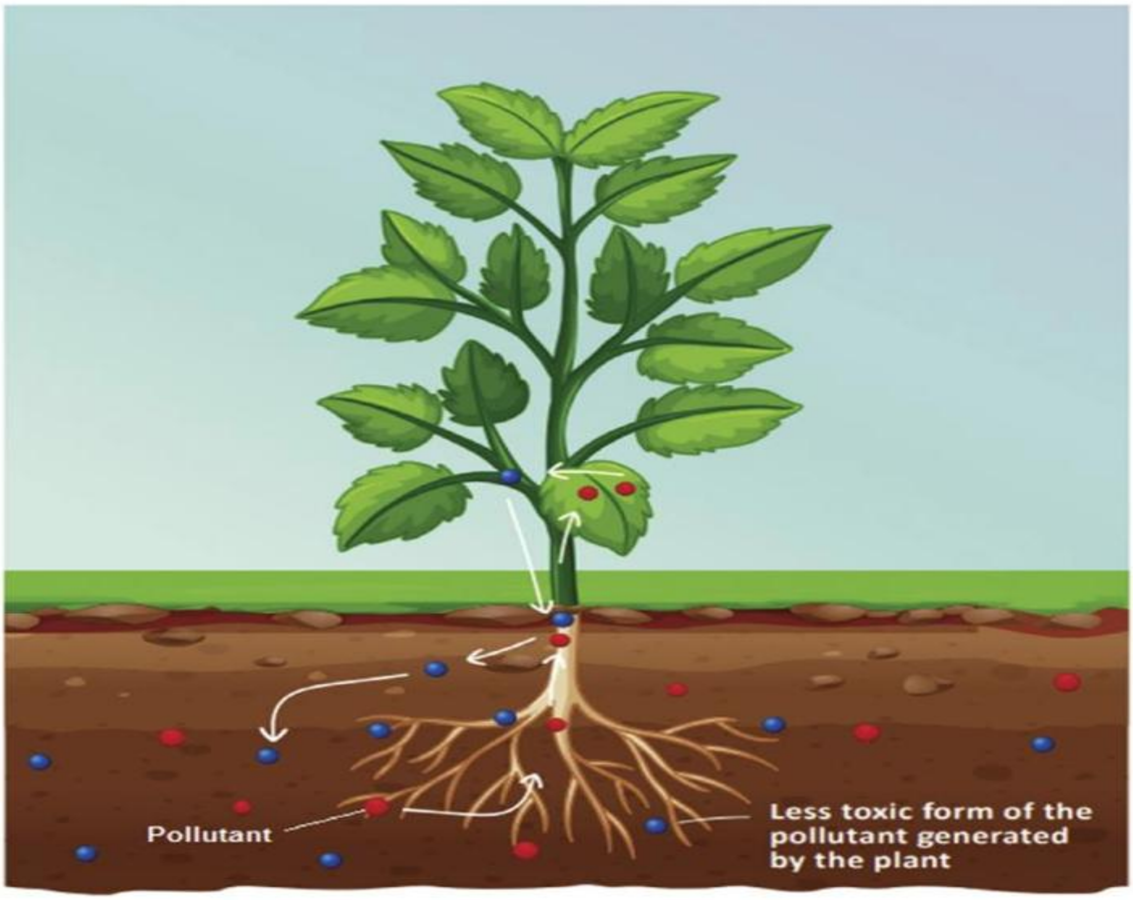


Figure 2-10-1. Mechanism of phytodegradation. Source: **(Menson et al., 2023) in (Tonelli et al., 2022)**

2.10.2. Strengths of phytodegradation

The advantages of phytodegradation, according to **Menson et al. (2023)** are listed below:

- The phytodegradation method is an in-situ method used for the remediation of contaminated sites, which does not generate any waste.
- During the remediation process, the contaminants are transformed into less toxic or harmless substances.

- Contaminants such as metabolites that are exposed to the atmosphere are likely to be degraded by natural degradation processes.

2.10.3. Limitations of phytodegradation

Although there are advantages to phytodegradation technology, there are also drawbacks to consider (**Menson et al., 2023**):

- During the remediation process, some metabolites are likely to transfer into the atmosphere.
- Can be unsuitable when available concentrations are too high, leading to phytotoxicity.
- This mechanism is not effective in the removal of metals, for they are nonbiodegradable, but it is good for the removal of organic pollutants only (**Islam et al., 2022**).
- It can be a time-consuming process, up to 5-10 years to degrade explosives.
- Requires long-term monitoring.

2.11. Rhizodegradation

Rhizoremediation, or Rhizodegradation, involves degradation processes similar to phytodegradation but differs in that microbial activity in the rhizosphere degrades different organic contaminants rather than within plant tissue. Rhizodegration process is known as phytostimulation, it is regarded as plant-assisted degradation or remediation and rhizosphere degradation is define as the process through which the microbial activity and plants species degrade enzymatic contaminants outside the plant tissue, or the microbial breakdown of various organic pollutants in the soil facilitated by the root zone (**Khan et al., 2023; Drenning, 2021; Neha et al., 2021**) Rhizodegradation is acknowledged as the most effective technique for the remediation of polycyclic aromatic hydrocarbons (PAHs) in soil, but it can also be used to remediate other pollutants such as total petroleum hydrocarbon (TPH). BTEX (Benzene, toluene, ethylbenzene, and xylenes), Chlorinated solvents (TCE, TCA), PCP (pentachlorophenol), Pesticides, PCBs (polychlorinated biphenyls), Surfactants according to **Menson et al., 2023**, and **Khan et al., 2023**. The synergistic interaction between the microbial community and the plant root system in the rhizosphere, including the release of root exudates (amino acids, sugars, organic acids, etc.), hydrogen cyanide (HCN), siderophores, phosphatases, and phytohormones produced by plant growth-promoting rhizobacteria (PGPR), facilitates the degradation of contaminants (**Khan et al., 2023**). Rhizosphere degradation, often called "Rhizo degradation," is the process of increasing the activity of soil microbes to break down pollutants. Organisms that live on plant roots break down contaminants in this way. Soils immediately adjacent to plant roots are where enhanced rhizosphere biodegradation occurs. Plant roots emit natural chemicals that provide bacteria with the nourishment they need. At the same time, the microbes make plant roots biologically more active. Plant roots also loosen the soil and subsequently die, creating channels for air and water to move through. This mechanism also draws water to the soil surface, drying out the lower saturated zones. Roots of plants, therefore, encourage microbial activity in the rhizosphere, or soil-root zone, to break down contaminants (**Abdel-Shafy & Mansour, 2018**).

2.11.1. Mechanism of rhizodegradation

The rhizodegradation mechanism works by directly affecting phytohormones, thereby increasing nutrient availability and controlling microbial abundance. This makes it feasible to break down pollutants with a developing root system. Plants take in pollutants and either store them in portions that may be harvested or release them into the air through their leaves or stems. The pace of rhizodegradation is influenced by plant-microbe interactions, soil conditions, and other factors that accelerate the process. (**Khan et al., 2023**). The improvement in pollutant degradation in the rhizosphere is primarily attributed to elevated microbial populations and metabolic activity, which can be encouraged by plant exudates. These secretions, comprising carbohydrates, amino acids, and flavonoids, can enhance microbial activity by a ratio of 10 to 100. Moreover, the nutrients released by root exudates act as sources of carbon and nitrogen, promoting a nutrient-dense environment that supports microbial proliferation. In addition to supplying organic substrates, plants produce specific enzymes that facilitate the breakdown of organic pollutants in the soil. (**Ali et al., 2013**; **Menson et al., 2023**). Plant roots also loosen the soil and subsequently die, creating channels for air and water to move through. This mechanism also draws water to the soil surface, drying out the lower saturated zones. (**Abdel-Shafy & Mansour, 2018**). Figure 2-11-1 explains the mechanism of Rhizodegradation.

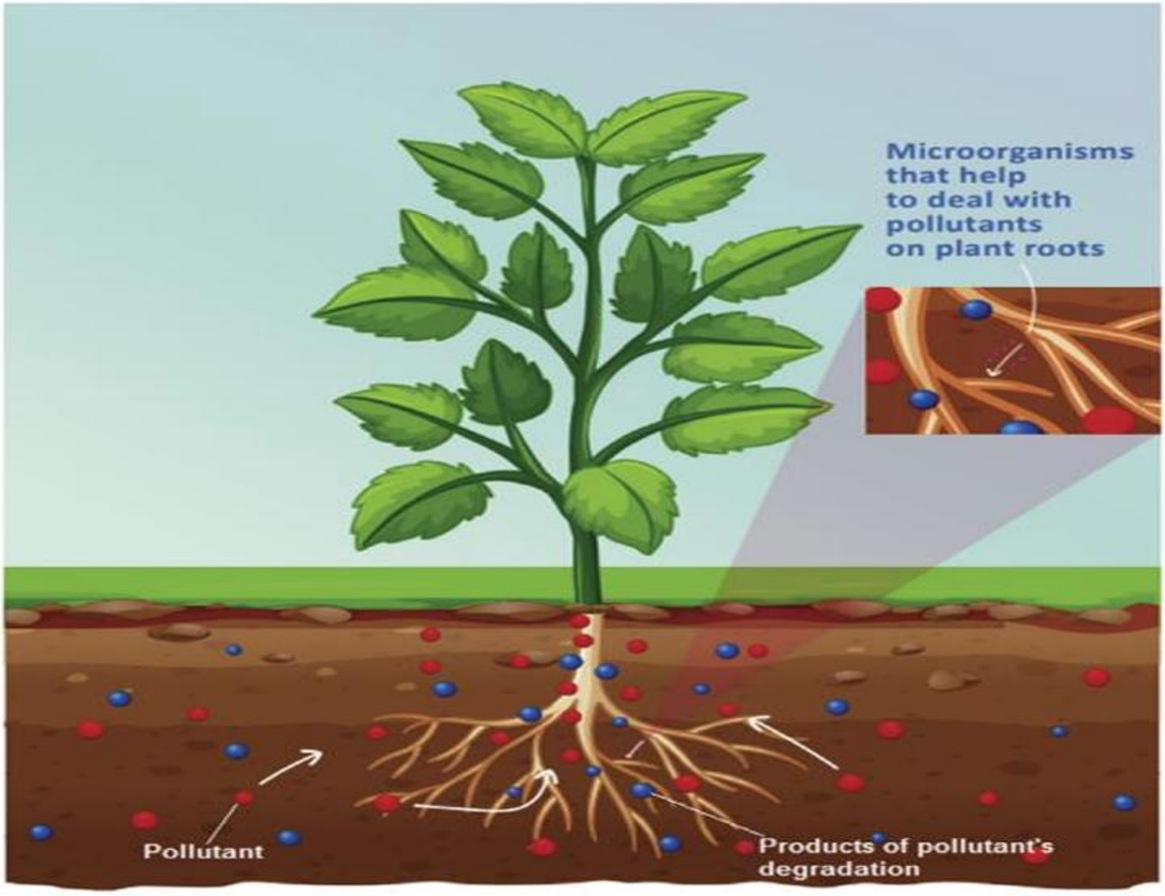


Figure 2-11-1: Mechanism of Rhizodegradation. Source: **(Menson et al., 2023) in (Tonelli et al., 2022)**

2.10.2. Strengths of rhizodegradation

According to **Menson et al. (2023)**, there are several advantages associated with the rhizoremediation method, which are listed below:

- The implementation of this method is possible in situ, in accordance with other phytoremediation technologies.
- IN comparison with other phytoremediation technologies, this method has a low installation and maintenance cost to consider.
- In addition to the low cost required, it also has a very low rate of translocation of contaminants to parts of the plants and atmosphere compared to other phytoremediation mechanisms.

- It is possible to achieve complete mineralization of contaminants with this method.

2.10.3. Limitations of rhizodegradations

Although several advantages are listed above, this method has disadvantages, as noted by **Menson et al. (2023).**

- This method has a distance limit range of 20 – 25 cm to enhance effective remediation of contaminants within the subsurface soil. It can also be considered a slow remediation process.
- The soil physical structure and composition play a significant role, which may cause hindrance to the growth and depth of the plant roots.
- Plants needed for this mechanism may require fertilizer for growth.
- Can be unsuitable when available concentration is too high, leading to phytotoxicity.
- It can be a relatively time-consuming process, up to 5-10 years for explosives.
- Requires a long-term monitoring.

3. Case study description

The chapter explains the current conditions of Ukrainian agricultural soil, including its properties, uses, and the impacts of the war.

3.1. Ukraine's agriculture

Ukraine's agricultural land coveres 50% of the country's geographical area, and, due to the significant amount of crops it produces and supplies to the global market, it can be considered one of the world's largest producers and exporters, helping ensure food security. (**Y. Li et al., 2026**). The high production of crops is significantly due to its vast fertile black soil, also known as the chernozem, which accounts for 40% of the global black soil, combined with very good climate conditions. This makes Ukraine the world's largest producer and exporter of sunflower oil, and also the fourth largest exporter of corn. (**Lissitsa & Odening, 2005**; **Glauben et al., 2022**). In addition to large quantities of sunflower oil and corn exports, Ukraine also supplies a large quantity of wheat to the global market, accounting for about 30% of global wheat production (**Backman et al., 2025**). Countries around the world that are entirely dependent on Ukraine's export of wheat, including the EU, are not the only ones affected, but the meat and dairy industries too, because the export of maize from Ukraine is essential for livestock feed (**Sytar & Taran, 2022**).

The agricultural sector played a major role in the country's economy. It was once considered the most important sector, contributing more than 35% to the Ukrainian economy, including to gross domestic product (GDP), exports, and employment. (**Qadir et al., 2024**; **Lissitsa & Odening, 2005**). Agricultural production in Ukraine mainly includes sunflowers, corn, wheat, barley, rapeseed, soybeans, and potatoes, which account for over a billion dollars in exports worldwide, enough to support a million people, in addition to the 40 million residents of Ukraine. (**Sytar & Taran, 2022**; **Backman et al., 2025**; **Li et al., 2026**). As reported by (**Sytar & Taran, 2022**), the ongoing war has impacted the majority of Ukrainian agricultural land. About 70% of the cultivated land contains wheat harvest, 50% of the corn cultivated land, and 70% of the cultivated land contains sunflower seeds. In addition, about 70% of barley-planted land and 43% of rapeseed-cultivated land are also affected by the Russian invasion as of March 2022.

3.2. Spatial distribution of Ukraine agricultural soils and areas of interest

The agricultural conditions in Ukraine are optimal, characterized by temperate climates, ample water resources, favorable conditions, and abundant sunlight. Landscapes are classified into three types: forests, forest-steppes, and steppes, as shown in Figure 3-2. Steppe regions are mostly utilized for agricultural activities, followed by forest-steppes. Forest-steppe regions are the most fertile and the most productive for arable cultivation. Figure 3-3 shows that two-thirds of the nation is covered by fertile black soil, primarily chernozem. **(Backman et al., 2025)**.

