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Phytoremediation technologies promising for the restoration of agricultural lands damaged by military actions

N. Martynova, T. Kolombar

Oles Honchar Dnipro National University, Dnipro, Ukraine

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Oles Honchar Dnipro National University,
Nauky av., 72,
Dnipro, 49010, Ukraine.
Tel. +38-056-760-83-06.
E-mail:
nadiamart.bg@gmail.com

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Soil disturbance as a result of military action can range from a short-term reduction in fertility to complete destruction of the soil. A special problem is the restoration of agricultural soils. The most promising way to solve this issue is to use phytoextraction and phytostabilization methods, especially those that combine remediation measures with simultaneous economic benefits. Recently, among phytoextraction strategies, preference has been given to growing plants that do not have the ability to hyperaccumulate, but which, due to their rapid growth and the formation of a large biomass, can remove toxicants from the soil in large quantities. The idea of combining the restoration of contaminated lands with the production of biomass for phytomining and renewable energy is especially attractive. Phytostabilization strategies can be implemented using useful plants that do not accumulate pollutants in the final raw material, for example, some agricultural, forage and pasture crops (*Vicia villosa*, *Secale cereale*, *Zea majus*, *Lupinus luteus*, *Festuca* sp., *Lolium perenne*, etc.), energy crops (*Spartina pectinata*, *Miscanthus* sp., etc.), essential oil plants (*Mentha*×*piperita*, *Melissa officinalis*, *Marrubium vulgare*). The attention of scientists is also drawn to the search for promising soil additives and the study of their application rates in order to improve soil conditions and increase biomass yields.

Keywords: disturbed soils; pollution; phytoextraction; phytostabilization; phytovolatization.

Introduction

In addition to its direct impact on humanity, military activity has a significant impact on various ecological levels of the biosphere. The extent of this impact on ecosystems depends on the type of stimulation, the sensitivity of the biological system, its ability to recover, and the duration of exposure. Soil disturbances caused by military actions can be divided into three types: physical, chemical and biological. Physical disturbances include soil compaction due to heavy equipment and troop movements, construction of fortifications, digging of trenches, formation of bomb craters, humus burning resulting in the formation of sintered soil particles because of explosions, etc. Chemical contamination includes contamination with substances such as petroleum, heavy metals, nitroaromatic explosives, organophosphorus nerve agents, dioxins, or radioactive elements. Biological disturbances are unintended consequences of impacts on the physical and chemical properties of the soil (for example, annihilation of plants, damage to the root system, death of symbiotic and soil microorganisms) or the deliberate introduction of microorganisms that are lethal to animals and humans (Certini et al., 2013). According to preliminary estimates, as of today, more than 180 thousand square kilometers of territory in Ukraine have been contaminated as a result of military actions (Tykhenko et al., 2025). Therefore, the search for effective technologies for cleaning up contaminated lands in the post-war period is becoming increasingly important. International experience can help solve this issue. According to Stadler et al. (2022), interest in this topic is high, with over 250 new publications appearing annually. Most research focuses on heavy metal and organic pollution, the effects of soil pollution in food chains, and land reclamation.

There are various approaches to reclaiming disturbed lands. If effective restoration is impossible, contaminated areas are conserved. In cases where restoration of biodiversity and hydrological conditions is possible, the creation of natural conservation reserves may be a solution. Another option is to use disturbed lands to create urban recreational areas: parks, squares, artificial forests, and tourist areas. Agricultural reclamation, which involves restoring disturbed lands to a condition suitable for agricultural activities, is the most complicated. Soil remediation can be accomplished using technical or biological technologies. However, integrated approaches are typically employed. For example, a number of authors (Fayiga, 2018; Celin et al., 2020; Fernández-López et al., 2024) report that not only technical methods (chemical leaching, hydrolysis, stabilization photolysis, electrokinetic remediation, etc.) but also soil bioremediation technologies are being used in post-war areas. Pollutant immobilization is also carried out using soil additives, which increase the effectiveness of toxicant stabilization (Fayiga, 2018). Although bioremediation has received considerable attention, a number of factors hinder its large-scale application. For example, in the case of using microorganisms to clean up soils from oil products and other organic pollutants, many field experiments report that not all factors are adequately controlled and analyzed. Moreover, a wide range of microorganisms and metabolites with deactivating properties have not been well studied (Sales da Silva et al., 2020). Similar difficulties arise when applying phytoremediation methods. Despite the extensive list of plants whose ability to accumulate or stabilize pollutants has been demonstrated in laboratory or microfield experiments, their practical application is often restricted or even impossible due to a number of limiting climatic, soil, and other factors (Arthur et al., 2005; Surriya et al., 2015). Despite the shortcomings of bioremediation methods, their application holds great promise. Research into the mechanisms of toxicant removal from soil and the interactions between plants and microorganisms will facilitate the expansion of bioremediation applications. A comprehensive analysis of these technologies can help select strategies appropriate to specific environmental conditions.

Materials and methods

This review analyzes phytoremediation technologies that are promising for restoring agricultural land damaged by military action. Published domestic and international studies in scientific databases of electronic libraries were used for the review. Google Scholar and the Google search engine were used for the search queries "land degradation," "soil pollution," "restoration of damaged soils," "recultivation," "bioremediation," "phytoremediation," "phytoextraction," "phytostabilization", "phytovolatization," and others. Based on the analysis of the reviewed materials, the most promising approaches to the successful restoration of agricultural land in the post-war period in Ukraine are identified.

Global and domestic experience in bioremediation of disturbed agricultural lands. The influence of soil type on the choice of remediation methods

Bioremediation is a complex of methods for cleaning soils and waters using plants, algae, invertebrates and microorganisms (bacteria, fungi). Bioremediation is safe for the environment; during its application, unlike other methods, there is no secondary waste. Although biological remediation processes take a long time, these technologies have a gentle impact on the environment and do not lead to significant changes in soil components. Another advantage of bioremediation methods is their low cost. Bioremediation is most often used to clean soils of heavy metals, radioactive elements, and petroleum products (Aparicio et al., 2022; Song et al., 2022; Sánchez-Castro et al., 2023).

Bioremediation can be accomplished in two different ways:

1) *ex situ* bioremediation involves removing contaminated soil and transporting it to specialized sites for subsequent treatment. After washing, extracting toxicants through land farming, biocomposting, or fermentation in bioreactors with the addition of nutrients, the soil is returned to its original location and reclamation work is carried out. This strategy is most often used to clean up soil heavily contaminated with petroleum products and other organic compounds (Koul & Taak, 2018; Pirog et al., 2018; Li et al., 2022). Although some ex situ bioremediation methods are quite expensive, they are highly effective, reducing toxicant concentrations in the soil by 90–99%;

2) *in situ* bioremediation involves cleaning the soil directly at the site of contamination, which can significantly reduce the cost of the work. For contamination by petroleum products, volatile, and semilight organic compounds, biostimulation technologies are most often used, that involve activating natural microflora (methods such as bioventilation, biobubbling, and vacuum biopumping), or bioaugmentation methods, that is, the introduction of microbiological destructor preparations that have a specialized effect on specific pollutants (Goswami et al., 2018; Ma et al., 2022). Phytoremediation technologies using vascular plants are more successful in cleaning soils from heavy metals (Ali et al., 2013; Shen et al., 2022).

The choice of soil remediation strategy depends on several factors: the degree of contamination, the forms and types of toxicants, and soil characteristics. For example, high soil cation exchange capacity, humus content, and amorphous inorganic material (e.g., ferrous hydroxides) facilitate the absorption and accumulation of pollutants. Through ion exchange and complexation, humic acids concentrate heavy metals and radionuclides in soils and bottom sediments. Humified organic matter in soils also more effectively retains most organic pollutants, especially those of a hydrophobic nature. Therefore, soils enriched with organic matter more strongly bind and retain organic toxicants and heavy metals (Holoubek et al., 2009; Zhang et al., 2013; Durães et al., 2018).

The ratio of the clay fraction components in soils also matters. Clays with high swelling capacity, such as montmorillonite and vermiculite, absorb more contaminants than clays with low swelling capacity (illite, kaolinite) (Yang-Guang et al., 2016). Soil pH is also an important physicochemical parameter that controls the sorption and desorption of ions in the soil. This parameter can significantly influence the mobility of heavy metal ions, causing them to be more or less active and thus affecting the environmental hazard of a contaminated area (Kazlauskaitė-Jadzevičė et al., 2014; Li et al., 2018; Kicińska et al., 2022). In addition, the pH factor has a significant impact on the dynamics and diversity of soil microbial populations, and on the metabolic activity of microorganisms (Wang et al., 2019; Naz et al., 2022).