Figure 3-2: shows the three Landscapes of Ukraine. Source: Backman et al., 2025 (in FAO, 2020). CC BY-NC-SA

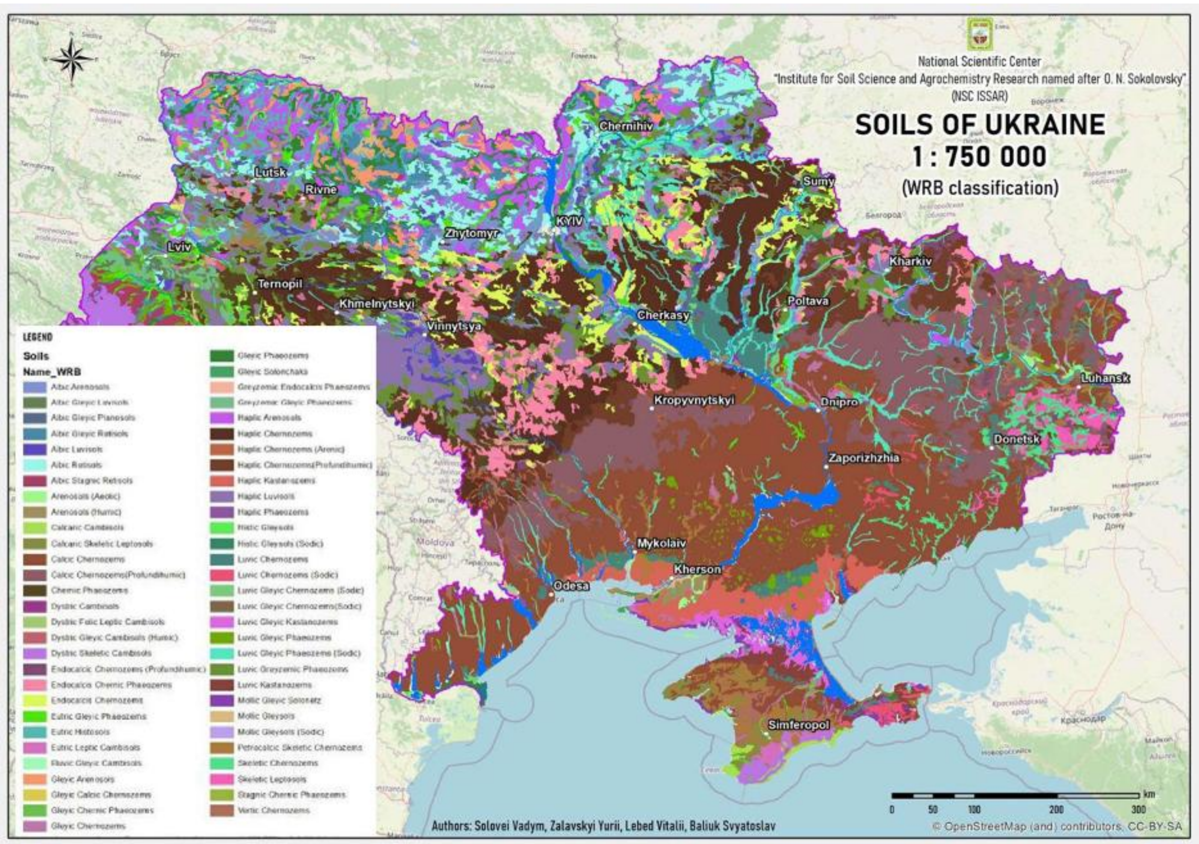


Figure 3-3: Shows the brown and dark green areas containing black and various soil types. Source: Backman et al., 2025 (in National Scientific Center "O.N. Sokolovsky Institute of Soil Science and Agrochemistry" [NSC ISAR], 2025). CC-BY-SA

Kharkiv, one of the areas affected by the ongoing war, is located in northeastern Ukraine and covers a total area of 31,415 km^2. Some regions of Kharkiv have elevations ranging from 230 to 250 m, resulting in an average elevation of 150 m above sea level. **(Bonchkovskyi et al.,** 2025). The area is significantly affected by its geographical location on the border with Russia. It has a vegetation zone of forest-steppe in the north and steppe in the south. The climate condition of the area of interest is temperate with an annual temperature ranging from (1981 - 2010; 1991 – 2020) according to (**Bonchkovskyi et al., 2025**; **Solokha et al., 2023**) is between +7.6 - 8.2°C. The temperature changes in January and July. In January, it was recorded to fall between –4.7 and ± 5.3 °C, and subsequently between +20.6 and +21.5 °C in July, with the annual precipitation ranging from 560 to 600 mm, and the soil classified as chernozems.

According to **Bonchkovskyi et al. (2025)**, before the war, the Kharkiv area had a vast amount of land used for agricultural activities, but saw a massive decrease in arable land in 2023 due to the ongoing war. The majority of the land in the Kharkiv region was used for agriculture before the invasion of Russia, covering approximately 60.7% (641,870ha), including 4,152 household plots (768.2ha) and fields (29,834ha) as of autumn 2021. Compared to cultivated agricultural land, uncultivated arable land increased by 25.7% (162,177ha) and included 8949 land plots, including 7229 fields and 1679 household plots, as of October 2023. Figure 3.2b showing the map of Kharkiv land cover, and Table 3.2 shows the properties of the polluted black soil.

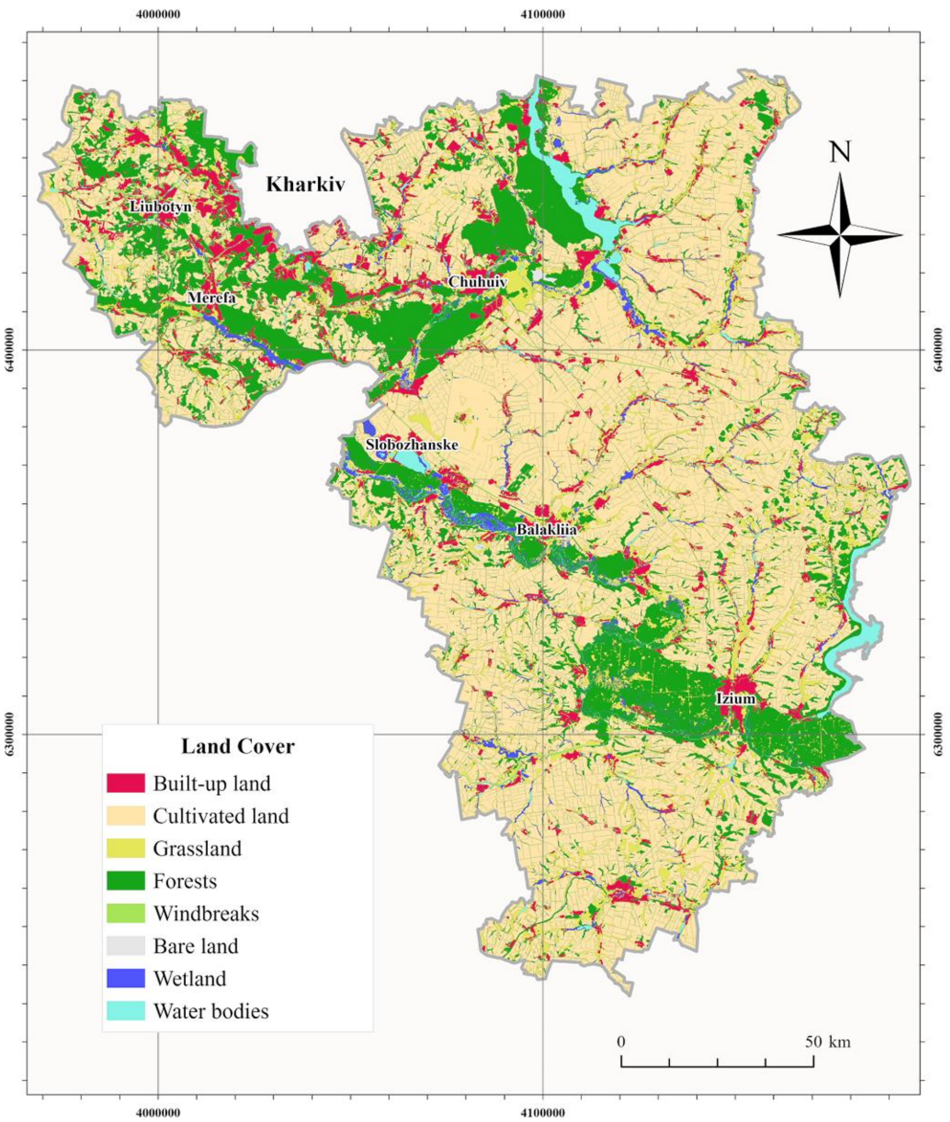


Figure 3.4 shows the map of Kharkiv land cover. **Source:** *Bonchkovskyi et al., 2025*

Table 3-2 shows the properties of polluted chernozem soil in the Kharkiv region. Sources: (Bonchkovskyi et al., 2025; Solokha et al., 2024; Backman et al., 2025)

Contaminated Black Soil (Chernozem) Properties	
Temperature	
Summer	**+20.6 ± 1.5**
Winter	**-4.7 ± 5.3**
Average annual	**+7.6 — 8. 2**
pH	**5.7 — 8.1**
Other	
Organic matter	**2.2 - 83**
Phosphorus (P) mg/kg	**16 – 45**
Potassium (K) mg/kg	**1 – 337.4**
Organic carbon (%)	**3.86 - 14.27**
Soil type / Soil texture	**Muddy clay, loamy, sandy loam**

3.3. Contamination caused by the war

Russia's invasion of Ukraine on February 24, 2022, has significant health and environmental consequences not only on humans and infrastructure but also on the soil, water, and ecosystems. (**Wei et al., 2025**). Ongoing military operations, such as the movement of military vehicles, the deployment of various types of military equipment, and the excavation of trenches, have negatively impacted soil physical properties. In addition, some activities carried out, like the use of bombs, grenades, shells, and mines, have major environmental impacts on the soil, leading to explosive residues and heavy metals, which are the major contaminants affecting the Ukrainian agricultural land. Moreover, the burning of military equipment and the spillage of lubricants also increase soil pollution. (**Bonchkovskyi et al., 2025**).

Military activities require significant amounts of fuel and hydrocarbons, which may result in oil and gas contamination of soil through lubricant spills. Lubricant-contaminated soils are most likely to be polluted with heavy metals such as Zn, Cu, and Ni. The use of weapons associated with heavy metal contamination is likely to cause heavy metal pollution in soil, groundwater, and surface water, especially Lead (Pb), due to its use in bullet production. Studies suggest that high concentrations of lead in soil may hinder plant growth and reduce soil fertility. (**Lawrence et al., 2015**). According to (**Sytar & Taran, 2022**) Metals such as Zn, Cu, Ni, Pb, and Cr can also be used in the production of missiles, gun barrels, coated bullets, and military vehicles, and the types of ammunition used will determine the environmental emissions. For example, the use of NM229 with a steel core may result in the release of high quantities of substances containing Cu and Zn. Moreover, the use of a weapon like the SS109 design with a soft lead core produces Pb particles. Cu, Zn, and Fe may also result from firing lead-free small-caliber weapons. Based on the above analysis, it can be concluded that military activities play a crucial role in soil contamination in Ukraine.

Military actions involve explosives and propellants, particularly nitroaromatics such as TNT and nitramines (e.g., RDX, HMX). Nitroaromatics include TNT and its impurity, DNT, a high-priority pollutant with poor solubility. RDX is the cornerstone for numerous military explosives, including nuclear uses, and HMX can be made from it. These chemicals offer major environmental dangers and are being investigated for cleanup. Propellants, primarily nitrocellulose-based, are also of concern; research on chemicals such as nitroglycerin in soil is sparse. These explosives and propellants have low affinity and volatility, making them mobile in the ecosystem. (**Fernandez-Lopez et al., 2022**). Table 3-3 shows contaminants caused by military activities.

Table 3.3 Organic contaminants from military activities.

Group	Example	Military activities	Method of analysis	Source
Toxic compounds	**Hazardous waste** (Lubricants spilled)	Storage areas, or accidental discharges	Gas chromatography	(**Fernandez-Lopez et al., 2022**)
	Pesticides (Camouflage netting or spatial repellent on the wall)	Used for pest control and for the protection of the military staff	GC/flame ionization	(**Fernández-López et al., 2022**)
	Per-and polyfluoroalkyl substances (PFASs) PFHxS, PFOS, PFOA	Firearm training practice	Liquid-liquid extraction	(**Fernández-López et al., 2022**)
Energetic compounds	**Explosives** (Nitroaromatics: TNT)	An explosive used in training practices	Solid-phase extraction	(**Fernández-López et al., 2022**)
	Nitramines: (RDX & HMX)	RDX (common military) explosive. HMX is used as a rocket propellant and an agglutinated explosive powder for nuclear weapons	Gas chromatograph with an electron capture detector	(**Fernández-López et al., 2022**)

3.4. Impacts of metals and explosives on agricultural crops in Ukraine

According to (**Pande et al., 2022**) health largely depends on its biology, and to enhance sustainable agriculture, maintaining healthy soil quality is essential. Anthropogenic activities, such as war, are the main cause of heavy metal pollution in soil, leading to imbalances in soil microbial communities through leaching into the soil environment. With the increase in these activities, contaminant concentrations rise, reducing microbial viability. (**Pande et al., 2022**). War can be considered a primary source of heavy metal pollution in the ecosystem, with significant contamination coming from military activities such as mines, grenades, bombs, and the destruction of constructed infrastructure. (**Sytar & Taran, 2022**).

The environmental impact of heavy metal concentration on Ukrainian agricultural production shows that Pb, Cr, and Cu are the most dominant contaminants in soil. Some regions in Ukraine, for example, Kharkiv, have a significantly high level of Cr due to numerous industries, with Ni, Zn, and Co reported to be at or below the maximum acceptable levels. (**Sytar & Taran, 2022**) High concentrations of heavy metals such as Pb, Cd, Cr, Ni, and Co have been reported to hinder the growth of plants such as corn (Zea mays L). (**Hussain et al., 2013; Sytar & Taran, 2022**). As stated by (**Hussain et al., 2013**) and Co, Pb has a detrimental impact on germination and the growth of corn (Zea mays L). It also reduces chlorophyll production by inhibiting iron and magnesium uptake and degrades the photosynthetic processes of plants such as wheat and corn. Cadmium and nickel reduce wheat germination and lower plants' nutritional content, while chromium slows the growth of wheat's shoots and roots (**Sytar & Taran, 2022**)

The contamination of soil by explosive, hazardous chemicals requires deliberate efforts to encourage the establishment of anaerobic and nitro-reducing microbes. Many of these microorganisms struggle to thrive in soils contaminated with nitroaromatic explosives due to the toxicity, which can cause mutagenic consequences, membrane changes, and disruptions in metabolic pathways. Addressing this problem is critical for minimizing explosive toxicity and restoring soil microbial balance, which is vital for soil health, crop development, and sustainable resource use. **(Corredor et al., 2024b)**

Contaminants from explosives have long-lasting and detrimental effects on soil. Persistent explosives such as TNT, RDX, and HMX produce toxic, hazardous, and mutagenic by-products that suppress microbial activity in soil. These effects, along with the elevated concentration of explosives, cause microbial suppression. Explosive pollution caused by high-energy nitrogen compounds has a substantial impact on the microbial community by boosting the abundance of environmental DNA from certain microbes, such as Pseudomonas, Arthrobacter, Archaea, and Geobacter. This shift affects soil diversity, resulting in poor soil quality, nutrient cycling, and overall land health, while disruptions from ammunition and detonations cause negative changes in geochemical characteristics. (**Corredor et al., 2024b**).

4. Method

This chapter outlines the approach utilized to investigate nature-based remediation techniques for soils contaminated by heavy metals and explosives. It is based on a systematic literature evaluation of the Scopus database, which adheres to the PRISMA paradigm for transparency and reproducibility. The research included identifying critical pollutants, determining remediation strategies, and using structured search strings to collect literature. The systematic review aimed to build a strong foundation for assessing nature-based solutions for contaminated agricultural soils by analyzing research on co-contamination, particularly involving metals and explosives such as TNT and RDX.

4.1. Identifying opportunities for complementing previous studies

This research builds on the established databases of nature-based remediation solutions compiled by **Menson et al. (2023**) and **Backman et al. (2025**), which predominantly address heavy metal pollution. Nevertheless, these sources already provide systematic overviews of remediation methods, including phytoextraction, phytostabilization, and phytoexclusion. However, their primary focus is on the use of plants, soil amendments, and microbes to remediate metals in soils. One major gap that needs to be addressed is explosive remnants like TNT and RDX in Ukrainian war-induced soil contamination. In terms of their chemical characteristics, environmental behavior, and cleanup, explosive pollutants differ markedly from metals. Metals are permanent and non-degradable, whereas explosive chemicals are organic pollutants that can be transformed and decomposed, especially via microbial processes. The examination of the current databases identified several chances for enhancement, especially in broadening their relevance to soils with a mixture of metal and explosive contamination. Table 4.1 provides a detailed evaluation of the coverage of previous studies.

Table 4.1. Nature-based Solutions covered by (Menson et al., 2023) and Backman et al. (2025) can be used to address metal contamination in soils. The gaps to be addressed in this study concern explosives in soils.

Mechanisms	Metals	Explosives Residues
Phytoextraction	Plants used for removal recommended by (Menson et al., 2023)	Plants?
Phytostabilisation	Plants, Amendments, and Microorganisms for removal (Menson et al., 2023; Backman et al., 2025)	Plants? Combined with amendments (immobilizing agents)? Microorganisms?
Phytoexclusion	Plants (often in combination with amendments) (Backman et al., 2025)	Plants excluders? Combined with amendments (immobilizing agents)?
Degradation	Not applicable.	Plants? Combined with amendments (chelating agents)? Microorganisms?
Immobilization	Amendments Backman et al., 2025)	Amendments (immobilizing agents)?

Menson et al. (2023) and Backman et al. (2025) delineate three principal remediation agents of nature-based solutions for soil contamination: Plants, Soil amendments, and Microorganisms. These agents are well-documented and compiled for managing risks posed by metals, but their roles in addressing explosive contamination in soils have not been systematically investigated. The investigation underscores the need to explore the role of plants in the absorption and transformation of explosives, assess the efficacy of soil amendments for immobilization of explosives in soils, and highlight the essential role of microorganisms in addressing explosive contamination in soils. This integrated viewpoint is especially crucial for managing co-contaminated soils in which metals and explosives co-occur.

4.2 PRISMA

A systematic literature review was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a transparent, repeatable, and organized approach to identifying relevant research. The review concentrated on nature-based remediation techniques for soils polluted with metals and explosive residues, specifically TNT and RDX. The Scopus database served as the primary source of literature. A set of predetermined search terms (refer to Section 4.2.4) was used to identify relevant studies, and only peer-reviewed studies in English were considered. The search procedure consisted of identifying and collecting peer-reviewed literature, critically screening and selecting relevant studies, and combining the findings in an Excel database, in which duplicate records and irrelevant literature were excluded. To make the review more relevant, the PRISMA process was broken down into three analytical steps: identification of supplementary contaminants, identification of nature-based remediation techniques, and identification of circumstances particular to Ukraine.

4.2.1. Identifying complementary contaminants

The initial phase of the PRISMA process focused on identifying the principal pollutants associated with post-conflict soils. This research primarily focuses on explosive residues, specifically TNT and RDX, and also examines supplementary pollutants, notably heavy metals. This technique is essential as contamination in post-conflict settings seldom happens in isolation. Military operations bring a variety of contaminants, including metals (such as lead, copper, zinc, and cadmium) and explosive chemicals, which may interact and affect each other's mobility and bioavailability.

Search phrases were thus formulated to encompass both explosives and metals, ensuring the inclusion of research on co-contamination scenarios. This facilitated a more thorough understanding of the actual circumstances and aided the assessment of remediation techniques capable of concurrently addressing multiple pollutants.

4.2.2 Identifying methods

The subsequent phase focused on identifying nature-based remediation options for agricultural soil contaminated with heavy metals and explosive residues. These remediation methods were suggested in accordance with studied literature and databases from **Menson et al. (2023)** and **Backman et al. (2025)** and were incorporated in the search string, including phytoremediation mechanisms such as (phytoextraction, phytostabilization, phytoexclusion, phytodegradation, Rhizodegradation), bioremediation (microbial decomposition of explosives), biosorption, and soil amendment-based immobilization.

Each option was chosen based on its proven efficiency in treating heavy metals or explosive residues in soils. Emphasis was placed on identifying the function of plants in absorption or stabilization, the use of soil amendments for immobilization (e.g., biochar, compost) or mobilization for improving phyto- and rhizodegradation or phytoextraction (chelating agents), and the role of microorganisms in the breakdown of explosive remnants. Understanding the variations in processes across pollutant kinds was also a priority. For example, although phytoextraction works well for metals, degradation-based techniques are more appropriate for explosives. This methodical methodology guaranteed that both metal-centric and explosive-centric remediation techniques were thoroughly documented and analyzed.

4.2.3. Identification of conditions specific to a particular location

The literature search encompassed worldwide studies, with a focus on discovering research pertinent to post-conflict agricultural situations. The specified requirements include the following: 1) Soil classification (e.g., chernozem soils characterized by large organic matter contents), 2) Utilization of agricultural land. 3) Post-disturbance situations (e.g., demined terrain, soil disruption due to explosions) and 4) Climatic and environmental variables affecting contaminant dynamics. Given the limited availability of Ukraine-specific research, relevant foreign studies conducted under environmental and agricultural conditions that to some extent resemble Ukrainian ones were also incorporated. This methodology facilitates the application of international knowledge to the Ukrainian setting. The interplay between toxins and site conditions such as pH, soil organic matter, and microbial activity was considered when assessing the suitability of remediation options.

4.2.4. Search for information using PRISMA

A systematic literature search was conducted using the Scopus database to identify relevant research on the nature-based remediation of soils polluted with explosive residues (specifically TNT and RDX) and heavy metals. The search strategy was established in alignment with the PRISMA framework to provide a systematic, transparent, and reproducible method for data collection. This stage aimed to compile a comprehensive collection of papers on various remediation strategies in environmental and agricultural contexts.

The search strings were constructed using a combination of terms related to pollutants, environmental media, and remediation strategies. The names “TNT,” “RDX,” and “Explosive*” were employed to denote the target pollutants, while “soil” was incorporated to specify the environmental context. These were amalgamated with method-specific keywords including “phytoremediation,” “amend*,” “stab*,” “immob*,” “phytoex*,” “biosorption,” and “bioremediation.” Boolean operators (AND, OR) were utilized to organize the search queries, and the implementation of wildcards (*) enabled the incorporation of variants of important phrases, thereby enhancing the sensitivity of the search. Five principal search keywords were created, each aligned with a distinct remediation strategy. The phytoremediation search string returned 237 entries; after eliminating four duplicates, 26 pertinent research articles remained. The search query for soil amendment, stability, and immobilization yielded 526 hits; two duplicates were eliminated, and four research articles were deemed relevant. The search for phytoextraction studies yielded 21 studies; however, none met the relevant requirements after screening. Likewise, the biosorption inquiry yielded seven results; however, no pertinent research was found. Conversely, the bioremediation search string yielded 471 matches, with 28 papers retained after screening, indicating a more robust representation of this strategy in the literature on explosive wastes.

In addition to duplicates found within individual search strings, the dataset was further refined by eliminating cross-string duplicates and triplicates. One hundred eighty-five duplicate records and thirty-six triplicate records were detected and eliminated. This procedure ensured that each study was included only once in the final dataset, thereby enhancing the overall reliability of the analysis.

After duplicates were removed, all papers were evaluated for relevance based on their titles and abstracts. Only studies concerning soil contamination by metals and/or explosive residues, as well as those emphasizing nature-based remediation strategies in environmental or agricultural contexts, were chosen for comprehensive examination. The screening approach guaranteed that the final 58 studies were pertinent and consistent with the study's aims.

The systematic search method facilitated the discovery of a varied corpus of literature, including several remediation techniques. The findings indicate that bioremediation and phytoremediation are the most extensively researched treatments for soils polluted with explosives. However, techniques such as phytoextraction and biosorption have limited application in this context. These findings provide a robust basis for the ensuing study and assessment of the remedial options discussed in the following sections. See Table 4-2-4 for the results of the search strings.

See Table 4-2-4 shows the results of the search strings for different methods.

Number of strings	Nature-Based Solutions	Search string line	Number of Hits	Duplicates *	Reference (relevantly)
String 1	Phytoremediation	TNT OR RDX OR Explosive* AND soil AND phytoremediation OR "nature-based solution*."	237	4	237 (26)
String 2	Amendment /Stabilization /Immobilization	TNT OR RDX OR Explosive* AND soil AND amend* OR stab* OR immob* OR "nature-based solution*"	526	2	526 (4)
String 3	Phytoextraction	TNT OR RDX OR Explosive* AND soil AND phytoex* OR "nature-based solution*."	21	-	21 (0)
String 4	Biosorption	TNT OR RDX OR Explosive* AND soil AND biosorption OR "nature-based solution*."	7	-	7 (0)
String 5	Bioremediation	TNT OR RDX OR Explosive* AND soil AND bioremediation OR "nature-based solution*."	471	-	471 (28)

*Additionally, cross-string **duplicates (185)** and **triplicates (36)** were detected and eliminated

4.3. Method of analysis

The selected studies were examined using a systematic qualitative comparative method. The evaluation focused on collecting and analyzing data on contaminants and nature-based remediation options, with a particular emphasis on explosive residues and heavy metals in soils. Each study was evaluated using key criteria, including remediation efficiency, pollutants, environmental conditions, and scalability.

Emphasis was also placed on investigating strengths and limitations across various nature-based remediation options. The study also addressed environmental conditions and pollutant interactions, as these pollutants exhibit divergent behaviors in soil systems.

Data from previous studies by Menson et al. (2023) and Backman et al. (2025) were combined with the complementary literature review in this thesis to synthesize the results.

The literature for this study was chosen using predetermined inclusion and exclusion criteria to guarantee consistency, relevance, and scientific quality throughout the review process. The criteria were used to screen articles, evaluate abstracts, and assess full texts using the PRISMA approach. Studies provided in the English language were considered for inclusion if they met one of the following criteria given below.

- Peer-reviewed journal articles from the Scopus database focused on remediation of metals and explosives in soil.
- Studies conducted on nature-based remediation options of Phytoremediation, bioremediation, soil amendments (immobilization) and biosorption.
- Research investigating field-scale, pilot-scale, and pot experiments relevant to contaminated soil cleanup.
- Articles focus on Ukraine agricultural land contamination, and environmental remediation under conditions relevant to Ukraine soil properties.
- Literature on contaminant sources, mobility, and bioavailability

Some studies were excluded from the review due to one or more of the following criteria given below.

- Literature with no relevance to soil contamination or remediation.
- Duplicates and triplicates identified during the PRISMA screening process.
- Not accessible articles or required purchasing.
- Literature containing reports, conference abstracts, editorials, or opinion papers.
- Literature unrelated to Nature-based remediation options, explosives, or heavy metals.
- Studies with insufficient experimental data or findings analysis.

4.4. Evaluation of results

The results were evaluated using a qualitative assessment methodology to examine the efficacy and suitability of nature-based restoration options for soils polluted with heavy metals and explosive residues in Ukraine. The selected studies, identified through a PRISMA-based review using Scopus, were evaluated based on remediation efficiency, scalability, environmental conditions, and relevance to agricultural settings.

Several evaluation criteria were applied during the assessment procedure. These included pollutant type, remediation efficacy, reduced contaminant mobility or bioavailability, environmental sustainability, and compatibility with agricultural soils. Additional requirements included field adaptability, compatibility with Ukrainian chernozem soils, scalability for vast polluted regions, and the possibility for long-term restoration.

The research was also evaluated under various experimental conditions, including laboratory, greenhouse, pot, pilot-scale, and field investigations. Studies conducted under real-world environmental settings received special consideration because they provide more credible information about practical remediation performance. Studies that provided detailed methodology explanations, pollutant analysis, and measurable remediation outcomes were deemed more relevant to the review process.

The review also considered each study's limits and uncertainties, such as climate variability, soil heterogeneity, remediation time, and variations between experimental and actual agricultural situations. The total study enabled the selection of the most appropriate remediation options for Ukraine's polluted agricultural soils, considering environmental, agronomic, and practical implementation considerations.

4.4.1. Assessment of Technology Readiness Level (TRL)

The Technology Readiness Levels (TRL) framework, created by NASA in the late 1970s, assesses technology maturity for space exploration. Originally consisting of seven stages, it was increased to nine in the 1990s, providing a consistent criteria for evaluating the advancement of technologies from theoretical conceptions to operational status. TRLs help engineers, researchers, and decisionmakers reach a common understanding, allowing for more informed discussions and effective technological development planning. This hierarchical scale facilitates effective resource allocation and project prioritization, as well as making technical information available to the general public. While the TRL scale is valuable, it is technology-neutral and may fail to account for the intricacies and specificities that distinguish various fields. Its simplicity, while appealing for communication, limits the depth of examination, frequently reducing complex technologies to a nine-step process (**Trucco, van Lopik and Zanobett et al., 2025**). Table 4.4-1 shows the nine steps of the TRL.

Table 4.4-1. Technology Readiness Levels (TRL) as defined in Scaling up ideas. Using Technology Readiness Levels to analyse technology progression in Horizon Europe. (European Commission 20225)

TRL	**Description**
TRL 1	The Basic principles need to be observed
TRL 2	Formulation of the Technology Concept
TRL 3	Evidence of the Experimental Concept
TRL 4	Laboratory validation of the Technology
TRL 5	Technology needs to be validated in a relevant environment such as (industrially relevant)
TRL 6	Technology needs to be demonstrated in a relevant environment, like (industrially relevant)
TRL 7	System prototype demonstration in a relevant operational environment.
TRL 8	System needs to be completed and qualified
TRL 9	The actual system must be proven in an operational environment (competitive manufacturing).

The Technology Readiness Level (TRL) framework was used in the evaluation process to determine the maturity and practical applicability of the selected nature-based remedial techniques. TRL offers a systematic method for discriminating between remediation procedures proven under controlled experimental circumstances and those performed in more realistic field situations.

This thesis categorizes remediation studies based on their experimental scale and technical advancement. Laboratory-based tests, such as controlled laboratory research, pot experiments, and greenhouse trials, were classified as low technological readiness levels (TRL 3-4). These investigations give valuable insights into remediation mechanisms pollutant behavior, and treatment efficiency under controlled settings; nevertheless, their direct applicability to large-scale agricultural systems is questionable.

Field-scale and pilot-scale studies were assigned higher technological readiness levels (TRL 5-6). These studies give more evidence for practical implementation since they assess restoration efficacy under actual environmental variables such as natural soil variability, climate change, and operational obstacles.The TRL assessment was combined with the evaluation criteria to find remediation approaches that are both chemically effective and potentially applicable to large-scale agricultural recovery in Ukraine. Methods backed just by laboratory evidence were deemed insufficient for rapid application, but approaches supported by field-based data were deemed more suited for practical implementation.

5. Results

This chapter presents and summarizes the results obtained from the PRISMA methodology of each identified nature-based remediation option that complement previous studies by **Menson (2023)** and **Backman et al. (2025)**. The appendices provide a comprehensive analysis of each table.

5.1. Phytoremediation

Phytoremediation, for example phytoexclusion, has been proven in small-scale farmland, but its application to remediate large-scale contaminated agricultural fields remains uncertain. One of the feasible and practical solutions to this problem is the selection of crops with the ability to accumulate low heavy metals such as cadmium and arsenic in the food chain (**Duan et al., 2017**). Table 5.1 shows results of phytoremediation of heavy metals and explosives, and Appendix A provides more detailed information about these experiments.

Table 5-1. Various crops used in phytoremediation of heavy metals and explosive residues, based on field experiments from relevant studies; all values presented are in accordance with the articles.