Phytoremediation of soils contaminated with heavy metals and other pollutants

One of the ways to solve the problem of heavy metal soil contamination caused during military operations is to use various methods using plants or plant products to clean, restore, and stabilize contaminated land. Phytoremediation uses the ability of plants to absorb, accumulate, and decompose organic and inorganic substances. It is an effective and inexpensive way to reduce heavy metal concentrations in various soil types.

One method for removing pollutants from soils using plants is phytoextraction. It involves plants absorbing pollutants from the soil and accumulating them in aboveground biomass, which is later utilized. When selecting plants for phytoextraction, several factors must be considered simultaneously: tolerance to high pollutant concentrations in the soil, rapid growth, the ability to actively transport toxicants from the root system to the aboveground organs, and adaptability to local soil and climatic conditions. It is clear that phytoextraction can only be successful if the rate of absorption of heavy metals or other toxicants by plants exceeds the rate of pollutant entry into the environment (Van Nevel et al., 2007; Robinson et al., 2015). Phytoextraction can be applied to extract metals (e.g. Ag, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Zn), metalloids (e.g. As, Se), radionuclides (e.g. ^{90}Sr, ^{137}Cs, ^{234}U, ^{238}U) and some non-metals (e.g. B) as they are generally not subject to further degradation or alteration within the plant (McGrath et al., 2002; Willey, & Collins, 2007; Yan et al., 2021). Phytoextraction is generally not considered for organic pollutants because plants can metabolize, alter, or volatilize them, thus preventing the accumulation of pollutants in the biomass.

Phytoextraction is accomplished using hyperaccumulator plants, which are capable of actively absorbing pollutants from the soil and rapidly transporting them from their roots to above-ground biomass. Hyperaccumulation occurs through a combination of mechanisms: 1) bioactivation of metals in the rhizosphere through interactions between roots and microorganisms. Chemical compounds found in the rhizosphere are associated with increased metal uptake from the soil and their transport to shoots. Low-molecular-weight organic acids and amino acids are the most important exudates in natural phytoextraction systems. They influence metal uptake by forming complexes with metal ions or by lowering the pH around the roots and altering soil properties; 2) overexpression of transmembrane metal transporters is thought to play a significant role in metal uptake, xylem loading, and vacuole sequestration; 3) metal detoxification via apoplast distribution, for example, cell wall binding and cytoplasmic metal chelation with various ligands such as phytochelatins, metallothioneins, and binding proteins (Yang et al., 2005; Sytar et al., 2021).

For plants to be classified as hyperaccumulators, they must be able to maintain minimum threshold concentrations of an element in tissues: 100 mg/kg for Cd, Se, and Tl; 300 mg/kg for Cu, Co, and Cr; 1000 mg/kg for Ni, As, and Pb; and 3000 mg/kg for Zn. Additionally, the bioconcentration (aboveground biomass/soil) and translocation (aboveground biomass/roots) coefficients must be greater than one (van der Ent et al., 2013; Egendorf et al., 2020). Although the total number of hyperaccumulator plants in the world is quite large – over 500 species, the list of those that can be grown in a temperate climate zone is much shorter. Table 1 shows the potential of some species of phytoextractors that have prospects for application in Ukrainian conditions. If hyperaccumulators have been registered and experimentally confirmed for elements such as nickel, zinc, cadmium, manganese, arsenic and selenium, then the hyperaccumulation of lead, copper, cobalt, chromium, thallium and other elements still leaves many questions (van der Ent et al., 2013).

Although hyperaccumulator plants can accumulate toxicants in large quantities, their use often faces several obstacles. These plants typically grow slowly and do not produce significant biomass. Therefore, extracting elements from the soil takes a long time. This is especially problematic for the clearing of agricultural land, which, under such conditions, is withdrawn from use for many years. Furthermore, selecting the appropriate plant species that will thrive in specific climatic conditions is also challenging.

In this regard, recent research has focused on plants that lack the ability to hyperaccumulate but which, thanks to rapid growth and high biomass production, are capable of removing toxicants from the soil in large quantities. The idea of combining the restoration of contaminated lands with the production of biomass for phytomining and renewable energy is particularly attractive (Van Ginneken et al., 2007; Dang & Li, 2022; Rabbani et al., 2024).

Table 1
The promises of some hyperaccumulator plants for temperate climate zone

Plant name	Lifeform	Accumulated element	Amount of element in aboveground biomass, mg/kg	Element uptake with annual harvest, kg/ha	References
Thlaspi caerulescens	biennial	Zn	8000–25000	125–250	Chaney et al., 2005; Banasova et al., 2008
		Cd	1000–4200	1–20	Chaney et al., 2005; Banasova et al., 2008
Alyssum murale	semi-shrub	Ni	9000–20000	25–200	Li et al., 2003; Chaney et al., 2005; Bani et al., 2007
		Co	1300	–	Li et al., 2003
Phytolacca americana	perennial	Mn	6500–32000	–	Min et al., 2007; DeGroote et al., 2018
Arabidopsis halleri	perennial	Zn	6000–32000	up to 10	Schwartz et al., 2001; Zhao et al., 2006
		Cd	230–1500	–	Zhao et al., 2006; Ueno et al., 2008
Armeria maritima	perennial	Zn	6000	–	Schwartz et al., 2001
Arrhenatherum elatius	perennial	Zn	6200	up to 10	Schwartz et al., 2001
Lolium perenne	perennial	Pb	2000	–	Egendorf et al., 2020
Salix × *smithiana*	tree	Cd	250	–	Wieshammer et al., 2007
		Zn	3300	–	Wieshammer et al., 2007
Leersia oryzoides	perennial	As	300	0.13	Ampiah-Bonney et al., 2007
Leersia hexandra	perennial	Cr	1844	–	Liu et al., 2011
Mentha longifolia	perennial	Se	365	–	Dhillon & Dhillon, 2009
Silene gallica	annual	Se	246	–	Dhillon & Dhillon, 2009
Verbascum cinerariifolium	biennial	Sr	105–149	–	Sasmaz & Sasmaz, 2009
Linum usitatissimum	annual	Cu	250	–	Saleem et al., 2020

Thus, experiments with willow (*Salix*) and poplar (*Populus*) in areas contaminated with Cd, Cu, Ni, Zn, Cr, and Pb showed the suitability of these plants for phytoextraction of these elements. Willows had higher extraction efficiency than poplars. Despite lower biomass, heavy metal extraction efficiency was best for willows due to higher concentrations in the wood (Algreen et al., 2013). *Salix alba* and *S. viminalis* have been shown to be able to extract several heavy metals (Salam et al., 2019). It has been noted that the rate of Cd uptake by willow (*Salix*) is higher compared to other trace elements (Dickinson & Pulford, 2005). *Salix viminalis* has also been noted as a promising tree for the remediation of oil-contaminated areas (Glibovytska et al., 2019). Various hybrids of energy paulownia (*Paulownia* sp.) have shown promise in the phytoextraction of Cu, Zn and Cd (Bahri et al., 2015; Tzvetkova et al., 2015).

Experiments with *Brassica juncea* have shown the potential of this plant for phytoextraction of several heavy metals. This plant is able to accumulate large amounts of cobalt, lead and zinc in aboveground biomass, and according to Saraswat & Rai (2009), also nickel.

The possibility of combining the cultivation of *Brassica napus*, which is widely cultivated in Ukraine as an oilseed energy crop, with phytoextraction of cadmium, lead and zinc on soils contaminated with heavy metals has been noted (Grispen et al., 2006; Cojocaru et al., 2016). This idea is most attractive in the light of the fact that the toxic elements Cd and Pb almost do not accumulate in seeds, but remain in residues. Therefore, oil extraction with subsequent production of diesel biofuel is possible without stopping agricultural activities (Park et al., 2012; Cao et al., 2019).