Phytoextraction Plants						
Common Name	**Variety**	**Scientific Name**	**Absorbable Contaminant**	**Initial Concentration C_0 (mg/L**	**Concentration in plants**	**References**
Maize	Guidan No. 0810	Zea mays L.	Cd	2.6 mg kg^{-1} pH 5.46 ± 0.02	**In Roots** 76% (49–108%, *P* <0.01); **In Stems** 69% (39–120%, *P* <0.01); **In Leaves** 85% (54–139%, *P* < 0.01); **In Grains** 74% (44–125%, *P* <0.01); [B]**pH-adjusted** LMWOAs (pH 7.0); **In Roots** 47% (17–77%, *P* <0.05); **No influence in Cd uptake in stems, leaves, and grains**	(**Y. Wang et al., 2025**)
Rapeseed	cv. Ganza 1,	(*Brassica napus* L.)	Cd	4.838 mg/kg	**Acetic acid (AA)** plant uptake of Cd (146%) **Oxalic acid (OA)** plant uptake of Cd (67%) **Citric acid (CA)** plant uptake of Cd (110%) **Malic acid (MA)** plant uptake of Cd (53%) **Tartaric acid** (TA) plant uptake of Cd (82%)	(**Qiao et al., 2020**)
Sunflower	Asteraceae	*Helianthus annuus* L.	U Cd	3.48 mg/kg and 0.29 mg/kg initial concentrations in soil 15 mg/kg (added to U and Cd pots)	5.0 mmol/kg Citric acid (CA) increases plant uptake of U, Cd (177.48%) 5.0 mmol/kg ethylenediamine disuccinate (EDDS) increases plant uptake of U, Cd (181.51%)	(**L. Chen et al., 2020**)
Sunflower	Asteraceae	*Helianthus annuus* L.	Pb	0, 10, 20, 40, 80, 100, and 200 mg kg^{-1}**.**	200 mg kg^{-1} **Pb** reduces weight of shoot and root (76.6% - 64.3%) Shoot and Root length (71.6% and 94.1%) Maximum concentration in shoot (40.1 mg kg^{-1} Dwt) Maximum concentration in Root (107.7 mg kg^{-1})	(**Alaboudi et al., 2018**)
			Cd		200 mg kg^{-1} **Cd** reduces weight of shoot and root (88.5% - 80.80%) Shoot and Root length (83.2% - 95.1%) Maximum concentration in shoot (65.7 mg kg^{-1} Dwt) Maximum concentration in Root (71.3 mg kg^{-1})	
Indian mustard		*Brassica juncea*	Zn	58 ± 10 mg/kg After contamination 993 $mgkg^{-1}$ ·	Indian mustard and ethylenediaminetetraacetic acid (EDTA) Reductions of (51.5%)	(**Pruteanu et al., 2026**)
			Cu	Initial $\mathbf{C_0}$ 18 ± 4 mg/kg **After contamination** 534 mg·kg^{-1}	Indian mustard and ethylenediaminetetraacetic acid (EDTA) Reductions of (27.5%)	
			Pb	8 ± 3 mg/kg **After contamination** 152 mg·kg^{-1}	Indian mustard and ethylenediaminetetraacetic acid (EDTA) Reductions of (36.3%)	

Phytoexclusion Plants						
Rice (not grown in Ukraine)	ShenYou957, LongPing602, Weiyou402, WeiYou463, ZhuLiangYou168, I-You899, Ilyou906	Oryza sativa L.	Cd	2014 (0.4 - 0.5) 2015 (1.4) pH: 7.5	**2014** (0.03 to 0.86 mg kg^{-1}) (0.06 - 0.58 mg kg^{-1}) **2015,** (0.02 - 0.24 mg kg^{-1}) (0.08 - 0.68 mg kg^{-1},) (0.14 -1.17 mg kg^{-1})	(**L. Wang et al., 2021); (Duan et al., 2017**)
Wheat	Taishan-24, Tanmai-98, Jinan-17, Xiayan-81, Jimai-22, Taishan-21, Yumai-34, Shi-4185, Wennong-14	Triticum aestivum L.	Cd	**Total Cd Field trial 1** 0.322 ± 0.020 mg kg^{-1} **Field trial 2** 0.421 ± 0.026 mg kg^{-1} **Field trial 3** 0.215 ± 0.058 mg kg^{-1}	***Groups I** 0.069 mg kg−1 ***Group II** 0.085 mg kg−1 ****Group III** (0.11 mg kg−1 *****Groups IV** (0.13 mg kg−1 *****Group V** (0.15 mg kg−1	(**Liu et al., 2020**)
Barley	Beitalys Shang 98-128	Hordeum vulgare L.	Cd	0.15 mg kg^{-1} pH 7.10	97.5% lowest Cd concentration in Beitalys and Shang 98-128	(**F. Chen et al., 2007**)
Soybean	Cultivar Tiefeng 31	Glycine max *L.*	Cd	Cd (0.15, 0.75 and 1.12 mg/kg) Ph (6.5, 6.6, 6.0) Temp. 15–25°C	**Root:** POT 1: 0.16 ± 0.05a Pot 2: 0.41 ± 0.02b Pot 3: 0.48 ± 0.01a	(**Zhi et al., 2015**)
Maize	Maize	*Zea mays* L.	TNT	Maize (213 mg TNT/kg)	**Under axenic conditions** (32% to 38%) **With only bacteria** (10%) Removal **Inoculated with *P. putida* JLR11(30**°C) (80% to 88%) **Regardless of inoculation** 96% removal in 60 days	(**van Dillewijn et al., 2007**)
Beans	Broad Beans	*Phaseolus vulgaris*	TNT	Beans (500 mg TNT/kg)	**Under axenic conditions** (32% to 38%) **Inoculated with *P. putida* JLR11** (80% to 88%)	
Switch Grass	*Panicum virgatum* L, SW	*Panicum virgatum L.*	TNT	1.0 mg kg^{-1} in soil	More than 95% TNT degradation in 7 days	(**N. Li et al., 2024**)
Eastern Gamma Grass	*Tripsacum dactyloides*, EG	*Tripsacum dactyloides*	TNT		More than 95% TNT degradation in 7 days	

*Groups I & II has the lowest Cd concentration in grains with an average of 0.069 mg kg^{-1}. and 0.085 mg kg^{-1}.
**Group III result shows medium Cd concentration in grains averaging 0.11 mg kg^{-1}.
*** Group IV & V shows the high, and extremely high concentration in Cd with an average of 0.13 mg kg^{-1}. and 0.15 mg kg^{-1}.
[B] Low Molecular Weight Organic Acids (LMWOAs) was used to mobilize Cd uptake with **pH-adjusted** (pH 7.0).

The phytoremediation studies examined showed different remediation efficiency for metals and explosive residues in greenhouse, pot, and field environments. Inorganic and organic chelating agents were often used to improve contaminant absorption and removal efficiency in soils by increasing pollutant bioavailability. Cadmium uptake rose by 146% after acetic acid treatment, while citric acid and EDDS boosted uranium and cadmium uptake by about 177% and 181%, respectively. (**Qiao et al., 2020; L. Chen et al., 2020**) (TRL 3-4). EDTA-assisted remediation significantly reduced zinc, lead, and copper contents in polluted soil by 51.5%, 36.3%, and 27.5%, respectively. (**Pruteanu et al., 2026**) (TRL 3-4). Several agricultural crops significant to Ukraine, such as maize, sunflower, rapeseed, and Indian mustard, have shown the ability to withstand and accumulate pollutants in their aboveground biomass. However, different varieties of maize can be either excluders or accumulators of metals. The investigations also demonstrated that increasing concentrations of dominating contaminants such as Cd and Pb significantly influenced biomass output and plant growth. At a total contamination concentration of 200 mg kg^{-1}, shoot and root biomass decreased by 64% to 89%, while shoot and root length decreased by 71% to 95%. (**Alaboudi et al., 2018**) (TRL 3-4). Despite these reductions in biomass, contaminant buildup persisted in plant tissues, demonstrating tolerance to contaminants.

Studies on phytoexclusion revealed that dominating contaminants, particularly Cd, were less likely to be transferred into edible tissues. Cadmium levels in grain remained low in field testing, ranging from 0.02 to 0.15 mg kg^{-1} based on contamination amount and cultivar. Some cultivars reduced cadmium transport into cereals by nearly 97.5%, (TRL 5-6), lowering food-chain contamination hazards. (**F. Chen et al., 2007**)

TNT, RDX, and HMX were all degraded significantly during rhizodegradation of explosive wastes. Under bacterial inoculation circumstances, explosive removal efficiency ranged from 80% to 88%, with certain remediation systems degrading more than 95% of TNT within seven days. Longer repair times resulted in degradation efficiencies surpassing 96% after 60 days (TRL 5-6) (**van Dillewijn et al., 2007**).

Overall, the analyzed phytoremediation studies indicate that agricultural crops relevant to Ukraine may provide long-term and low-cost remediation options for contaminated agricultural land. However, pollutant content, soil pH, amendment application, plant species, and environmental variables all had a significant impact on remediation efficiency.

5.2. Biodegradation

The bioremediation studies that were examined investigated the potential of bacteria, fungi, and microbial consortia to break down explosive residues and decrease heavy metal pollution in laboratory and pilot-scale conditions. The identified research studies mostly addressed the risks posed by TNT, RDX, HMX, TPT, chromium (Cr), cadmium (Cd), lead (Pb), and copper (Cu) in soils. Several studies investigated the integrated impact of ambient factors on remediation effectiveness, such as nutrient availability and microbial augmentation. See Table 5.2 and for more information about the various experiments referred to Appendix A

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Table 5.2 illustrates the results table for various bacteria and fungi used in bioremediation explosive residues and metals based on field experiments from relevant studies in which all values presented are in accordance with the various articles.

Bioremediation					
Additive	**Scientific Name**	**degradable Contaminant**	**Initial Concentration C_0 (mg/L)**	**Degradation Efficiency**	**References**
Bacteria	Mirobial consortium and animal-waste compost	RDX TNT HMX	120.46 ± 34.54 mg kg^{-1} 144.73 ± 36.95 mg kg^{-1} <LOQ	W = 12, p = 0.050 W = 12, p = 0.0319 W = 0.01, p = 0.0436	(**Ben Laish et al., 2025**)
	Waste glycerol (WG)	RDX	0 to 0.4 mg kg^{-1} DW (mean ± SD = 0.1 ± 0.1 mg kg^{-1} DW soil)	In (0 –7.5-cm) RDX un-detectable In (7.5–15-cm) RDX decrease 90%	(**Jugnia et al., 2018**)
		DNT	0 to 247.4 mg kg^{-1}(DW) (mean ± SD = 52.1 ± 65.4 mg kg^{-1} DW soil)	In (0 –7.5-cm) and (7.5–15-cm) No clear decrease	
	Indiicoccus explosivorum (S5-TSA-19); Concentration (900–1000 mg/Kg)	TNT	60, 80, 100, 120 mg/L,; Temperature (30 ˚C (± 5 ˚C), and pH (7)	100% TNT (120 mg/L degradation achieved	(**Lamba et al., 2022**)
	Pseudarthrobacter chlorophenolicus	TNT	900–1000 mg/kg	100% ; TNT (120 mg/L Degradation achieved	(**Lamba et al., 2021**)
	Bacillus cereus	TNT	50 mg L^{-1} 75 mg L^{-1}	68% 77%	(**Mercimek et al., 2013**)
	GNJ1 & GNJ2 *Firmicutes (Bacillus albus AB and Bacillus havnesii 190311L225)* GNJ3 *Proteobacteria (Pseudomonas balearica A69)*	TPT	Surface soil (depth 0–10 cm), 888,615.75 mg kg^{-}	**Surface** 99.87%, **Middle** 96.04%, **Deep** 71.63% ; in the Bioaugmentation (BA) Group	(**Nong et al., 2023**)
			Middle soil (depth 10–20 cm) 15,342.13 mg kg^{-1}	**Surface Soil**: 99.75%, **Middle soil**: 95.73%, **Deep soil**: 99.84%; in the Biostimulation (BS) group	
			Deep soil (depth 20–40 1630.06 mg kg^{-1}	Surface soil :8.55%, Middle soil: 8.64%, Deep soil 9.84% in the Natural attenuation (NA) group	
	Bacillus sp strain FM1	Cr (VI)	50 – 200 mg/L	100% reduction 50 & 100 mg/L in 12h & 48h; Temp. 37 ˚C; pH 8.0	(**Masood & Malik, 2011**)
White-rot Fungi	Gymnopilus luteofolius 466 (X9), Kuehneromyces mutabilis 508 (K22), Mycena galericulata 598 (K175), Phanerochaete velutina 941 (T244i), Physisporinus rivolosus 939 (T24li) , Stropharia rugosoannulata 475 (11372).	TNT	19000 mg kg^{-1} Diluted soil (1:1) 9500 mg kg^{-1} Diluted soil (1:20) 1000 mg kg^{-1} Diluted soil (1:40) 500 mg kg^{-1}	80% TNT degradation in Lab scale 70% TNT degrade in Pilot scale	**Anasonye et al., 2015**)

The bioremediation studies examined indicated high degradation efficiencies for major contaminants such as TNT, RDX, HMX, TPT, DNT and chromium (Cr), under laboratory and pilot-scale experiments. Significant reductions were seen after bioaugmentation, compost-assisted remediation, and microbial consortium application. Statistical analysis revealed considerable reductions in TNT and HMX, but only moderate decreases in RDX. TNT was completely degraded (100%) within 7 days of incubation at an initial concentration ranging from 60, 80, 100, 120 mg/L in optimal laboratory conditions of neutral pH and temperatures near 30°C. (**Lamba et al., 2021**) (TRL 3-4). Other investigations found that TNT degradation efficiency ranged from 68% to 77% depending on pollutant concentration and cleanup settings. (**Mercimek et al., 2013**) (TRL 3-4). For TPT-contaminated soils, bioaugmentation and biostimulation techniques yielded removal efficiency of more than 95% in a time span of 300 days, whereas natural attenuation efficiencies were significantly lower, below 10%. (**Nong et al., 2023**) (TRL 3-4)

Pilot-scale fungal remediation studies produced roughly 70% TNT degradation over 70 days (TRL 5-6), whilst laboratory-scale research showed over 80% degradation efficiency even at high TNT concentrations for 90 days (**Anasonye et al., 2015**) (TRL 3-4). Overall, the evaluated research indicate that bioremediation might be a successful remediation technique for explosive-contaminated soils in Ukraine. However, degradation efficiency is affected by environmental factors such as pollutant concentration, microbial activity, oxygen availability, and nutrients' supply.

5.3. Biosorption (immobilization by microbes)

The ability of biological materials to adsorb and immobilize heavy metals in regulated laboratory environments is the main topic of the reviewed biosorption research studies. Aqueous remediation techniques that target heavy metals like lead (Pb), cadmium (Cd), copper (Cu), nickel (Ni), chromium (Cr), and zinc (Zn) have received the most attention. Temperature, pH levels, pollutant concentrations, and the properties of the biosorbents utilized are important variables affecting the effectiveness of adsorption. Together, these investigations demonstrate biosorption's promise as a practical technique for eliminating heavy metals from tainted water sources.

Table 5.3 shows the results table for biosorption with absolutely no relevant to the contaminated black soil since all experiments were conducted in aqueous solution instead of soil.

Biosorption						
Additive	**Scientific Name**	**Location**	**Absorbable Contaminant**	**Initial Concentration C_0 (mg/L)**	**Absorption Efficiency**	**References**
Bacteria	*Bacillus* cereus BPS-9	Rohtak, India	Pb	100 to 2500 mg/L	79.26% Temperature 25 °C–45 °C pH 7.0	(**B. Sharma & Shukla, 2021**)
	Bacillus cereus 12–2	Youxi, Fujian Province China	Pb (II)	100 to800 mg/L @ pH 4.0	224.8 mg/g @ initial concentration 400 mg/L 226 mg/g @ initial concentration	(**Z. Chen et al., 2016**)

					800 mg/L @ pH 4.0,	
	Bacillus thuringiensis strain OSM29	Aligarh, North India	Ni Cu Pb Cr Cd	25, 50, 75, 100,125 and 150 mg l^{-1} @ 30min. 32 ± 2 °C for each for each metal	94% - pH 7.0 91.8% - pH 6.0 90.6% - pH 6.0 89.8% - pH 7.0 87% - pH 6.0 @ 25mg l^{-1}	(**Oves et al., 2013**)
	Endophytic Bacterium Bacillus sp. L14		Cd (II) Pb (II) Cu (II)	10 mg/L, pH 7.0 30 °C	75.78% 80.48% 21.25%	(**Guo et al., 2010**)
Micro Algae	*Nannochloropsis oceanica* strain CCMP1779	Kraków, Poland	Pb Cd Cu Zn	2.0720 mg/L 0.1124 mg/L 0.3177 mg/L 0.3269 mg/L	51.5% 0.7% 15.3% 1.7%	(**Lintner et al., 2025)**

The biosorption experiments examined indicated substantial adsorption capabilities for numerous heavy metals in aqueous laboratory settings. Under optimal pH and temperature conditions, lead removal efficiency approached 79% over 72 hours **(B. Sharma & Shukla, 2021)** (TRL 3-4). High lead concentrations and acidic pH conditions resulted in adsorption capabilities exceeding 224 mg/g. (**Z. Chen et al., 2016**). Multiple metal biosorption tests revealed removal efficiency of 87% to 94% for nickel, copper, lead, chromium, and cadmium at lower multiple metal concentrations (**Oves et al., 2013**) (TRL 3-4). Over 72 hours. Lead often demonstrated the highest adsorption efficiency when compared to other metals. Microalgal biosorption tests revealed a lead removal efficiency of roughly 51.5%, whereas cadmium, copper, and zinc removal efficiencies were significantly lower, ranging from 0.7% to 15.3% for approximately 12 days. (**Lintner et al., 2025**) (TRL 3-4). Additional studies examined also showed high remediation efficiency for major heavy metals immobilization by microbes. Chromium reduction achieved 100% at lower contamination levels in 12 to 48 hours under optimal circumstances. (TRL 3-4). Cadmium and lead removal efficiency from porewater were roughly 76% and 80%, respectively, while copper removal remained at around 21%. (**Guo et al., 2010**) (TRL 3-4). However, the majority of reported biosorption investigations were done in aquatic environments rather than agricultural soils. Although biosorption has great laboratory-scale sorption potential, its direct applicability for large-scale agricultural soil remediation in Ukraine may be restricted when compared to phytoremediation and bioremediation by means of degradation of organic pollutants.

5.4. Soil Amendment (immobilization)

The examined soil amendment studies focused on both organic and inorganic mobilizing agents targeted at minimizing contaminant mobility, improving soil characteristics, and increasing remediation efficacy in contaminated soils. The various research focused on metal contaminants such as cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), molybdenum (Mo), and explosives including TNT, RDX, and HMX. The amendments investigated in the study comprised biochar, compost, manure, vermicompost, sewage sludge, and different bioformulations.

Table 5.4. *Soil amendment for managing risks posed by metals, and explosives residues in soils, based on field experiments from relevant studies in which all values presented are in accordance with the various articles. The overall concentration of pollutants in soil, as stated in the corresponding column. The temperature linked with biochar represents the manufacturing temperature; if no temperature is included, it means that the original article did not mention this characteristic. Furthermore, the term "concentration" refers to the concentration levels mentioned throughout the context.*

Soil Amendments (immobilization)							
Additive	**Variety**	**Diversity**	**Immobilized Contaminants**	**Initial Concentration C_0 (mg/L)**	**pH**	**Absorption Efficiency**	**References**
Biochar	Asteraceae species	Sunflower straw (300 °C	**Pb (II)**	80	5.0	94.83% Removal from pore water	(**Nguyen et al., 2021**)
		Sunflower seed husk 450 °C	**Cu (II)**	95.32	6.39	>95.0% Removal from pore water	
Cow Manure	Brassica juncea	Mighty mustard, Black mustard, Yellow mustard	Ni	17.5 a mg kg^{-1}	7.95 a	0.301 ± 0.14 b	(**Nepal et al., 2024)**
			Cd	0.23 a mg kg^{-1}		0.434 ± 0.12 a	
			Pb	31.2 a mg kg^{-1}		0.689 ± 0.54 a	
			Mo	0.64 a mg kg^{-1}		1.76 ± 0.51	
			Cu	10.17 a mg kg^{-1}		4.31 ± 0.73 a	
			Zn			30.3 ± 12.02 a	
vermicompost			Ni	17.5 a mg kg^{-1}	5.71 a	0.373 ± 0.32 b	
			Cd	0.23 a mg kg^{-1}		0.332 ± 0.17 a	
			Pb	31.2 a mg kg^{-1}		0.484 ± 0.16 b	
			Mo	0.64 a mg kg^{-1}		2.06 ± 0.49 a	
			Cu	10.17 a mg kg^{-1}		5.2 ± 2.00 a	
			Zn			34.2 ± 9.3 a	
Leaf Compost			Ni	17.5 a mg kg^{-1}	7.4 a	0.204 ± 0.13 b	
			Cd	0.23 a mg kg^{-1}		0.48 ± 0.2 a	
			Pb	31.2 a mg kg^{-1}		0.493 ± 0.16 b	
			Mo	0.64 a mg kg^{-1}		2.06 ±0.6 a	
			Cu	10.17 a mg kg^{-1}		4.49 ± 0.77 a	
			Zn			30.2 ± 10.76 a	
			Ni	17.5 a mg kg^{-1}	6.15 a	0.565 ± 0.51 a	

Chicken Manure							
			Cd	0.23 a mg kg^{-1}		0.417 ± 0.28 a	
			Pb	31.2 a mg kg^{-1}		0.632 ± 0.33 a	
			Mo	0.64 a mg kg^{-1}		1.76 ± 0.6 a	
			Cu	10.17 a mg kg^{-1}		4.72 ±1.17 a	
			Zn			32.9 ± 9.74 a	
Sewage Sludge			Ni	17.5 a mg kg^{-1}	8.4 a	0.47 ± 0.41 ab	
			Cd	0.23 a mg kg^{-1}		0.518 ± 0.21 a	
			Pb	31.2 a mg kg^{-1}		0.119 ± 0.11 c	
			Mo	0.64 a mg kg^{-1}		1.52 ± 0.41 a	
			Cu	10.17 a mg kg^{-1}		4.39 ± 0.45 a	
			Zn			34.5 ± 10.99 a	
Swine Manure, Salicylic Acid (SA) and Potassium Chloride (KCl)	*Helianthus annuus* L	Ornamental Sunflower	Cd	Cd in soil (2.91 mg kg−1) In manure (0.37 mg kg−1)	7.4 In soil & 8.9 in manure	CK: 11.4±1.0d PM: 18.4±2.0c SA:18.8±0.33c KE: 39.4±4.2a KM:34.4±2.0b	(**HAO et al., 2012**)
			Zn	In Soil (1352 mg kg−1) In manure (120 mg kg−1)		CK: 990±168c PM:1932±268 ab SA:1893±204 b KE:2199±319 ab KM:2307±286 a	
Biochar	Wheat straw (350 – 550 ºC Organic carbon 467 g kg^{-1}, total N 5.9 g kg^{-1}, Cd 0.2 mg kg^{-1}		Cd	5 mgkg^{-1}	5.36	**Cd ($CaCl_2$)** **2010:** 54.5–70.9% **2011**: 53.5–64.8% **2012**: 28.3–60.9% **Cd (DTPA)** 12.0% **2010;** 24.0% **2011;** 20.9% **2012**	(**Bian et al., 2014**)
			Pb	100 mgkg^{-1}		**Pb ($CaCl_2$)** **2010:** 16.7–33.3%	
						2011: 65.0–79.6%	
						2012: 18.1–59.1%	

	and Pb 12.9 mg kg^{-1},					**Pb** (DTPA) **2010:** 17.8–18.4% **2011:** 20.7–27.7% **2012:** 17.8–26.9%	
biochar-based bioformulation	Coconut husk-derived biochar (500 ºC) **Plus (+)** *Arthrobacter subterraneus*(S5-TSB-17)		RDX	**Pot with bioformulation** (50 mg/kg) **Pot without bioformulation (50 mg/kg** **Pot with bioformulation** (100 mg/kg) **Pot without bioformulation (100 mg/kg**	7.0	85.98% 29.4% 65.14% 25.13%	(**K. Sharma et al., 2023**)
			HMX	**Pot with bioformulation** (50 mg/kg) **Pot without bioformulation (50 mg/kg** **Pot with bioformulation** (100 mg/kg) **Pot without bioformulation (100 mg/kg**		80.4% 23.88% 53.7% 21.6%	

- CK=Cd-and Zn contaminated soil without application of amendments.
- PM=swine manure applied at 30gkg−1;
- SA=sunflower leaves sprayed with 0.5mmolL−1 salicylic acid for three times
- KE= Potassium Chloride (KCl) solution applied at 0.54gkg−1 before seeding.
- KM=KCl solution applied at 0.54gkg−1 at the middle stage of growth.

According to the research studies examined, soil amendments such as biochar, compost, manure, vermicompost, sewage sludge, and bioformulations can significantly and rapidly reduce contaminant mobility and enhance remediation efficiency in polluted soils. Biochar modifications have shown significant immobilization potential for both metals and explosives in soils. Sunflower-derived biochar eliminated over 94% of Pb and 95% of Cu from pore water in soils. (**Nguyen et al., 2021**)(TRL 3-4). Wheat straw biochar also decreased bioavailable Cd and Pb concentrations throughout numerous cropping seasons, indicating long-term stability. (**Bian et al., 2014**) (TRL 5-6). Cow dung, chicken manure, vermicompost, and leaf compost improved soil characteristics while decreasing metal bioavailability. The application of immobilizing amendments increased the pH of the soil and therefore helped to improve Cd, Pb, Ni, Cu, and Zn sorption. (**Nepal et al., 2024**) (TRL 3-4). Pig manure in combination with salicylic acid and potassium chloride dramatically increased sunflower growth in the presence of Cd and Zn (**HAO et al., 2012**). (TRL 3-4). Biochar-based bioformulations mixed with microbial inoculation also resulted in more explosive breakdown. Coconut husk biochar injected with Arthrobacter subterraneus dramatically enhanced RDX and HMX decomposition as compared to untreated controls. At low contamination concentrations, removal efficiency for RDX and HMX surpassed 85% and 80%, respectively (**K. Sharma et al., 2023**)(TRL 3-4) Overall, the reviewed studies show that soil additives can significantly improve remediation performance by immobilizing pollutants, improving soil conditions, enhancing microbial activity, and promoting plant growth. These findings indicate that combined amendment-assisted remediation procedures may be particularly effective for soil contaminated with both heavy metals and explosives by substantially improving contaminant stabilization and degradation in contaminated agricultural soils.

5.5. A summary table of the literature review results

The polluted chernozem soils in the Kharkiv region exhibit varying physicochemical conditions, which have a direct impact on the selection and efficacy of nature-based remediation options. The soil parameters in this region show moderately acidic to alkaline pH levels (5.7-8.1), varied organic matter contents, variable nutrient availability, and various soil textures such as muddy clay, loamy, and sandy loam soils. (**Bonchkovskyi et al., 2025; Backman et al., 2025**). Soil pH, texture, organic matter, and nutrient availability have a significant impact on contaminant movement in soils, microbial activity, and plant development (**Alloway, 2013; Corredor et al., 2024**).

Some metals such as Cadmium (Cd), lead (Pb), copper (Cu), zinc (Zn), nickel (Ni), chromium (Cr), and explosives such as TNT, RDX, and HMX are identified to be the most common pollutants found in Ukraine's war-affected agricultural soil (**Bonchkovskyi et al., 2025; Solokha et al., 2023; Corredor et al., 2024**). Heavy metals remain in soil over long periods of time due to their non-degradability, whereas explosive residues may progressively degrade depending on microbial activity, oxygen availability, and environmental circumstances (**Mustapha et al., 2026b**; **Bolan et al., 2014**). The varying pH conditions of Kharkiv chernozem soils may promote Cd and Zn mobility under acidic circumstances, but Pb and Cu are more firmly adsorbed in soils with higher organic matter content (**Bolan et al., 2014**). Importantly, Cr and As, in contrast to other heavy metals, are more mobile in alkaline soils. Organic-rich chernozem soils may have already good natural conditions for immobilization of metals in soils.

According to the research studies reviewed in this thesis, phytostabilisation and soil amendment for immobilization seem to be the most suitable nature/based remediation options for large-scale agricultural land rehabilitation in Ukraine. Phytostabilisation lowers pollutant movement while reducing soil disturbance, facilitating long-term agricultural soil restoration, but it is flagged that it should not be considered as the final solution for a contaminated site because of contaminants' containment in soils (**Ali et al., 2013**; **Vangronsveld et al., 2009**). Organic amendments for immobilization such as biochar, compost, and manure improve soil structure, boost microbial activity, increase water retention, and, mostly, lower pollutant bioavailability (**Zheng et al., 2022**; **Beesley et al., 2011**). Note, that manure, in some cases, can increase the mobility of metals (**Kumpiene, 2019**). Still, these nature-based remediation options are judged to be relevant for degraded chernozem soils that have suffered from compaction, erosion, and organic matter loss because of military actions and demining activities.

Phytoextraction may be appropriate for moderately polluted agricultural regions with bioavailable and elevated metal concentrations in porewater in soils where long-term remediation is feasible. However, phytoextraction necessitates a large number of growing seasons, generates large amounts of waste (metal/polluted harvested biomass) to be disposed of and restricts the use of the site for agriculture during remediation periods (**Ali et al., 2013**). In contrast, phytoexclusion crops may offer the possibility to immediately use the site for agriculture, especially combined with immobilizing soil amendments, by reducing pollutant transfer into edible plant tissues while sustaining crop cultivation (**Tang et al., 2012**; **Haller & Jonsson, 2020**).

Bioremediation by means of biodegradation has shown great promise for explosive-contaminated hotspots, especially when TNT, RDX, and HMX residues are predominant in soils. Microbial remediation techniques use bacterial and fungal metabolic mechanisms to degrade explosive substances into less harmful forms (**Kao et al., 2016**; **Park et al., 2003)** Bioremediation systems may be more successful in organic-rich environments, since microbial activity is increased in chernozem soils with greater organic matter contents (**Singh et al., 2009**). However, low winter temperatures in Kharkiv may lower microbial breakdown rates during the colder months.

The literature review results in the use of microbes for biosorption of metals in soils appear less ideal for direct field-scale agricultural restoration because most investigations were conducted in aqueous laboratory settings rather than in damaged soil environments. Biosorption is the passive sorption of pollutants onto biological materials such as bacterial, fungal, algal, and yeast biomass.

Table 5.5 A Decision Support Summary Table. Note: Maize should be used with caution because different cultivars can either exclude or uptake soil metals.

Method	Targeted contaminants	Suitability for Ukraine	Advantages	Limitations	Applicable location
Phytoextraction with e.g. Sunflower, Rapeseed, Indian mustard, and Maize (Guidan No. 0810, Zea Mays L.).	Cd, Zn, Cu, Pb	Low	Environmentally friendly; appropriate for vast agricultural regions; promotes long-term soil healing.	Slow cleanup procedure; biomass disposal necessary; no agricultural output during remediation	Agricultural soils with bioavailable and elevated concentrations of metals in porewater as a polishing technique
Phytostabilisation with e.g. Miscanthus, Salix	Pb, Cu, Cr, Cd	High	Restrict pollutant mobility; avoids erosion and dust transmission; appropriate for deteriorated soils.	Contaminants stay in soil immobile especially when combined with immobilizing soil amendments	Large military affected agricultural soils, can potentially co-produce benefits of biomass for energy
Phytoexclusion (specify e.g. Wheat, Barley, Soybean, and Maize (Zea Mays L.)	Cd, Pb	High	Restricts contaminants transfer to the food chain, and promotes continues agriculture production	Does not absorb sufficient contaminants from the soil, especially when combined with immobilizing soil amendments	Agricultural food production
Bioremediation/biodegradation (bacteria, White rot fungi)	TNT; RDX, HMX	High	Improves the decomposition of explosive remnants; appropriate for explosive-contaminated locations.	Sensitive to pH, oxygen conditions, and temperature.	Military contaminated soil
Immobilizing soil Amendments (Biochar, Compost, and Manure)	Cd, Pb, Zn, Cu, TNT, RDX	High	Enhances soil fertility, immobilizes pollutants, enhances microbial activity, and soil structure.	Required repeated application	Large-scale agricultural farmlands
Bioremediation by means of biosorption (Bacteria, Algae)	Pb, Cd, Cu, Ni, Cr	Very uncertain	Efficient in laboratory aqueous conditions.	Limited application for contaminated soil	Potential use for metal-contaminated water. Soil tests are necessary.