In case of moderate contamination of agricultural lands, sunflower (*Helianthus annuus*) can also be considered as a dual-purpose plant. It is known that its above-ground biomass is able to accumulate Zn, Cu, Pb, and Ni without significant accumulation in the seeds (Shuliak et al., 2022; Tkachuk et al., 2024). After harvesting the seeds, the biomass can be used for ethanol production, and the residues can be safely disposed of (Dhiman et al., 2017). Although it takes 55–207 cycles of sunflower cultivation to return the contaminated area to arable land (Kötschau et al., 2014), sequential reclamation with simultaneous cultivation of biofuel crops is possible without compromising food production. It is reported that cadmium can actively accumulate in sunflower seeds (Angelova et al., 2004; Shuliak et al., 2022). Therefore, when soils are contaminated with this element, growing sunflower as an oilseed crop is impossible.

In recent years, the energy potential of *Miscanthus* sp. has been actively studied in various climatic conditions, including in Ukraine. When considering this plant from the perspective of phytoremediation, most researchers favour the use of *Miscanthus* for phytostabilization due to the accumulation of pollutants primarily in the root system (Nsanganwimana et al., 2015; Dražić et al., 2017; Zhang et al., 2023). However, there is evidence that *Miscanthus* is capable of accumulating zinc not only in the roots but also in the aboveground biomass (Kocoń et al., 2017). Based on their accumulation activity in *Miscanthus* biomass, heavy metals can be ranked in the following order (from highest to lowest): inc, lead, copper, nickel, and cadmium. In general, more metals are extracted from sandy soils (Kocoń et al., 2017). Experiments with cultivating *Miscanthus* × *giganteus* on soils taken from mining and former military sites contaminated with As, Pb, Zn, Co, Ni, Cr, Cu, V, Mn, Sr and U, as well as on soils artificially contaminated with Zn and Pb, showed that *M.* × *giganteus* was an accumulator plant for two elements: Mn and Sr (Nurzhanova et al., 2019). In the experiment on different types of technosols, a tendency to accumulate in the aboveground biomass of lithium, cadmium (mainly in leaves) and, especially, strontium was also noted; the biological mobility coefficients of these elements were from 1.2 to 2.9 in stems and from 5.2 to 9.7 in leaves (Kharytonov et al., 2023). Another Ukrainian experiment, in which *M.* × *giganteus* was grown on three soil types, showed that the accumulation of Pb, Cd, Zn, and Cu in the aboveground plant mass varied depending on the soil type. The lowest accumulation of heavy metals was observed on gray forest soils, while the features of sod-podzolic soils contributed to increased concentrations of Cd, Zn, and Cu. The highest Pb content was recorded when *M.* × *giganteus* was grown on black soils (Razanov et al., 2025). A study by Romantschuk et al. (2024) on two energy crops, *M.×giganteus* and *Phalaris arundinacea,* found that they were capable of accumulating both heavy metals and organic pollutants and petroleum products. The content of mobile forms of heavy metals (Cr, Sb, Cd) in the soil decreased by 10–40%, and petroleum products by 18–35%, following the cultivation of energy crops.

Another promising energy crop for Ukraine (especially in arid regions) is switchgrass (*Panicum virgatum*). Due to its simple cultivation techniques and high biomass production, it can be used in situ for the phytoextraction of Zn, Mn, and Cu (Chen et al., 2012; Kharytonov et al., 2025). This crop also actively accumulates chromium; however, high concentrations of this element can be toxic and significantly reduce biomass yield (Gomes et al., 2019). For regions with more humid climate, *Spartina pectinata* can be suggested for cadmium extraction (Pogrzeba et al., 2018). There is evidence that sorghum (*Sorghun bicolor*) is also a good Cd extractor, especially on acidic sandy loam soils (Wang et al., 2017; Perlein et al., 2021). Thus, there is potential for the simultaneous use of energy crops for bioethanol or biogas production and remediation.

Many questions remain regarding the disposal of biomass after toxicant extraction. At the pre-treatment stage, composting, compaction, and pyrolysis are considered the safest. For final disposal, incineration (melting) is proposed as the most rational, cost-effective, and environmentally friendly technology (Sas-Nowosielska et al., 2004;

Šyc et al., 2012). Recently, there has been an active search for effective methods to enhance the accumulation of heavy metals by plants that are not hyperaccumulators. As is known, chelating chemicals, such as ethylenediaminetetraacetic acid (EDTA) and its derivatives, or organic fertilizers, increase the availability of heavy metals to plant roots, thereby increasing the efficiency of phytoextraction. Thus, Kos et al. (2003) noted that the use of EDTA promoted the accumulation of Zn, Pb and Cd in some plant species, including agricultural ones: *Sinapis alba*, *Zea mays*, *Linum usitatissimum*, *Sorghum vulgare*. It has been proven that the addition of EDTA increases the absorption of Cu, Zn, Mn, Pb and Cd by *Brassica napus* plants (Zaier et al., 2010; Habiba et al., 2014). In experiments with sunflower, Sinegani & Khalilikhah (2008) determined the optimal doses of 0.5 and 2 g EDTA/kg soil for phytoextraction of lead.

Despite the effectiveness of synthetic chelating agents, their use is associated with certain risks. Their high mobility in soil and the persistence of the chelate-heavy metal complex can lead to the transfer of toxicants to uncontaminated areas. In addition, chelating chemicals can lead to an excess of heavy metal uptake by plants and, thus, become a factor of toxicity for the plant (Souza et al., 2013).

Natural low-molecular-weight organic acids (LMWOAs): citric, oxalic, malic, acetic, etc., can serve as an alternative to synthetic chelating agents. Their molecules are capable of forming low- and medium-stability complexes with metals. These compounds exhibit a high rate of biodegradation in soil and do not cause negative effects (do Nascimento et al., 2006; Souza et al., 2013; Gao, & Fu, 2023). Although data on the effective use of LMWOAs to improve phytoextraction are still insufficient, there are positive results from the use of organic acids in enhancing the absorption of heavy metals by plants such as *Zea majus*, *Amaranthus hypochondriacus*, *Celosia argentea*, and *Brassica napus* (Sabir et al., 2014; Yu et al., 2020; Stojanov et al., 2024).

Also interesting are experiments with a combination of several additives to improve phytoextraction. Thus, according to Brunetti et al. (2011), the addition of composts from municipal solid waste and a strain of *Bacillus licheniformis* enhanced the accumulation of Cu, Pb, Zn, and especially Cr, by *Brassica napus* plants. In the experiment of Gasco et al. (2019), the use of biochar from rabbit manure prepared at temperatures of 450 °C and 600 °C had a similar effect on the absorption of Co, Cr, Cd, Cu, Ni, Zn, Pb, and As.

Another approach to solving the phytoextraction problem is the use of transgenic plants. Developing transgenic plants with enhanced phytoremediation capacity requires a thorough study of the genetic mechanisms and biochemistry of metal uptake, transport, and storage in hyperaccumulator plants. Currently, many plant species are being studied to determine their usefulness for phytoextraction, particularly high-biomass crops (Bhargava et al., 2012; Venegas-Rioseco et al., 2021).

In some cases, such as the remediation of soils with high humic acid content (black soils), it is better to use phytostabilization methods which involve reducing the mobility and bioavailability of pollutants in the environment through physical or chemical action. It is very effective when rapid immobilization is required to conserve groundwater and surface water. The presence of plants also reduces soil erosion. Requirements for stabilizer plants: the ability to develop a branched and powerful root system; the ability to keep metal translocation from roots to shoots at a low level; the ability to retain pollutants in the roots or rhizosphere (exclusion mechanism) to limit spread along the food chain. The main mechanism of phytostabilization is the complexation of metal ions with root exudates or cell walls, as well as binding to metal-binding molecules (phytochelatins and metallothioneins), and, finally, their sequestration in the root vacuole (Shackira & Puthur, 2019).

Phytostabilization of contaminated soils can be accomplished in two ways: using woody species or herbaceous plants. When using woody species, two strategies are proposed: the use of trees in long cycles (over 20 years), i.e., actual afforestation of the area; or the cultivation of tree crops in short rotations (3–8 years) to produce feedstock for renewable energy. Although the selection of the most suitable species for afforestation of contaminated lands remains a matter of debate, there is positive data on the use of *Quercus* sp., *Robinia pseudoacacia*, *Betula pendula*, *Pinus sylvestris*, *Alnus* sp., and other species for phytostabilization (Van Nevel et al., 2011; Luo et al., 2019; Sozoniuk et al., 2020; Pietrzykowski et al., 2022; Chirilă Băbău et al., 2024).