5.6. An integrated decision support table

This section presents and summarizes the results of the major gap identified in **section 4.1** on the use of plants to degrade explosive remnants like TNT and RDX in Ukrainian war-induces soil contamination. Nature-based remediation methods compiled by **Menson et al. (2023)** and **Backman et al. (2025)**, which predominantly address heavy metal pollution.

*Table 5.6. An integrated Decision-Support Table. Nature-based Solutions covered by (**Menson et al., 2023**) and **Backman et al. (2025)**, and in this thesis, can be used to address metal and explosives contamination in soils.*

Mechanisms	Metals	Explosives Residues
Phytoextraction	Plants used for removal recommended by (Menson et al., 2023): Maize ,	Maize (Guidan No. 0810, Zea Mays L.), Beans, Switch grass, Eastern Gamagrass
Phytostabilisation	Plants, Amendments, and Microorganisms for removal (Menson et al., 2023; Backman et al., 2025)	No relevant literature was found in this study.
Phytoexclusion	Plants (often in combination with amendments) (Backman et al., 2025)	Maize (Zea Mays L.)
Degradation	Not applicable.	Bacteria, White-rot fungi
Immobilization	Amendments Backman et al., 2025)	Biochar

6. Discussion

6.1. General reflections

The identified nature-based remediation options in the reviewed studies targeted mainly pollutants such as cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), TNT, RDX, and HMX. However, the efficiency of each remediation option is highly dependent on soil conditions, pollutant climate, and the expected future use of agricultural land. Because of their variable organic matter content, varied pH conditions, and widespread agricultural value, the Kharkiv region's polluted chernozem soils provide both opportunities and challenges for restoration.

According to the reviewed literature, heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), and nickel (Ni) are the most common pollutants found in war-affected soils. These pollutants are persistent in the environment because they are non-degradable and can remain in soil for extended periods of time after military actions. Similar pollution concerns have been linked to industrialization, urbanization, mining, and intensive agriculture operations across the world (**Alloway, 2013; Rahim et al., 2024**). In addition to heavy metals, explosive residues such as TNT, RDX, and HMX have been identified as significant pollutants connected to military activities and ammunition residues. They are harmful to soil organisms, groundwater quality, agricultural safety, biodiversity, and human health.

Phytoremediation, for example Phytoexclusion and Phytostabilisation have shown great promise for polluted agricultural land since it is ecologically friendly, cost-effective, and adaptable across wide regions. The evaluated research found that phytostabilization can limit pollutant mobility and aid in the progressive regeneration of damaged soils while avoiding soil disturbance. This is especially critical for Ukraine, where military actions have resulted in soil compaction, erosion, organic matter loss, and decreased fertility. In comparison to physical and chemical remediation options, nature-based remediation option using plants is a less harmful remediation method that protects soil structure and ecological processes (**Ali et al., 2013**).

However, some limitations of phytoextraction were observed in the analyzed research. One key constraint is that cleanup sometimes takes a long time before significant reductions in pollutant concentrations are achieved. The efficacy of phytoremediation is also heavily impacted by soil conditions, pollutant concentrations, climate, and plant tolerance. The unique properties of polluted chernozem soils in Ukraine have physicochemical features that significantly differ from numerous experimental soils used in investigations published in the reviewed literature. This therefore necessitates tests with Ukrainian soils in field conditions because pH, organic matter contents, soil texture, nutrient conditions, and climate may all impact remediation efficacy in Ukrainian fields.

The research studies examined also revealed that many remediation efforts were carried out in greenhouses or laboratories rather than on field-scale agriculture systems. Greenhouse facilities frequently lessen temperature swings and environmental unpredictability when compared to actual agricultural fields. Small-scale pot studies may also fail to correctly simulate pollutant dispersion, root growth, microbial interactions, and water flow in the environment. As a result, remediation efficiency demonstrated under controlled settings may not accurately represent long-term performance in polluted agricultural soils in Ukraine.

Another significant restriction found in the research studies examined is the duration of remediation trials. Many experiments were conducted over very short time periods, but field-scale rehabilitation of polluted soils may take multiple growing seasons or years to produce significant changes. This is especially crucial for phytoextraction, as pollutant absorption, stability, and ecological recovery are all progressive processes driven by seasonal circumstances and long-term soil growth. Short-term research may hence overstate remediation efficacy in actual agricultural circumstances.

The studied literature also emphasized the use of immobilizing soil amendments in phytostabilization and phytoexclusion systems. Biochar, compost, manure, and vermicompost all helped to improve soil structure, boost microbial activity, retain water, and limit pollutant bioavailability. These enhancements are especially important for degraded war-affected soils, where agricultural output has suffered owing to compaction and loss of organic matter. Combined remediation systems that incorporate phytostabilization or phytoexclusion and immobilizing soil amendments may thus have more long-term remediation potential than a single remediation option alone (**Beesley et al., 2011; Bolan et al., 2014**).

Under aqueous laboratory circumstances, the reviewed experiments with microbes for biosorption of metals revealed their high efficacy. However, the majority of the listed research focused on wastewater systems rather than polluted agricultural soils. As a result, the direct field-scale application of this nature-based remediation option for agricultural soil in Ukraine is still very uncertain. Additional laboratory and field tests with Ukrainian soils are required to evaluate the viability for large-scale applications for polluted agricultural soils in Ukraine.

6.2. Challenges, limitations, and uncertainties

Several challenges, limitations, and uncertainties emerged during the evaluation of nature-based remediation options for polluted agricultural soils in Ukraine. One key challenge is the high seasonal variability of Ukrainian climatic conditions. Large temperature changes between summer and winter may significantly affect plant growth, microbial activity, pollutant transport, and overall remediation effectiveness. This is especially crucial for remediation solutions involving microbes, since microbial degradation processes targeting explosives often require precise temperature and moisture conditions to achieve maximum performance.

Another identified challenge is that many of the analyzed studies in this thesis were carried out under controlled greenhouse or laboratory circumstances rather than in field-scale agriculture settings. Controlled experiments frequently maintain consistent temperatures, irrigation, and nutrient levels while minimizing external environmental impacts like rainfall, drought, wind, sunshine variations, and seasonal freezing. As a result, remediation efficacy measured in laboratories may not fully reflect performance in real-world polluted fields in Ukraine or elsewhere. This constraint is particularly critical because environmental variables have a significant impact on the behavior of pollutants, plants, and microbes.

A limitation of this thesis is that the evaluation targeted mainly soil contamination, although physical and biological soil restoration processes are critical components of long-term ecosystem recovery. This study did not assess the effects of reviewed nature-based options on soil biodiversity, microbial ecology, soil fauna recovery, or physical soil rehabilitation. Previous studies, however, indicated that these remediation options can have a pronounced positive effect on soil health, i.e., the ability of soil to deliver ecosystem services (**Drenning et al., 2024**).

Moreover, the aging and weathering of soil pollutants create uncertainty in remediation efficacy because aged contaminants may have less mobility and bioavailability than freshly polluted soils, which is the case in Ukraine. Controlled laboratory results with spiked soils may not accurately reflect the behavior of the aged pollutants in the field, particularly for heavy metals. It is therefore important to perform tests with Ukrainian recently contaminated soils. Furthermore, the PRISMA-based method was adapted to address shortcomings due to possible rejections of relevant research owing to confusing titles, language hurdles, and insufficient data, as well as biases from human factors in the selection of relevant studies. No screening of the hits was performed by another researcher, although required by the PRISMA method, to reduce this bias in this study.

Finally, no single nature-based remediation option was found to be capable of properly and simultaneously resolving both metal and explosive contamination in the war-affected agricultural soils in Ukraine. There is a need to investigate integrated systems with Ukrainian contaminated soils under both laboratory and field conditions to minimize uncertainty and improve future remediation plans.

7. Conclusions and recommendations

7.1. Conclusions

According to the research examined, heavy metals such as cadmium (Cd), lead (Pb), zinc (Zn), copper (Cu), chromium (Cr), and nickel (Ni), as well as explosive residues such as TNT, RDX, and HMX, were identified as key contaminants of concern connected to military activities. These contaminants threaten agricultural productivity, groundwater quality, ecosystem health, biodiversity, and food safety. In addition to chemical pollution, military actions cause soil deterioration through compaction, erosion, and loss of soil organic matter, lowering agricultural land quality.

Among the nature-based remediation options tested in the reviewed literature, phytostabilisation or phytoexclusion in combination with immobilizing soil amendment showed the most promise for large-scale agricultural restoration in Ukraine. This can be considered an environmentally friendly and cost-effective remediation approach that reduces pollutant mobility while maintaining soil structure, rapidly returns land into productive use and increase ecosystem services. Soil amendments such as biochar, compost, and manure enhance remediation efficacy by restricting mobility of metals, improving soil fertility, and decreasing metal bioavailability. However, Cr and As may be more mobile at higher pH. This necessitates careful use of immobilizing soil amendments. These combinations appear to be especially suited for contaminated chernozem soils, especially taking into consideration chernozem's natural ability to bind metals due to their high organic matter and clay contents.

Bioremediation using microbes for degradation processes has shown great promise for isolated explosive-contaminated hotspots, where microbial systems may degrade TNT, RDX, and similar organic chemicals under appropriate environmental circumstances. However, temperature, oxygen availability, nutritional conditions, and microbial adaptation all have a significant impact on remediation effectiveness. No reviewed studies resemble chernozems, which necessitate tests with Ukrainian soils.

Using microbes for metal immobilization by means of biosorption revealed promising pollutant removal capabilities from water environments in laboratory settings, however the examined literature found just a few field-scale agricultural uses.

The use of Technology Readiness Level (TRL) to analyze remediation procedures provides insight into their maturity and practical applicability. Laboratory tests at TRL 3-4 demonstrate technological viability under controlled laboratory conditions, whereas field trials at TRL 5-6 offer performance data under more realistic settings in the field. This assessment emphasizes the necessity of distinguishing strategies with laboratory success from those verified at the field scale as not laboratory successes translate to success in the field. However, TRL is not the only factor that determines a method applicability at scale; it must be considered alongside remediation effectiveness across diverse sites and contexts and implementation practicality. Field-validated methods provide more robust basis for their transferability and testing under field conditions in Ukraine for restoring demined contaminated agricultural land, but lower-TRL methods require additional laboratory tests with Ukrainian contaminated soils and subsequent field validation and replication before being applied at scale.

The outcomes of this thesis also revealed that the majority of investigations were carried out in greenhouses or laboratories rather than in actual agricultural fields. Furthermore, climate variability, pollutant age, ongoing military actions, and variations between experimental and Ukrainian chernozem soils all contribute to uncertainty about long-term remediation efficacy in the field. The analysis also indicated that no single nature-based remediation option can handle both metals and explosives simultaneously. As a result, integrated remediation systems that combine several options should be tested for Ukraine's war-affected agricultural soils in laboratory and field conditions.

7.2. Recommendations

The recommendations that emerged from the findings of this thesis are summarized below.

- Laboratory tests and long-term field experiments should be conducted in Ukraine using the war-affected contaminated chernozem soil to assess the actual efficacy of nature-based remediation options under the local climate conditions.

- Nature-based solutions for remediation should be considered in a planning framework, evaluating the level of contaminant concentrations, soil properties affecting the mobility of contaminants, the timeline objectives of agricultural use, and the economic feasibility of the remediation options.

- There is a need for further research on the long-term impacts of biochar, compost, and manure on pollutant mobility, soil fertility, and ecosystem recovery, because no long-term data is available in the literature.

- Furthermore, research is also needed on the behavior and degradation potential of TNT, RDX, and HMX under Ukrainian soil and climate conditions.

- Future studies should also focus on contaminant transfer to edible crops and the safety of agricultural production during and after remediation with the help of nature-based solutions.

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APPENDIX A. A detailed summary of literature review

1.0 Phytoremediation

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
Phytoextraction									
Cd	Chongzuo City, Guangxi Zhuang Autonomous Region, China.	The soils had a clay silt (43% clay, 17% silt). The concentrations of soil total Cd was (0.2–18.9 mg kg− 1). The soil samples were collected from the topsoil layer depth at (0–20 cm) organic matter 9.62 ± 0.34 g kg− 1, TP (0.52 ± 0.04 g kg− 1), TN (1.53 ± 0.18 g kg− 1)	Maize (Zea mays L.) Guidan No. 0810	Inductively coupled plasma source mass spectrometry (ICP-MS, X-series, Thermo Fisher Scientific, USA).	Pots Experiments	110 days.	Cd concentration of 2.6 mg kg− 1. pH 5.46 ± 0.02 the pH-adjusted Low Molecular Weight Organic Acids (LMWOAs) was (pH 7.0)	The result for the pot experiment shows low molecular weight organic acids (LMWOAs) considerably elevated cadmium (Cd) concentrations in maize organs: 76% in roots, 69% in stems, 85% in leaves, and 74% in grains. LMWO with modified pHCd uptake increased by 47% in roots ($P < 0.05$), but did not influence other organs. LMWOAs caused a higher increase in root Cd concentrations than pH-adjusted LMWOAs. The Impact of LMWOIn terms of Cd levels, citric acid rated higher than oxalic acid and malic acid, but pH-adjusted LMWOCitric acid was followed by malic acid and then oxalic acid.	(Y. Wang et al., 2025)
Cd	Henan province, China	The soil samples were fluvo-aquic soil (sandy loam) collected from the top layer depth at (0–20 cm),	Rapeseed(Brassica napus L.)	Analysis of variance (ANOVA) with SPSS 19.0.	Pots Experiments	5 months ,	Plastic pots packed with a sandy loam soil contaminate	The result for the pot experiment was amended with acetic acid (AA), oxalic acid (AO), citric acid (CA), malic acid (MA) and tartaric acid (TA), respectively.	(Qiao et al., 2020)

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		compring of 11.53% of particles <0.002 mm, 75.37% of particles in 0.002–0.05 mm, and 13.1% of particles >0.05 mm. Its bulk density and field capacity are 1.39 g/cm3 and 24% (weight), respectively. The average Cd content in the soil is 0.838 mg/kg, and the total soil nitrogen, phosphorus and potassium are 1.14 g/kg,					d by Cd at 4.838 mg/kg were amended with acetic acid, oxalic acid, citric acid, malic acid and tartaric acid, respectively,	The result shows a considerably elevated cadmium (Cd) concentrations in rapessed plants with the following amendment AA plant uptake of Cd (146%); OA plant uptake of Cd (67%); CA plant uptake of Cd (110%); MA plant uptake of Cd (53%); TA plant uptake of Cd (82%).	
U, Cd	Mianyang, Sichuan Province, Chima	Soil samples (silty clay) with pH 7.08 were collected at depths of 0–25 cm. The soil properties are organic matter content 19.03 g/kg, available phosphorus 40.12 mg/kg, available potassium 59.15 mg/kg, available alkali	Sunflower Helianthus annuus L	ICP-MS (Agilent Technologies 7500 Series, Santa Clara, USA).	Pots Experiments	2 months	Cd concentration of U and Cd added to the soil was 15 mg kg with (pH 7.08)	The study discovered that when exposed to uranium (U) and cadmium (Cd), plant biomass fell by 12.12% for shoots and 15.74% for roots. Chelating agent treatments, particularly those with ethylenediamine disuccinate (EDDS), exacerbated U and Cd stress, resulting in decreased biomass, hindered photosynthesis, and elevated levels of malondialdehyde and	(L. Chen et al., 2020)

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		hydrolysable nitrogen 158.93 g/kg, cation exchange capacity 105.72 mmol/kg, clay 36.5%, silt 45.2% and sand 18.3%.						H_2O_2. Citric acid (CA) addition resulted in much higher U uptake than Oxalic acid (OA) and EDDS, although EDDS had a greater influence on Cd uptake. Maximum U and Cd removal efficiency were achieved with 5.0 mmol/kg CA and 5.0 mmol/kg EDDS, resulting in increases of 177.48% and 181.51%, respectively, as compared to the control.	
Pb Cd	Burnley campus garden-Melbourne University, Australia	The pH and EC values of the studied soil were 6.24 and 0.27 dS m−1, respectively, and the textural class is loamy sand with sand (81.00), silt (12.80), and clay (6.20) with an average organic matter content of 10.23%. Total Pb with an average concentration of 26.3 mg kg−1, and the concentration of Cd was below the detection limit	Sunflower Helianthus annuus L	All results were statistically analyzed using the SAS package (ver. 9.1).	Pots Experiments	8 Weeks	contamination of the soil with Pb and Cd at different concentrations of 0, 10, 20, 40, 80, 100, and 200 mg kg−1.	The study indicated that adding 200 mg kg−1 of lead (Pb) and cadmium (Cd) to soil considerably lowered the fresh weights of shoots (by up to 76.6%) and roots (by up to 64.3%). Furthermore, shoot and root lengths declined by up to 71.6%, 94.1%, and 83.2%, 95.1%, respectively. The supplemented soil resulted in the highest quantities of Pb and Cd in shoots (40.1 mg kg−1 and 65.7 mg kg−1, respectively) and roots (107.7 mg kg−1 and 71.3 mg kg−1).	(Alaboudi et al., 2018)

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
Zn, Cu, Pb	Bucharest, Romania	The soil fall in category of light organic soils, with a loamy-sandy texture with organic matter content (61 ± 4%),980 ± 80 mg/kg total nitrogen, 580 ± 60 mg/kg phosphates and 1050 ± 100 mg/kg potassium. The electrical conductivity recorded was (1.55 ± 0.25 mS/cm), so the soil had a moderate salinity, suitable for the growth of young plants.	Indian Mustard (Brassica juncea)	Statistical analyses of the ANOVA type and post-hoc tests (Tukey HSD)	Pots Experiments	(80 days).	concentration of the soil for Zn was (58 ± 10 mg/kg, and 993 mg·kg−1) for initial and after contamination, and for Cu (Initial 18 ± 4 mg/kg, and 534 mg·kg−1) and for Pb 8 ± 3 mg/kg, and 152 mg·kg−1(representing initial and after contamination.	The result for pot experiments showed significant differences ($p < 0.001$) between treatments and metal types, indicating a synergistic interaction between chelation and phytoextraction processes. The combined treatments Indian mustard and EDTA in concentrations of 1.0 mmol·kg−1 and 2.0 mmol·kg−1, ensured the highest decontamination efficiency, with reductions of 51.5% for Zn, 36.3% for Pb and 27.5% for Cu. Finally, the combined technique is a practical, environmentally friendly, and reproducible strategy for remediating heavy metal-contaminated soils.	(Pruteanu et al., 2026)
Phytoexclusion									
Cd	Hunan and Zhejiang Sichuan provinces, China,	The field experimental sites in 2014 was conducted in Youxian county, Hunan province, and in the Fuyang district,	ShenYou957, LongPing602, Weiyou402, WeiYou463,	Phenotypic screening from 471 cultivars.	Field Experiment	2 years	The total Cd concentrations in the paddy soils were around 0.5 and	Out of 471 cultivars, 466 and 662 grew and havested at Youxian, Hanan Province in 2014. the resut shows Cadmium concentration in rice grain (unpolished brown rice range	(Duan et al., 2017); (Wang

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		Zhejiang province. The soils at the Youxian Fuyang site are acidic (pH 4.9 - 5.6)	ZhuLiangYou168, T-You535, JieFengYou1, I-You 899				0.4 mg kg-1 for Youxian and Fuyang sites, respectively both exceeding the Cd limit of the Chinese soil environmental quality standard (0.3 mg kg-1 for soils with pH < 7.5.	from 0.03 to 0.86 mg kg-1 in Youxian and 0.06 to 0.58 mg kg-1 in Fuyang. Another field experiement was conducted in 2015 for the above pronvinces in addition province of Xiangtan. After the experiement the result shows an increase in Cadmuim concentration ranging from (0.02 - 0.24 mg kg-1) (0.08 - 0.68 mg kg-1,) (0.14 -1.17 mg kg-1) Youxian, Fuyang and Xiangtan, respectively.	et al., 2021
Cd, Pb	Zhaoyuan, Liaocheng, Laizhou, China	Field experiememt was carried out at at three provinces in China located in Zhaoyuan (pH 5.90±0.28, Annual Temp. 650 mm Organic matter 18.0 ± 3.07 g kg−1), Liaocheng (pH 7.48±0.04, Annual temp. 610 mm, Organic matter 19.6 ± 1.98 g kg−1 for	Wheat cultivars (Triticum aestivum L.)	Phenotypic screening from 72 cultivars.	Field Experiment	3 years	The soil was derived from a lacustrine deposit and classified as a hydroagric Stagnic Anthrosol. The topsoil contained organic carbon of 20.20 g kg−1, total N of	Significant variations in grain Cd contents were found when 72 wheat cultivars were examined for cadmium (Cd) deposition in a marginally polluted area. Based on Cd levels, the cultivars were divided into five groups by cluster analysis: Groups I and II showed extremely low (0.069 mg kg−1) and low (0.085 mg kg−1) concentrations, Group III showed medium concentration (0.11 mg kg−1), and Groups IV and V showed high (0.13 mg kg−1) and	(Liu et al., 2020); (Wang et al., 2021

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		field 2), and Laizhou (pH 6.18±0.16, and Annual temp. 587 mm, Organic matter 20.9 ± 1.39 g kg−1 for Field 3). The soil texture for the three farmlands is silt loam.					5.94 g kg−1, cation exchange capacity of 23.07 cmol kg−1 and pH (H2O) of 5.36. soil Cd for field trial 1 (0.322 ± 0.020 mg kg-1) Field trial 2 (0.421 ± 0.026 mg kg-1) and Field trial 3 (0.215 ± 0.058 mg kg-1) respectively	extremely high (0.15 mg kg−1) concentrations, respectively.	
Cd	Shenyang City, Liaoning province, China	The average temperature (15-25), soils depth (0-20 cm),Ph (6.5, 6.6, 6); Organic matter (1.94, 1.25, 1.37); TN (0.89, 1.12, 1.08); Available P (0.35, 0.43, 0.46) mg/kg	Soybean (Shennong 10, Tiefeng 31, Tiedou 36, Tiefeng 37 and Liaodou 21) as cultivars	Phenotypic screening from 12 cultivars.	Field Experiment	4 months	Cd (0.15, 0.75 and 1.12 mg/kg) in three diferent types of Chinese soybean. Temperature 15–25°C	The study discovered that soybean seeds cultivated in soil containing 1.12 mg/kg Cd surpassed the acceptable range for human health. Even if soil Cd levels are acceptable, certain cultivars may develop harmful Cd amounts. The study also looked at the interactions between Cd and other critical	(Zhi et al., 2015)

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
								elements (Ca, Cu, Fe, Mg, Mn, and Zn), finding that high Cd levels reduced Mn uptake but increased Fe and Zn accumulation in seeds. Notably, the Tiefeng 31 cultivar was discovered as a Cd-free choice across a range of soil Cd values.	
Cd	Zhejiang province, China	Powdery–loamy paddy with (depth 0–15 cm), pH 1.10,	Barley ((Hordeum vulgare L.) Beitalys, Shang 98–128	Phenotypic screening from 600 cultivars.	Field Experiment	2 years	The total Cd concentrations in the powdery–loamy paddy soils was 0.15 mg kg-1 for Zn 3.54 kg-1, Mn 16.22 mg kg-1, Cu 3.53 mg kg-1, Fe 52.59 mg kg-1	The field trial results show continuous genotype differences over two years, with Beitalys and Shang 98-128 having the lowest grain cadmium (Cd) concentration, 97.5% lower than the highest accumulators, E-barley 6 and Zhenong 8, in the second harvest year. The large genotypic changes in Cd concentrations indicate that cultivar selection and breeding can successfully lower Cd content in barley, particularly in locations where grain Cd levels exceed the maximum permitted concentration (MPC).	(F. Chen et al., 2007)
TNT	Unión Española de Explosivos (Madrid, Spain)	The soil is a loamy sand classified as a Dystric Xerorthents (23) with the following	Maize (Zea mays L.) and broad beans (Vicia faba L.)	The modified version of the US-EPA 8330 method was used to	Field experiment	60 days	Maize (213 mg TNT/kg) and Beans (500 mg TNT/kg)	In studies with spiked hydroponic medium, bacteria inoculation had no effect on TNT levels, whereas axenic plants eliminated 32% to 38% of TNT.	(van Dillewijn et al., 2007)

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		characteristics: 82% sand, 8% clay, and 10% silt; pH 4.7; organic matter content of 0.8%; and 0% CaCO3 content.		determine TNT and transformation product concentrations in bulk or rhizosphere soil				Inoculated plants had higher removal rates, ranging from 80% to 88%, indicating the potential role of P. putida JLR11 in rhizoremediation. In outdoor tests, neither natural attenuation nor bioaugmentation had a substantial effect on TNT levels. However, extractable TNT in rhizosphere soil related to maize roots fell by more than 96% in 60 days, demonstrating that phytoremediation by maize outperformed rhizoremediation effects by P. putida JLR11.	
TNT	Missouri, United States,	The soil contained a mixture of 50% sand and 50% silt	Eastern gamma grass (Tripsacum dactyloides, EG) and Switchgrass (Panicum virgatum L, SW)	The 14C-TNT degradation and degradative metabolite profile in the rhizosphere soils were determined by liquid scintillation counter and high-performance liquid	Pots Experiments	8 weeks	Twenty grams of fresh rhizosphere soils were treated with 0.5 µCi C14-TNT (PerkinElmer Life and Analytical Sciences) and 17.86 µg of 1,000 µg mL−1 TNT	The results showed that both native grass species greatly increased TNT decomposition in the rhizosphere soils as compared to the control soils. More than 95% of the applied 14C-TNT was degraded within the first 7 days, after which the rate stabilized, but less than 10% of the TNT was totally mineralized and turned into CO2.	(N. Li et al., 2024)

Soil Contamination	LOCATION	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
				chromatography			(Spex Certiprep, Inc.) to achieve a total TNT concentration of 1.0 mg kg−1.		

2.0 Bioremediation

Soil Contamination	Loctaion	Soil Properties	Organisms used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
RDX, DNT	Garrison Petawawa, Ontario, Canada	A dark brown, coarse, sandy soil with pH (7.84), humidity (17.9%), carbon content (1.63%), TN (< 0.5%), hydrogen content < 0.5%, gravel (33%), sand (50%), silt (16%), clay (< 3.9 μm) = 0% Annual rain (853 mm)	Waste glycerol (WG)	The experiment was conducted using the Waters HPLC system	Field pilot test	3 months	RDX (0 to 0.4 mg kg−1) DW (mean ± SD = 0.1 ± 0. 1 mg kg−1 DW soil) and DNT (0 to 247.4 mg kg−1(DW) (mean ± SD = 52.1 ± 65.4 mg kg−1 DW soil)	In treated plots, RDX biodegradation occurred across the depth studied; in the 0-7.5-cm samples, RDX was undetectable 37 days after treatment application, while in the 7.5-15-cm samples, the concentration of RDX fell by roughly 90% during the same time period. There was no evident diminishing trend in 2,4-DNT concentrations over time in the surface (0-7.5 cm) and bottom (7.5-15 cm) soil layers for both	(Jugnia et al., 2018)

Soil Contamination	Loctaion	Soil Properties	Organisms used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
								control and treated plots (Fig. 3). This indicated that treatment with WG was ineffective.	
TNT	Chandigarh, India	The strain S5-TSA-19 is a soil bacterium named Indiicoccus explosivorum isolated from the sample collected from an explosive manufacturing site containing up to a concentration of 900–1000 mg/Kg	Soil bacterium (Indiicoccus explosivorum (S5-TSA-19) is soil bacterium	The study was conducted through the Minimal Salt Medium (MSM) for microbial proliferation and associated experimentations, and the Isolation and characterization process through 16 s Rrna sequencing	Laboratory Experiment	30 days	TNT (60, 80, 100, 120 mg/L), temperature (20 to 35 °C), and pH (5 to 9)	The study was conducted in the presence of a unique soil isolate I. explosivorum, strain S5-TSA-19, in an aerobic environment. Throughout the investigation, the growth medium containing TNT (120 mg/L) showed adequate bacterial multiplication. Following I. explosivorum action, TNT, a recognized xenobiotic chemical, completely degraded. Despite the study's 30-day duration, TNT (120 mg/L) completely vanished on the seventh day of incubation.	(Lamba et al., 2022)
TNT	Chandigarh, India	An explosive contaminated (the TNT concentration was 900–1000 mg/kg) site for biodegrading TNT	Indigenous soil bacterium P. chlorophenolicus, strain S5-TSA-26.	HPLC and LC-MS (negative electrospray ionization (ESI) technique).	Laboratory Experiment	25 days	TNT (900–1000 mg/kg)	This study describes how the native soil bacterium P. chlorophenolicus, strain S5-TSA-26, degrades TNT aerobically. In 15 days, the bacteria completely eliminated	(Lamba et al., 2021)

Soil Contamination	Loctaion	Soil Properties	Organisms used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		under aerobic conditions						120 mg/L of TNT, which normally prevents development. Two metabolites, 2,4-dinitrotoluene (DNT) and 2-amino-4,6-dinitrotoluene (2-ADNT), were produced from TNT during this bioconversion.	
TNT	İzmir, Turkey	Clayey limestone	Bacteria (Bacillus cereus)	GC-MS and TLC methods.	Laboratory Experiment	96 hours	50 mg L−1 and 75 mg L−1	The result for the soil sample isolated from NATO soil was examined, and the experiments performed in flasks at an initial concentration of 50 and 75 mg L−1 TNT, and the result shows 68 % and 77 % of the TNT was degraded in 96 h respectively	(Mercimek et al., 2013)
Cr	India, Kanpur	Composite soil contained 1,126.25 mg Cr pH (4, 5, 6, 7, 8, 9, 10, 11)	Bacteria (Bacillus sp strain FM1.)	16S rDNA analysis using the primers 27 f (5′ AGAGTTTGATCCTGGCTCAG 3′) and 1,492 r (5′ GGTTACCTTGTTACGACTT 3′).	Laboratory Experiment	48 hours	50 - 200 mg/L	A Complete 100% Cr(VI)-reduction was observed for 50 and 100 mg/L at 12 h and 48 h, with a pH 8.0 and a Teperature 37°C.	(Masood & Malik, 2011)