There are currently many more questions than answers regarding the success of using energy trees for phytostabilization. For example, for poplar and willow, it has been shown that the accumulation and distribution of heavy metals in organs depends on genotype, age, soil characteristics, and other environmental conditions (Hrkić Ilić et al., 2020; Jr et al., 2020). Therefore, depending on various conditions, these plants can act as extractors or stabilizers, complicating the choice of phytoremediation strategy. For the arid steppe and forest-steppe regions of Ukraine, the use of energy trees may also be inappropriate due to the mismatch between the needs of these plants and regional climatic conditions.

For the restoration of agricultural lands contaminated by military actions, the use of herbaceous plants, while simultaneously generating economic benefits, appears more promising. In this case, phytostabilization can be achieved through several strategies, such as:

1) growing agricultural crops that do not accumulate pollutants in their above-ground mass;
2) creating pastures from grasses or forbs;
3) growing energy herbaceous plants;
4) growing perennial medicinal or essential oil plants.

In some cases of moderate pollution, agricultural land can continue to be used for its intended purpose after chemical stabilization of the soil. For example, growing forage crops has great potential under such conditions. There is positive experience with the use of annuals *Lolium multiflorum*, *Vicia villosa*, *Secale cereale*, *Lupinus luteus* and the perennial *Trifolium pratense* for the phytostabilization of cadmium, lead, zinc, arsenic, and copper with the simultaneous production of feed raw materials (Dary et al., 2010; Kim et al., 2018). Corn can be useful for phytoremediation of areas contaminated with zinc and copper, but it should not be used as a phytostabilizing crop on soil contaminated with nickel because of its low tolerance to this element (Korzeniowska et al., 2011).

If growing agricultural crops is not feasible, a strategy of creating pastures from grasses or forbs can be used. There is data that *Festuca* sp., *Lolium perenne*, *Koeleria* sp., *Agrostis* sp., and *Trifolium* sp. accumulate heavy metals in their roots, so sowing such plant mixtures can contribute to the phytostabilization of soils contaminated with Zn, Cu, Cd, and Pb (Frérot et al., 2006; Bidar et al., 2007; Santibáñez et al., 2008; Radziemska et al., 2017; Lebrun et al., 2021; Oleńska et al., 2022). Aboveground biomass can be used for grazing and forage production. Intercropping with legumes improves the physical properties of disturbed soils and increases fertility. Furthermore, experiments with *Lupinus albus* demonstrated its ability to increase the pH of acidic soils, likely due to the release of citrate, which contributed to a decrease in the soluble fractions of As and Cd in the soil (Vázquez et al., 2006).

Another strategy for phytostabilization of contaminated arable land is the establishment of energy crop plantations. Experiments with *Spartina pectinata* revealed its ability to phytostabilize zinc. Although to a lesser extent, it is also capable of stabilizing copper and nickel (Korzeniowska & Stanislawska-Glubiak, 2015). Dry-stemmed sorghum species have the potential for the phytostabilization of Cu and Ni. *Miscanthus* is a good candidate for the phytostabilization of lead (Pavel et al., 2014; Alasmary et al., 2021), as well as mercury (Zgorelec et al., 2020), chromium and arsenic (Kharytonov et al., 2023). It was found that switchgrass doesn't accumulate Co, Ni, Pb and Cd in its aboveground biomass; that is why it is promising for the phytostabilization of these elements (Kharytonov et al., 2025). It should be taken into account that *Miscanthus* and switchgrass are extractors for some elements and stabilizers for others. Therefore, in the case of complex soil pollution, it is better to reorient the use of biomass to the production of bioethanol instead of solid fuel.

Some essential oil plants can also be grown as an alternative to food crops in soils contaminated with heavy metals because the pollutants do not migrate into the essential oil (Pandey et al., 2019). It has been proven that high levels of cadmium, copper and lead can reduce the yield of dill (*Anethum graveolens*) and basil (*Ocimum basilicum*), and slightly reduce the menthol content in peppermint oil (*Mentha*× *piperita*), but none of these metals were detected in the essential oil of these species (Zheljazkov et al., 2006). Similar results were obtained in an experiment with *Melissa officinalis*, *Marrubium vulgare* and *Origanum heracleoticum* grown in soils contaminated with zinc, lead, copper and cadmium. The metal content in teas prepared from these species was negligible, and the essential oils did not contain any metals (Zheljazkov et al., 2008).

Brief information about the most promising useful plants for phytostabilization of contaminated soils in Ukrainian conditions is presented in Table 2.

Table 2
Useful plants that can be used for phytostabilization of contaminated soils in temperate climates

Plant name	Lifeform	Neutralized element	Economic use	References
Robinia pseudoacacia	tree	Pb, Cu, Zn, Cd	woody, energetic, melliferous	Luo et al., 2019; Chirilă Băbău et al., 2024
Quercus robur	tree	Cd	woody, medicinal, melliferous	Sozoniuk et al., 2020
Agrostis ssp.	perennial	As, Pb	pasture, fodder	Lebrun et al., 2021
Festuca arvernensis	perennial	Zn, Cd, Pb	pasture, fodder	Frérot et al., 2006
Festuca rubra	perennial	Cu	pasture, fodder	Radziemska et al., 2017
Koeleria vallesiana	perennial	Zn, Cd, Pb	pasture, fodder	Frérot et al., 2006
Lolium perenne	perennial	Cu, Zn, Mo, Cd	pasture, fodder	Bidar et al., 2007; Santibáñez et al., 2008
Trifolium repens	perennial	Cd, Zn, Pb	pasture, fodder	Bidar et al., 2007; Oleńska et al., 2022
Trifolium pratense	perennial	Cd, Pb, As	pasture, fodder	Kim et al., 2018
Marrubium vulgare	perennial	Cd, Pb, Cu	medicinal	Zheljazkov et al., 2008
Melissa officinalis	perennial	Pb	medicinal, essential oil	Zheljazkov et al., 2008
Menta piperita	perennial	Cd, Pb, Cu, Mn	medicinal, essential oil	Zheljazkov et al, 2006
Ricinus commumis	annual	Ni	oil, energy, medicinal	Adhikari & Kumar, 2012
Lupinus albus	annual	Cd, As	fodder, food	Vázquez et al., 2006
Lupinus luteus	annual	Cd, Pb, Cu	fodder	Dary et al., 2010
Sorghum bicolor	annual	Cd, Zn	energy, fodder, food	Soudek et al., 2012
Sorghum halepense	annual	Ni	energy, fodder	Rabêlo et al., 2018
Sorghum sudanense	annual	Cu	energy, fodder	Rabêlo et al., 2018
Miscanthus sp.	perennial	Cd, Hg, Pb	energy	Pavel et al., 2014; Zgorelec et al., 2020; Nsanganwimana et al., 2021

Phytostabilization of toxic metal ions in the rhizosphere can be significantly improved by treating the soil with various organic and inorganic amendments to reduce the bioavailability of pollutants and improve the condition of contaminated soil, thereby promoting plant growth. For example, an experiment with limestone addition in postwar areas contaminated with Cu, Ni, Cd, Pb, Zn, and Cr revealed a significant increase in soil pH and a decrease in Cu, Ni, and Cd content. Heavy metals in the biomass of *Festuca rubra* growing in the experimental plot accumulated primarily in the root biomass (Radziemska et al., 2019). In experiments with *Miscanthus*, the addition of inorganic phosphorus (triple superphosphate, applied in a ratio of 5:3) and organic phosphorus (class B biological fertilizers, with an application rate of 45 t/ha) resulted in a significant reduction in total lead uptake, its concentration in plant tissues, and bioavailability in soil (Alasmary et al., 2021). The use of red mud (a by-product of the alumina industry) as a soil amendment on heavily contaminated soils near a former Pb-Zn smelter in Copșa Mică (Romania) reduced the exchangeable or phytoavailable fractions of Zn, Cd and Pb, resulting in no accumulation of these elements in the above-ground biomass of *Miscanthus* (Pavel et al., 2014). When growing *Brassica juncea* and *Dactylis glomerata* on soils heavily contaminated with As, Cd and Pb, the addition of compost and biochar resulted in increased yields of these crops and an overall reduction in the toxicant concentration in plants compared to the control. Furthermore, both plant species showed a higher accumulation of pollutants in roots than in shoots (Visconti et al., 2020).

Of course, phytostabilization has its drawbacks. Since toxicants remain in place, plants and soil may require long-term care to prevent re-release and further leaching of pollutants. Plants may also require significant fertilization or other soil amendments. Constant monitoring is necessary to prevent excessive metal uptake by plants and their transfer to the aboveground parts. However, phytostabilization methods are less expensive and less destructive than other, more effective soil remediation methods. Furthermore, growing perennials promotes ecosystem restoration.

In the case of soil contamination with volatile substances, phytovolatization of pollutants can be applied. This is the process of absorption of pollutants by plants, transformation and their subsequent evaporation into the atmosphere through stems or leaves (direct phytovolatility) or from the soil as a result of the activity of plant roots (indirect phytovolatility). During this process, pollutants, such as mercury ions, can be converted into less toxic substances. Plants that are resistant to toxicants, have a high adsorption surface area, and are tolerant to hypoxia can be used in this strategy. In woody species, direct phytovolatization from tree trunks and branches occurs through the diffusion of volatile organic compounds (VOCs) through the secondary xylem, secondary phloem, and periderm, eventually reaching the atmosphere, where the VOC activity becomes lower than in the wood. In herbaceous plants, when VOCs are transported to aboveground tissues, these compounds can leave the stem and leaves through the epidermis via two parallel pathways: diffusion through open stomata and diffusion through the cuticle (Limmer & Burken, 2016).

Despite the difficulties of conducting experiments to determine the ability of plants to phytovolatility, there is reliable evidence that poplars (*Populus* sp.), willows (*Salix* sp.), and Russian olive (*Elaeagnus angustifolia*) are good at removing trichloroethylene from the soil (Doucette et al., 2003). In another experiment, hybrid poplars demonstrated the ability to absorb and effectively decompose not only trichloroethylene, but also other organic pollutants, including atrazine and 1,4-dioxane. The data obtained are particularly interesting for Ukraine because these plants are typical of the region. Research by Arnold et al. (2007) presented data on the uptake of methyl tert-butyl ether by pine trees (*Pinus* sp.) at a site contaminated with gasoline oxygenates and tert-butyl alcohol.

Phytovolatization has limitations and disadvantages. For example, the pollutant or hazardous metabolite may be released into the atmosphere or accumulate in plants and be transferred to industrial products such as fruit or wood.

When surface or groundwater is contaminated, rhizofiltration methods can be used for purification. It is carried out by absorbing pollutants in solution around the root zone. This can be a wide range of inorganic (heavy metals, cyanides, nitrates, phosphates, radionuclides) and organic (explosives) pollutants. Rhizofiltration can be implemented *in situ* to clean contaminated surface water. However, *ex situ* rhizofiltration is most commonly used, in which artificial wetlands or reservoirs are created, where marsh (*Carex* sp., *Phragmites* sp., *Acorus calamus*, etc.) and aquatic plants (*Lemna* sp., *Azolla* sp., *Myriophyllum* sp., *Elodea* sp., etc.) are grown, and contaminated water is supplied using a specially designed tank system (Biswal, 2025). Terrestrial plants with high biomass, such as *Brassica juncea*, *Helianthus annuus*, grown hydroponically, are also often used for rhizofiltration (Yang & Lee, 2008). Rhizofiltration technologies were successfully used to treat water bodies after the Chernobyl nuclear accident. Different plants have varying efficiencies in removing different pollutants. For example, corn and wheat, while suitable for rhizofiltration of polyacetates, may be unsuitable for removing other organic pollutants (Kristanti et al., 2021). Key challenges that can arise with rhizofiltration also include the need to maintain the solution's pH at a level that ensures optimal absorption of elements, as well as the need to consider the chemical properties of pollutants and their interactions. Furthermore, there is always a risk that previous positive results obtained in laboratory experiments will not translate consistently under field conditions.

Conclusions

Phytoremediation offers a wide range of technologies, the choice of which depends on many factors, the most important of which are the degree and scale of contamination, types of pollutants, and soil characteristics. Each technology has its advantages and disadvantages, which should be considered in each specific case. Unfortunately, many unknowns remain in the search for the most suitable and universal phytoremediation strategies. A combination of several methods can minimize the disadvantages of each and contribute to increased land restoration efficiency. For the restoration of agricultural soils in the post-war period, using phytoextraction and phytostabilization methods, combining remediation measures with simultaneous economic benefits appears most attractive. The challenge of expanding the range of forage grasses, energy plants, or essential oil plants capable of extracting or stabilizing pollutants on disturbed lands without contaminating the final raw materials offers a wide range of opportunities for scientific research. The search for effective soil amendments and the study of application rates to improve soil health and increase biomass yields are also promising areas of research interest.

References

Adhikari, T., & Kumar, A. (2012). Phytoaccumulation and tolerance of *Riccinus communis* L. to nickel. International Journal of Phytoremediation, 14(5), 481–492.

Alasmary, Z., Hettiarachchi, G. M., Roozeboom, K. L., Davis, L. C., Erickson, L. E., Pidlisnyuk, V., Stefanovska, T., & Trögl, J. (2021). Phytostabilization of a contaminated military site using *Miscanthus* and soil amendments. Journal of Environmental Quality, 50(5), 1220–1232.

Algreen, M., Trapp, S., & Rein, A. (2013). Phytoscreening and phytoextraction of heavy metals at Danish polluted sites using willow and poplar trees. Environmental Science and Pollution Research, 21(15), 8992–9001.

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

Ampiah-Bonney, R. J., Tyson, J. F., & Lanza, G. R. (2007). Phytoextraction of arsenic from soil by *Leersia oryzoides*. International Journal of Phytoremediation, 9(1), 31–40.

Angelova, V., Ivanova, R., & Ivanov, K. (2004). Heavy metal accumulation and distribution in oil crops. Communications in Soil Science and Plant Analysis, 35(17–18), 2551–2566.

Aparicio, J. D., Raimondo, E. E., Saez, J. M., Costa-Gutierrez, S. B., Álvarez, A., Benimeli, C. S., & Polti, M. A. (2022). The current approach to soil remediation: A review of physicochemical and biological technologies, and the potential of their strategic combination. Journal of Environmental Chemical Engineering, 10(2), 107141.

Arnold, C. W., Parfitt, D. G., & Kaltreider, M. (2007). Phytovolatilization of oxygenated gasoline-impacted groundwater at an underground storage tank site via conifers. International Journal of Phytoremediation, 9(1), 53–69.

Arthur, E. L., Rice, P. J., Rice, P. J., Anderson, T. A., Baladi, S. M., Henderson, K. L., & Coats, J. R. (2005). Phytoremediation – an overview. Critical Reviews in Plant Sciences, 24(2), 109–122.

Bahri, N. B., Laribi, B., Soufi, S., Rezgui, S., & Bettaieb, T. (2015). Growth performance, photosynthetic status and bioaccumulation of heavy metals by *Paulownia tomentosa* (Thunb.) Steud growing on contaminated soils. International Journal of Agronomy & Agricultural Research, 6, 32–43.

Banasova, V., Horak, O., Nadubinska, M., Ciamporova, M., & Lichtscheidl, I. (2008). Heavy metal content in *Thlaspi caerulescens* J. et C. Presl growing on metalliferous and non-metalliferous soils in Central Slovakia. International Journal of Environment and Pollution, 33(2–3), 133–145.

Bani, A., Echevarria, G., Sulçe, S., Morel, J. L., & Mullai, A. (2007). *In-situ* phytoextraction of Ni by a native population of *Alyssum murale* on an ultramafic site (Albania). Plant and Soil, 293, 79–89.

Bhargava, A., Carmona, F. F., Bhargava, M., & Srivastava, S. (2012). Approaches for enhanced phytoextraction of heavy metals. Journal of Environmental Management, 105, 103–120.

Bidar, G., Garçon, G., Pruvot, C., Dewaele, D., Cazier, F., Douay, F., & Shirali, P. (2007). Behavior of *Trifolium repens* and *Lolium perenne* growing in a heavy metal contaminated field: Plant metal concentration and phytotoxicity. Environmental Pollution, 147(3), 546–553.

Biswal, T. (2025). Rhizofiltration: A sustainable green technology for remediation of heavy metals from aquatic systems. In: Kuanar, A., Kar, D., Das, A. P., & Bhanja, D. (Eds.). Recent advances in bioremediation and phytoremediation. Springer Nature Switzerland, Cham. Pp. 1–21.

Brunetti, G., Farrag, K., Rovira, P. S., Nigro, F., & Senesi, N. (2011). Greenhouse and field studies on Cr, Cu, Pb and Zn phytoextraction by *Brassica napus* from contaminated soils in the Apulia Region, Southern Italy. Geoderma, 160(3–4), 517–523.