Soil Contamination	Loctaion	Soil Properties	Organisms used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
Cd (II), Pb (II), Cu (II)	Changsha, China	Composite soil sewage discharge canal bank of Zhuzhou Smeltery. The bacteria strains removed from the plants contained 10 g tryptone, 5 g yeast extract, 5 g NaCl/L. The pH of 7.2–7.4.	Endophytic Bacterium Bacillus sp. L14	16S rDNA analysis using the primers 27 f (5′ AGAGTTTGATCCTGGCTCAG 3′) and 1,492 r (5′ GGTTACCTTGTTACGACTT 3′).	Pot Experiment	24 hours	10 mg/L	The result for the soil sample isolated from NATO soil was examined, and the experiment result shows 75.78%, 80.48%, 21.25% of Cd (II), Pb (II) and Cu (II) under the initial concentration of 10 mg/L was degraded in 96 h respectively	(Guo et al., 2010)
TPT	southeastern Tianjin, China	The sampling depths were 0–10, 10–20, and 20–40 cm, which were numbered GN1, GN2, and GN3, respectively. GN1 (pH (7.67), moisture content (35.92%), Organic carbon (66,531.32 mg kg−1), TN (143.67 mg kg−1) TP (1202.80 mg kg−1); GN2 ((pH (7.66), moisture content (13.42%), Organic carbon (23.44 mg kg−1), TN (57.77 mg kg−1) TP (948.08	Bacteria community Firmicutes (Bacillus albus AB and Bacillus havnesii 190311L225) Proteobacteria (Pseudonas balearica A69)	Gas chromatography, and high-throughput sequencing	Pot Experiment	300 days	The concentration at GN1 (888,615.75 mg kg−1) GN2 (15,342.13 mg kg−1), and GN3 (1630.06 mg kg−1)	This study used microcosmic studies to evaluate bioremediation strategies such as natural attenuation (NA), bioaugmentation (BA), and biostimulation (BS). Gas chromatography and high-throughput sequencing were used to investigate hydrocarbon breakdown and bacterial community structure in contaminated soil layers. The results showed that deep soil mostly comprised C17-C21 components. Over 300 days, the total petroleum hydrocarbon degradation	(Nong et al., 2023)

Soil Contamination	Loctaion	Soil Properties	Organisms used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		mg kg−1); , and GN3 ((pH (8.47), moisture content (11.32%), Organic carbon (4.39 mg kg−1), TN (501.99 mg kg−1) TP (1039.61mg kg−1) respectively						rates were 99.87%, 96.04%, and 71.63% in the BA group; 99.75%, 95.73%, and 99.84% in the BS group; and 8.55%, 8.64%, and 9.84% in the NA group.	
TNT	Helsinki, Finland,	TNT contaminated soil originating from a military storage area with organic matter 5.1%, dry matter 91%	Fungi (Gymnopilus luteofolius 466 (X9), Kuehneromyces mutabilis 508 (K22), Mycena galericulata 598 (K175), Phanerochaete velutina 941 (T244i), Physisporinus rivolosus 939 (T24li) Stropharia rugosoannulata 475 (11372))	Phenotypic screening from fungal strains	Laboratory and Pilot-sacle Experiments	Lab experiment 90days Piolot-scale experiment 107 days	The concentration of the contaminated was 19000 mg kg−1) Diluted soil (1:1) 9500 mg kg−1), Diluted soil (1:20) mg kg−1), and Diluted soil (1:40) 500 mg kg−1	The investigations revealed that the most efficient fungus, P. velutina, destroyed 80% of TNT in 2.5 months in the laboratory trial and was chosen for a larger scale-up experiment in the pilot scale with 0.3 t (0.56 m3) of soil and an inoculum soil ratio of 1:30. The degradation of TNT reached 70% in 49 days.	(Anasonye et al., 2015)

Soil Contamination	Loctaion	Soil Properties	Organisms used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
TNT; RDX; HMX	Ramat Beka, southern Israel	Sandy-loam soil with a capacity of the soil approximately 20% moisture by weight. Baseline, included particle-size fractions only (sand (64%), silt/clay (20%)and clay (16%).	microbial consortium, and animal waste compost	HPLC and LC–MS/MS (MRM), and QA/QC	Field experiment	85 days	Initial mean concentrations were 120.46 ± 34.54 mg kg^{-1} (RDX), 144.73 ± 36.95 mg kg^{-1} (TNT), and < LOQ (HMX)	The experiment results reveal HMX, RDX, and TNT decreased sharply from day 55 onward and maintained at or near non-detectable levels until day 85 (GLMM contrasts, all $p < 0.001$ after day 55); start-to-end differences supported these reductions (RDX: $W = 12$, $p = 0.050$; TNT: $W = 12$, $p = 0.0319$). HMX showed a non-monotonic trend, peaking at day 40 (mean 4.66 ± 1.06 mg kg^{-1}) and then dropping, leaving a minor residue at day 85 (0.12 ± 0.25 mg kg^{-1}; start-to-end $W = 0.01$, $p = 0.0436$).	(Ben Laish et al., 2025)

3.0 Soil Amendment

Soil Contamination	Location	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference

Soil Contamination	Location	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
Cd, Pb	Jingtang village, Yixing Municipality, Jiangsu Province, China	The topsoil contained organic carbon of 20.20 g kg−1, total N of 5.94 g kg−1, cation exchange capacity of 23.07 cmol kg−1 and pH (H2O) of 5.36. The annual temperature of 15.7 °C and mean annual precipitation of 1246.3 mm	Wheat straw (350 – 550 oC Organic carbon 467 g kg−1, total N 5.9 g kg−1, Cd 0.2 mg kg−1, and Pb 12.9 mg kg−1,	one-way analysis of variance (ANOVA). All statistical analyses of crop yields and soil characteristics were carried out using SPSS, version16.0 (SPSS Institute, USA, 2007).	Field study	3-year	Initial concentration in soil for Cd (5 mg kg−1) and for Pb (100 mg kg−1)	The study found that Biochar effectively reduced soil extractable cadmium (Cd) and lead (Pb) levels over three years. Specifically, soil CaCl2 extractable Cd dropped by 54.5-70.9% in 2010, 53.5-64.8% in 2011, and 28.3-60.9% in 2012. Only in the third year was there a considerable reduction in DTPA extractable Cd, with values of 12.0%, 24.0%, and 20.9% under varied treatments. In terms of Pb, soil CaCl2 extractable levels decreased by 16.7-33.3% in 2010, 65.0-79.6% in 2011, and 18.1-59.1% in 2012, while DTPA extractable Pb decreased by 17.8-18.4% in 2010, 20.7-27.7% in 2011, and 17.8-26.9% in 2012.	(Bian et al., 2014)
RDX, HMX	Chandigarh, India	Garden soil was dug out from the top layer (5–20 cm) and screened through a	Coconut husk-derived biochar (500 oC) Plus (+)	Performance Liquid Chromatograph (HPLC)	Laboratory Experiment	30 days	TNT and HMX (50 and 100 mg/kg)	According to the lab results, Arthrobacter subterraneus was able to survive and grow in soil	(Sharma et al., 2023)

Soil Contamination	Location	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		2 mm sieve. 1 kg of garden soil contaminated with RDX and HMX was filled in each plastic pot of 15.5 cm diameter and 14.5 cm high	Arthrobacter subterraneus (S5-TSB-17)					polluted with RDX and HMX thanks to a biochar-based bioformulation. In soil spiked with an initial concentration of 50 mg/kg RDX and HMX, the bioformulation effectively decomposed 85.98% RDX and 80.4% HMX. The biochar's sorption qualities in the bioformulation made more RDX and HMX available for the bacteria to biodegrade.	
Cd, Zn	Fuyang City, Zhejiang Province, China	fluvio-marine yellow soil containing clay 22.5%, silt 59.8% and sand 17.7%, pH 7.4, Organic matter 35.2 g kg−1, TN 1.78 g kg−1, TP 0.61 g kg−1, and	Swine Manure, Salicycle Acid (SA), and Potassium Chloride (KCL)	Statistical tests were performed using SPSS Ver sion 11.0 software. The data for metal concentra tions in sunflower were subject to analysis of variance (ANOVA),	Pot experiment	1 year	Initial concentration in soil for Zn (1352 mg kg−1) and Cd (2.91 mg kg−1) and for manure Zn (120 mg kg−1) and Cd (0.37 mg kg−1)	A pot experiment looked at the effects of swine manure, salicylic acid (SA), and potassium chloride (KCl) on ornamental sunflower (Helianthus annuus L.) grown in polluted soil. The modifications increased sunflower height, flower diameter, and biomass. Swine manure considerably reduced cadmium (Cd) and zinc (Zn) levels, lowering the	(HAO et al., 2012)

Soil Contamination	Location	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
								bioaccumulation coefficient (BCF) for both metals. In contrast, KCl raised Cd concentrations and BCF while increasing its transfer from roots to aboveground portions. Additionally, pig manure and SA reduced Cd/Zn ratios in flowers, whereas KCl increased these ratios.	
Ni, Cd, Pb, Mo, Cu, Zn	Kentucky State University, Frankfort, KY 40601, USA	Bluegrass–Maury Silty Loam, comprising 56% silt, 38% clay, and 6% sand, pH (6.8 a), organic matter (2.6 b),TN (0.15 c), TP (0.17 c)	Cow Manure, Chicken Manure, Vermicompost, Leaf Compost, Sewage Sludge, with Mustard (Brassica juncea) with three vareities (might, black, and, yellow)mustard	Metal concentrations were quantified using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) in standard mode following the SW-846 EPA 6010 B method	Pot experiment	1 year	Initial concentration in soil for Ni (17.5 a mg kg−1), Cd (0.23 a mg kg−1), Pb (31.2 a mg kg−1), Mo (0.64 a mg kg−1), and Cu (10.17 a mg kg−1)	The results show that total metal concentrations vary among soil amendments. Mustard absorbed the most Cd and Zn from sewage sludge, with heavy metal concentrations increasing from Ni to Cd, Pb, Mo, Cu, and Zn. Cu and Mo absorption were highest with vermicompost, Ni with chicken manure, and Pb with cow manure. Soil concentrations were in the following order: Cd < Mo < Cu < Ni < Pb < Zn, with leaf compost	(Nepal et al., 2024)

Soil Contamination	Location	Soil Condition	Plants/Additvie used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
								containing the most Cd and chicken dung containing the most Cu, Mo, Pb, and Zn.	
			Potassium Chloride (KCl)						

4.0 Biosorption

Soil Contamination	Location	Soil Condition	Organisiams used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
Pb, Cd	Jingtang village, Yixing Municipality, Jiangsu Province, China	The soil was derived from a lacustrine deposit and classified as a hydroagric Stagnic Anthrosol. The topsoil contained organic carbon of 20.20 g kg−1, total N of 5.94 g kg−1, cation exchange capacity of 23.07 cmol kg−1 and pH (H2O) of 5.36. tmperature was 350 and 550 °C	Wheat straw was used to ptoduce biochar	the amended rate of the biochar was 0 (C0), 10 (C10), 20 (C20) and 40 (C40)tha−1 It was done by spreading the biochar on the soil surface and subsequently mixing it to a depth of 0–15 cm with a plough before leveling the surface. Rice cultivar	Field Experiment	3 years	Cd 0.2 mg kg−1 and Pb 12.9 mg kg−1, and had a surface area of 8.92 m2 g−1 with a bulk density of 0.6 g cm−3 and pH (H2O) of 10.4 as well as a cation exchange capacity of 21.7 cmol kg−1.	Soil CaCl2 extractable Cd was significantly decreased throughout the three years, by 54.5–70.9% in 2010, by 53.5–64.8% in 2011 and by 28.3–60.9% in 2012, respectively. However, a significant reduction in DTPA extractable Cd was only observable in the third year, by 12.0%, 24.0% and 20.9% under C10, C20 and C40 treatments respectively. Meanwhile, soil CaCl2 extractable Pb in the rice field was significantly	(Bian et al., 2014)

Soil Contamination	Location	Soil Condition	Organisiams used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
				Wuyunjing-19 (O. sativa L., cv. Japonica) was in each pot yearly with total N, P and K fertilizers were applied at the rates of 300 kg N ha−1, 204 kg P2O5 ha−1 and 204 kg K2O ha−1 in the forms of urea, Ca(H2PO4)2 and KCl.				reduced by 16.7–33.3% in 2010, 65.0–79.6% in 2011 and 18.1–59.1% in 2012 for biochar treatments compared to the control. Comparatively, the reduction in soil DTPA extractable Pb was much lower, by 17.8–18.4% in 2010, 20.7–27.7% in 2011 and 17.8–26.9% in 2012, respectively.	
Pb	Youxi, Fujian Province, China	The soil sample was Isolated from lead–zinc mine tailings	Bacteria (Bacillus cereus 12–2)	The experiment was conducted using the sequence homology analysis of 16S rRNA gene, and inductively coupled plasma optical emission spectroscopy (ICP-OES) (Ultima2).	Laboratory experiment	24 h	100 to 800 mg/L @ pH 4.0	uptake of B. cereus 12-2 was increased from 99.5 mg/g to 224.8 mg/g with the increase of initial Pb(II) concentration from 100 mg/L to 400 mg/L after interaction for 24 h at pH 4.0, while it tended to be stabilized when the Pb(II) concentration was further increased from 400 mg/L to 800 mg/L. The maximum Pb(II) uptake of B. cereus 12-2	(Chen et al., 2016)

Soil Contamination	Location	Soil Condition	Organisiams used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
								was determined as 226 mg/g (dry weight).	
Pb	IMT (Industrial Model Township), Rohtak (Haryana), India.	Composite soil containing food, paint, and battery manufactural industries. Elevation is 222 m (Above Sea level). The soil was preserved at 4 °C	Bacteria (Bacillus cereus BPS-9)	The experiment was conducted using the 16S rDNA sequencing and phylogenetic analysis	Laboratory experiment	72 h	100 to 2500 mg/L for 72 h at 120 rpm, while pH and temperature were maintained 7.0 and 37 °C,	The results showed that the isolate namely Bacillus cereus BPS-9 as identified based on 16S rDNA gene sequences was shown to have the highest Lead accumulation potential 79.26 %	(B. Sharma & Shukla, 2021)
Ni, Cu, Cd, Cr, Pb	Aligarh, North India	The soil samples were collected from rhizosphere of cauliflower grown in soils irrigated.	Bacteria (Bacillus thuringiensis strain OSM29)	The experiment was conducted using the 16S rDNA sequencing and phylogenetic analysis	Laboratory experiment	72 h	The concentration (25–150 mgl−1) varies for Ni, Cu, Pb, Cr, Cd, at a temperature of 32 ± 2 °C for each metal with the optimum contact time at 30 min. the pH 7.0 for Ni, and Cr, and p H 6.0 for Cu, Cd, and Pb respectfully.	The results showed that the isolate namely Bacillus thuringiensis strain OSM29) identified based on 16S rDNA gene sequences for metallic ions was the highest for Ni (94%), Cu (91.8%), Pb (91.6%), Cr (89.8%, and Cd (87%) all at the lowest concentration (25 mg/l−1	(Oves et al., 2013)
Pb, Cd, Cu, Zn	Kraków, Poland	The sediment samples containing Ammonia were collected from Kiel Fjord. The Kiel Fjord, located in northern Germany, is heavily influenced	Micro Algae (Nannochloropsis oceanica strain CCMP1779)	The experiment was carry out using the Atomic Absorption Spectrometry (AAS) using a	Laboratory experiment	12 days	The concentration varies for Pb (2.0720 mg/L), Cd (0.1124 mg/L), Cu (0.3177 mg/L), and Zn (0.3269 mg/L) respectfully.	The result of the laboratory experiment on the examined algae had a significant ability to remove Pb (51%) and Cu (15%) from the culture medium, but were less effective at removing Cd	(Lintner et al., 2025)

Soil Contamination	Location	Soil Condition	Organisiams used	Method	Scale/Scope	Time Frame	Concentration in the Collected Increment	Result	Reference
		by human activity, such as intensive traffic, shipyard and harbour operations,		Thermo Scientific ICE 3500 AAS spectrometer				(0.7%) and Zn (1.7%). In general, adsorption of dissolved metals in algae differs between species.	

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