Cao, X., Wang, X., Tong, W., Gurajala, H. K., Lu, M., Hamid, Y., Feng Y., He, Z., & Yang, X. (2019). Distribution, availability and translocation of heavy metals in soil-oilseed rape (*Brassica napus* L.) system related to soil properties. Environmental Pollution, 252, 733–741.

Celin, S. M., Sahai, S., Kalsi, A., & Bhanot, P. (2020). Environmental monitoring approaches used during bioremediation of soils contaminated with hazardous explosive chemicals. Trends in Environmental Analytical Chemistry, 26, e00088.

Certini, G., Scalenghe, R., & Woods, W. I. (2013). The impact of warfare on the soil environment. Earth-Science Reviews, 127, 1–15.

Chaney, R. L., Angle, J. S., McIntosh, M. S., Reeves, R. D., Li, Y. M., Brewer, E. P., Chen, K. Y., Roseberg, R. J., Perner, H., Synkowski, E. C., Broadhurst, C. L., Wang, S., & Baker, A. J. (2005). Using hyperaccumulator plants to phytoextract soil Ni and Cd. Z Naturforsch C, 60(3–4), 190–198.

Chen, B. C., Lai, H. Y., & Juang, K. W. (2012). Model evaluation of plant metal content and biomass yield for the phytoextraction of heavy metals by switchgrass. Ecotoxicology and Environmental Safety, 80, 393–400.

Chirilă Băbău, A. M., Micle, V., Damian, G. E., & Sur, I. M. (2024). Lead and copper removal from sterile dumps by phytoremediation with *Robinia pseudoacacia*. Scientific Reports, 14(1), 9842.

Cojocaru, P., Gusiatin, Z. M., & Cretescu, I. (2016). Phytoextraction of Cd and Zn as single or mixed pollutants from soil by rape (*Brassica napus*). Environmental Science and Pollution Research, 23, 10693–10701.

Dang, P., & Li, C. (2022). A mini-review of phytomining. International Journal of Environmental Science and Technology, 19, 12825–12838.

Dary, M., Chamber-Pérez, M. A., Palomares, A. J., & Pajuelo, E. (2010). "*In situ*" phytostabilisation of heavy metal polluted soils using *Lupinus luteus* inoculated with metal resistant plant-growth promoting rhizobacteria. Journal of Hazardous Materials, 177(1–3), 323–330.

DeGroote, K. V., McCartha, G. L., & Pollard, A. J. (2018). Interactions of the manganese hyperaccumulator *Phytolacca americana* L. with soil pH and phosphate. Ecological Research, 33, 749–755.

Dhillon, K. S., & Dhillon, S. K. (2009). Selenium concentrations of common weeds and agricultural crops grown in the seleniferous soils of Northwestern India. Science of the Total Environment, 407(24), 6150–6156.

Dhiman, S. S., Zhao, X., Li, J., Kim, D., Kalia, V. C., Kim, I. W., Kim, J. Y., & Lee, J. K. (2017). Metal accumulation by sunflower (*Helianthus annuus* L.) and the efficacy of its biomass in enzymatic saccharification. PloS One, 12(4), e0175845.

Dickinson, N. M., & Pulford, I. D. (2005). Cadmium phytoextraction using short-rotation coppice *Salix*: The evidence trail. Environment International, 31(4), 609–613.

do Nascimento, C. W. A., Amarasiriwardena, D., & Xing, B. S. (2006). Comparison of natural organic acids and synthetic chelates at enhancing phytoextraction of metals from a multi-metal contaminated soil. Environmental Pollution, 140, 114–123.

Doucette, W. J., Bugbee, B. G., Smith, S. C., Pajak, C. J., & Ginn, J. S. (2003). Uptake, metabolism, and phytovolatilization of trichloroethylene by indigenous vegetation: Impact of precipitation. In: McCutcheon, S. C., & Schnoor, J. L. (Eds.). Phytoremediation: Transformation and Control of Contaminants. John Wiley & Sons, Inc. Pp. 561–588.

Dražić, G., Milovanović, J., Stefanović, S., & Petrić, I. (2017). Potential of *Miscanthus × giganteus* for heavy metals removing from industrial deposol. Acta Regionalia et Environmentalica, 14(2), 56–58.

Durães, N., Novo, L. A., Candeias, C., & Da Silva, E. F. (2018). Distribution, transport and fate of pollutants. In: Duarte, A. C., Cachada, A., & Rocha-Santos, T. (Eds.). Soil pollution. Academic Press. Pp. 29–57.

Egendorf, S. P., Groffman, P., Moore, G., & Cheng, Z. (2020). The limits of lead (Pb) phytoextraction and possibilities of phytostabilization in contaminated soil: A critical review. International Journal of Phytoremediation, 22(9), 916–930.

Fayiga, A. O. (2018). Remediation of inorganic and organic contaminants in military ranges. Environmental Chemistry, 16(2), 81–91.

Fernández-López, C., Temple, T., Persico, F., Coulon, F., & Ortega-Calvo, J. J. (2024). Remediation of soils polluted by military activities. In: Ortega-Calvo, J. J., & Coulon, F. (Eds.). Soil remediation science and technology. Springer Nature Switzerland, Cham. Pp. 161–190.

Frérot, H., Lefèbvre, C., Gruber, W., Collin, C., Santos, A. D., & Escarré, J. (2006). Specific interactions between local metallicolous plants improve the phytostabilization of mine soils. Plant and Soil, 282, 53–65.

Gao, C. H., & Fu, R. B. (2023). The removal of heavy metals by low molecular organic acids (LMWOAs) from contaminated soils and key influencing factors: A literature review. Polish Journal of Environmental Studies, 32(1), 491–507.

Gasco, G., Alvarez, M. L., Paz-Ferreiro, J., & Mendez, A. (2019). Combining phytoextraction by *Brassica napus* and biochar amendment for the remediation of a mining soil in Riotinto (Spain). Chemosphere, 231, 562–570.

Glibovytska, N. I., Karavanovych, K. B., & Kachala, T. B. (2019). Prospects of phytoremediation and phytoindication of oil-contaminated soils with the help of energy plants. Journal of Ecological Engineering, 20(7), 147–154.

Gomes, L., Cumbane, B., Costa, J., Pires, J., Rodrigues, C., Santos, F., ... & Fernando, A. L. (2019). Phytoremediation potential of the perennial crops giant reed and switchgrass to soils contaminated with heavy metals. In: Proceedings of the 27th European Biomass Conference and Exhibition. EUBCE. Pp. 175–177.

Goswami, M., Chakraborty, P., Mukherjee, K., Mitra, G., Bhattacharyya, P., Dey, S., & Tribedi, P. (2018). Bioaugmentation and biostimulation: A potential strategy for environmental remediation. Journal of Microbiology and Experimentation, 6(5), 223–231.

Grispen, V. M., Nelissen, H. J., & Verkleij, J. A. (2006). Phytoextraction with *Brassica napus* L.: A tool for sustainable management of heavy metal contaminated soils. Environmental Pollution, 144(1), 77–83.

Habiba, U., Ali, S., Farid, M., Shakoor, M. B., Rizwan, M., Ibrahim, M., Abbasi, G. H., Hayat, T., & Ali, B. (2014). EDTA enhanced plant growth, antioxidant defense system, and phytoextraction of copper by *Brassica napus* L. Environmental Science and Pollution Research, 22(2), 1534–1544.

Holoubek, I., Dušek, L., Sáňka, M., Hofman, J., Čupr, P., Jarkovský, J., Zbíral, J., & Klánová, J. (2009). Soil burdens of persistent organic pollutants – their levels, fate and risk. Part I. Variation of concentration ranges according to different soil uses and locations. Environmental Pollution, 157(12), 3207–3217.

Hrkić Ilić, Z., Pajević, S., Borišev, M., & Luković, J. (2020). Assessment of phytostabilization potential of two *Salix* L. clones based on the effects of heavy metals on the root anatomical traits. Environmental Science and Pollution Research, 27, 29361–29383.

Jr., R. S. Z., Zhu, J. Y., Headlee, W. L., Gleisner, R., Pilipović, A., Acker, J. V., Bauer, E. O., Birr, B. A., & Wiese, A. H. (2020). Ecosystem services, physiology, and biofuels recalcitrance of poplars grown for landfill phytoremediation. Plants, 9(10), 1357.

Kazlauskaitė-Jadzevičė, A., Volungevičius, J., Gregorauskienė, V., & Marcinkonis, S. (2014). The role of pH in heavy metal contamination of urban soil. Journal of Environmental Engineering and Landscape Management, 22(4), 311–318.

Kharytonov, M., Martynova, N., Babenko, M., Klimkina, I., Rula, I., Wiche, O., & Heilmeier, H. (2023). The energy and trace elements bioaccumulation with the biomass of *Miscanthus* grown on different kinds of technosols. In: Veress, B., & Szigety, J. J. (Eds.). Horizons in earth science research. Nova Science Publishers, Inc., New York. Volume 24. Chapter 3. Pp. 89–117.

Kharytonov, M., Martynova, N., Babenko, M., Lemishko, S., Samarska, A., & Gispert, M. (2025). The effect of biodigestate and sewage sludge on the switchgrass growth, biomass elemental composition and thermal characteristics. International Journal of Environmental Studies, in press.

Kicińska, A., Pomykała, R., & Izquierdo-Diaz, M. (2022). Changes in soil pH and mobility of heavy metals in contaminated soils. European Journal of Soil Science, 73(1), e13203.

Kim, M. S., Min, H. G., Lee, S. H., & Kim, J. G. (2018). A comparative study on poaceae and leguminosae forage crops for aided phytostabilization in trace-element-contaminated soil. Agronomy, 8(7), 105.

Kocoń, A., & Jurga, B. (2017). The evaluation of growth and phytoextraction potential of *Miscanthus x giganteus* and *Sida hermaphrodita* on soil contaminated simultaneously with Cd, Cu, Ni, Pb, and Zn. Environmental Science and Pollution Research, 24, 4990–5000.

Korzeniowska, J., & Stanislawska-Glubiak, E. (2015). Phytoremediation potential of *Miscanthus× giganteus* and *Spartina pectinata* in soil contaminated with heavy metals. Environmental Science and Pollution Research, 22(15), 11648–11657.

Korzeniowska, J., Stanislawska-Glubiak, E., & Igras, J. (2011). Applicability of energy crops for metal phytostabilization of soils moderately contaminated with copper, nickel and zinc. Journal of Food, Agriculture and Environment, 9(3–4), 693–697.

Kos, B., Greman, H., & Lestan, D. (2003). Phytoextraction of lead, zinc and cadmium from soil by selected plants. Plant Soil and Environment, 49(12), 548–553.

Kötschau, A., Büchel, G., Einax, J. W., von Tümpling, W., & Merten, D. (2014). Sunflower (*Helianthus annuus*): Phytoextraction capacity for heavy metals on a mining-influenced area in Thuringia, Germany. Environmental Earth Sciences, 72, 2023–2031.

Koul, B., & Taak, P. (2018). *Ex situ* soil remediation strategies. In: Koul, B., & Taak, P. (Eds.). Biotechnological strategies for effective remediation of polluted soils. Springer, Singapore. Pp. 39–57.

Kristanti, R. A., Ngu, W. J., Yuniarto, A., & Hadibarata, T. (2021). Rhizofiltration for removal of inorganic and organic pollutants in groundwater: A review. Biointerface Research in Applied Chemistry, 11, 12326–12347.

Lebrun, M., Michel, C., Joulian, C., Morabito, D., & Bourgerie, S. (2021). Rehabilitation of mine soils by phytostabilization: Does soil inoculation with microbial consortia stimulate *Agrostis* growth and metal (loid) immobilization? Science of the Total Environment, 791, 148400.

Li, G., Lu, N., Wei, Y., & Zhu, D. (2018). Relationship between heavy metal content in polluted soil and soil organic matter and pH in mining areas. In: IOP Conference Series: Materials Science and Engineering, 394, 052081.

Li, S., He, L., Zhang, B., Yan, Y., Jiao, W., & Ding, N. (2022). A comprehensive evaluation method for soil remediation technology selection: Case study of ex situ thermal desorption. International Journal of Environmental Research and Public Health, 19(6), 3304.

Li, Y. M., Chaney, R. L., Brewer, E. P., Angle, J. S., & Nelkin, J. (2003). Phytoextraction of nickel and cobalt by hyperaccumulator *Alyssum* species grown on nickel-contaminated soils. Environmental Science and Technology, 37(7), 1463–1468.

Limmer, M., & Burken, J. (2016). Phytovolatilization of organic contaminants. Environmental Science and Technology, 50(13), 6632–6643.

Liu, J., Duan, C., Zhang, X., Zhu, Y., & Lu, X. (2011). Potential of *Leersia hexandra* Swartz for phytoextraction of Cr from soil. Journal of Hazardous Materials, 188(1–3), 85–91.

Luo, Y., Wu, Y., Qiu, J., Wang, H., & Yang, L. (2019). Suitability of four woody plant species for the phytostabilization of a zinc smelting slag site after 5 years of assisted revegetation. Journal of Soils and Sediments, 19, 702–715.

Ma, H., Zhao, Y., Yang, K., Wang, Y., Zhang, C., & Ji, M. (2022). Application oriented bioaugmentation processes: Mechanism, performance improvement and scale-up. Bioresource Technology, 344, 126192.

McGrath, S. P., Zhao, J., & Lombi, E. (2002). Phytoremediation of metals, metalloids, and radionuclides. Advances in Agronomy, 75, 1–56.

Min, Y., Meizhen, T., & Aoyama, I. (2007). Accumulation and uptake of manganese in a hyperaccumulator *Phytolacca americana*. Minerals Engineering, 20(2), 188–190.

Naz, M., Dai, Z., Hussain, S., Tariq, M., Danish, S., Khan, I. U., Qi, S., & Du, D. (2022). The soil pH and heavy metals revealed their impact on soil microbial community. Journal of Environmental Management, 321, 115770.

Nsanganwimana, F., Al Souki, K. S., Waterlot, C., Douay, F., Pelfrêne, A., Ridošková, A., Louvel, B., & Pourrut, B. (2021). Potentials of *Miscanthus x giganteus* for phytostabilization of trace element-contaminated soils: *Ex situ* experiment. Ecotoxicology and Environmental Safety, 214, 112125.

Nsanganwimana, F., Pourrut, B., Waterlot, C., Louvel, B., Bidar, G., Labidi, S., Fontaine, J., Muchembled, J., Lounes-Hadj Sahraoui, A., Fourrier, H., & Douay, F. (2015). Metal accumulation and shoot yield of *Miscanthus× giganteus* growing in contaminated agricultural soils: Insights into agronomic practices. Agriculture, Ecosystems and Environment, 213, 61–71.

Nurzhanova, A., Pidlisnyuk, V., Abit, K., Nurzhanov, C., Kenessov, B., Stefanovska, T., & Erickson, L. (2019). Comparative assessment of using *Miscanthus× giganteus* for remediation of soils contaminated by heavy metals: A case of military and mining sites. Environmental Science and Pollution Research, 26, 13320–13333.

Oleńska, E., Małek, W., Sujkowska-Rybkowska, M., Szopa, S., Włostowski, T., Aleksandrowicz, O., Swiecicka, I., Wojcik, M., Thijs, S., & Vangronsveld, J. (2022). An alliance of *Trifolium repens-Rhizobium leguminosarum* bv. *trifolii*-mycorrhizal fungi from an old Zn-Pb-Cd rich waste heap as a promising tripartite system for phytostabilization of metal polluted soils. Frontiers in Microbiology, 13, 853407.

Pandey, J., Verma, R. K., & Singh, S. (2019). Suitability of aromatic plants for phytoremediation of heavy metal contaminated areas: A review. International Journal of Phytoremediation, 21(5), 405–418.

Park, J., Kim, J. Y., & Kim, K. W. (2012). Phytoremediation of soil contaminated with heavy metals using *Brassica napus*. Geosystem Engineering, 15(1), 10–18.

Pavel, P. B., Puschenreiter, M., Wenzel, W. W., Diacu, E., & Barbu, C. H. (2014). Aided phytostabilization using *Miscanthus sinensis× giganteus* on heavy metal-contaminated soils. Science of the Total Environment, 479, 125–131.

Perlein, A., Bert, V., Desannaux, O., Fernandes de Souza, M., Papin, A., Gaucher, R., Zdanevitch, I., & Meers, E. (2021). The use of sorghum in a phytoattenuation strategy: A field experiment on a TE-contaminated site. Applied Sciences, 11(8), 3471.

Pietrzykowski, M., Woś, B., Chodak, M., Sroka, K., & Pająk, M. (2022). Use of alders for the phytostabilization of a combustion waste disposal site. Eurasian Soil Science, 55(5), 686–693.

Pirog, T. P., Paliychuk, O. I., Iutinska, G. O., & Shevchuk, T. A. (2018). Prospects for the use of microbial surfactants in crop production. Microbiological Journal, 80(3), 115–135 (in Ukrainian).

Pogrzeba, M., Krzyżak, J., Rusinowski, S., Hebner, A., Kopielski, K., Werle, S., & Ratman-Kłosińska, I. (2018). Possibility of using energy crops for phytoremediation of heavy metals contaminated land – a three-year experience. In: Mudryk, K., & Werle, S. (Eds.). Renewable energy sources: Engineering, technology, innovation. ICORES 2017. Springer International Publishing. Pp. 33–45.

Rabbani, M., Rabbani, M. T., Muthoni, F., Sun, Y., & Vahidi, E. (2024). Advancing phytomining: Harnessing plant potential for sustainable rare earth element extraction. Bioresource Technology, 401, 130751.

Radziemska, M., Bęś, A., Gusiatin, Z. M., Cerdà, A., Mazur, Z., Jeznach, J., Kowal, P., & Brtnický, M. (2019). The combined effect of phytostabilization and different amendments on remediation of soils from post-military areas. Science of the Total Environment, 688, 37–45.

Radziemska, M., Vaverková, M. D., & Baryła, A. (2017). Phytostabilization – management strategy for stabilizing trace elements in contaminated soils. International Journal of Environmental Research and Public Health, 14(9), 958.

Razanov, S., Alieksieiev, O., Snitynskyi, V., Alieksieieva, O., Razanova, A., Postoienko, V., Kerek, S., Lopotych, N., Dydiv, O., & Dydiv, I. (2025). Peculiarities of lead, cadmium, zinc and copper accumulation in *Miscanthus× giganteus* grown on different soil types in Ukraine. Journal of Ecological Engineering, 26(8), 143–152.

Robinson, B. H., Anderson, C. W. N., & Dickinson, N. M. (2015). Phytoextraction: Where's the action? Journal of Geochemical Exploration, 151, 34–40.

Romantschuk, L., Matviichuk, N. H., Mozharivska, I., Matviichuk, B. V., Ustymenko, V., & Tryboi, O. (2024). Phytoremediation of soils by cultivation *Miscanthus x giganteus* L. and *Phalaris arundinacea* L. Ecological Engineering and Environmental Technology, 6(25), 173–147.

Sabir, M., Hanafi, M. M., Zia-Ur-Rehman, M., Saifullah, Ahmad, H. R., Hakeem, K. R., & Aziz, T. (2014). Comparison of low-molecular-weight organic acids and ethylenediaminetetraacetic acid to enhance phytoextraction of heavy metals by maize. Communications in Soil Science and Plant Analysis, 45(1), 42–52.

Salam, M. M. A., Mohsin, M., Kaipiainen, E., Villa, A., Kuittinen, S., Pulkkinen, P., Pelkonen, P., & Pappinen, A. (2019). Biomass growth variation and phytoextraction potential of four *Salix varieties* grown in contaminated soil amended with lime and wood ash. International Journal of Phytoremediation, 21(13), 1329–1340.

Saleem, M. H., Kamran, M., Zhou, Y., Parveen, A., Rehman, M., Ahmar, S., Malik, Z., Mustafa, A., Ahmad Anjum, R. M., Wang, B., & Liu, L. (2020). Appraising growth, oxidative stress and copper phytoextraction potential of flax (*Linum usitatissimum* L.) grown in soil differentially spiked with copper. Journal of Environmental Management, 257, 109994.

Sales da Silva, I. G., Gomes de Almeida, F. C., Padilha da Rocha e Silva, N. M., Casazza, A. A., Converti, A., & Asfora Sarubbo, L. (2020). Soil bioremediation: Overview of technologies and trends. Energies, 13(18), 4664.

Sánchez-Castro, I., Molina, L., Prieto-Fernández, M.-Á., & Segura, A. (2023). Past, present and future trends in the remediation of heavy-metal contaminated soil – Remediation techniques applied in real soil-contamination events. Heliyon, 9(6), e16692.

Santibáñez, C., Verdugo, C., & Ginocchio, R. (2008). Phytostabilization of copper mine tailings with biosolids: Implications for metal uptake and productivity of *Lolium perenne*. Science of the Total Environment, 395(1), 1–10.

Saraswat, S., & Rai, J. P. N. (2009). Phytoextraction potential of six plant species grown in multimetal contaminated soil. Chemistry and Ecology, 25(1), 1–11.

Sasmaz, A., & Sasmaz, M. (2009). The phytoremediation potential for strontium of indigenous plants growing in a mining area. Environmental and Experimental Botany, 67(1), 139–144.

Sas-Nowosielska, A., Kucharski, R., Małkowski, E., Pogrzeba, M., Kuperberg, J. M., & Kryński, K. (2004). Phytoextraction crop disposal – an unsolved problem. Environmental Pollution, 128(3), 373–379.

Schwartz, C., Gérard, E., Perronnet, K., & Morel, J. L. (2001). Measurement of in situ phytoextraction of zinc by spontaneous metallophytes growing on a former smelter site. Science of the Total Environment, 279(1–3), 215–221.

Shackira, A. M., & Puthur, J. T. (2019). Phytostabilization of heavy metals: Understanding of principles and practices. In: Srivastava, S., Srivastava, A. K., & Suprasanna, P. (Eds.). Plant-metal interactions. Springer, Cham. Pp. 263–282.

Shen, X., Dai, M., Yang, J., Sun, L., Tan, X., Peng, C., Ali, I., & Naz, I. (2022). A critical review on the phytoremediation of heavy metals from environment: Performance and challenges. Chemosphere, 291, 132979.

Shuliak, S. V., Chechet, O. M., Haidei, O. S., Dobrozhan, Y. V., Kobysh, A. I., Bardyk, I. Y., Krushelnytska, O. V., & Gutyj, B. V. (2022). Monitoring of the content of heavy metals in sunflower seeds and its processing products in Ukraine for 2018–2021. Scientific Messenger of LNU of Veterinary Medicine and Biotechnologies, Series: Veterinary Sciences, 24(107), 17–22.

Sinegani, A. S., & Khalilikhah, F. (2008). Phytoextraction of lead by *Helianthus annuus*: Effect of mobilising agent application time. Plant, Soil and Environment, 54(10), 434–440.

Song, P., Xu, D., Yue, J., Ma, Y., Dong, S., & Feng, J. (2022). Recent advances in soil remediation technology for heavy metal contaminated sites: A critical review. Science of the Total Environment, 838, 156417.

Soudek, P., Petrová, Š., & Vaněk, T. (2012). Phytostabilization or accumulation of heavy metals by using of energy crop *Sorghum* sp. In: 3rd International conference on biology, environment and chemistry IPCBEE. IACSIT Press, Singapore.

Souza, L. A., Piotto, F. A., Nogueirol, R. C., & Azevedo, R. A. (2013). Use of non-hyperaccumulator plant species for the phytoextraction of heavy metals using chelating agents. Scientia Agricola, 70, 290–295.

Sozoniuk, M., Nowak, M., Dudziak, K., Leśniowska-Nowak, J., & Kowalczyk, K. (2020). *Quercus robur* as a potential Cd phytostabilizator. Russian Journal of Plant Physiology, 67, 294–302.

Stadler, T., Temesi, Á., & Lakner, Z. (2022). Soil chemical pollution and military actions: A bibliometric analysis. Sustainability, 14(12), 7138.

Stojanov, N., Maletić, S., Beljin, J., Đukanović, N., Kiprovski, B., & Zeremski, T. (2024). Enhancing phytoextraction potential of *Brassica napus* for contaminated dredged sediment using nitrogen fertilizers and organic acids. Plants, 13(6), 818.

Surriya, O., Sarah Saleem, S., Waqar, K., & Gul Kazi, A. (2015). Phytoremediation of soils. In: Hakeem, K. R., Sabir, M., ... & Mermut, A. R. (Eds.). Soil remediation and plants. Academic Press. Pp. 1–36.

Šyc, M., Pohořelý, M., Kameníková, P., Habart, J., Svoboda, K., & Punčochář, M. (2012). Willow trees from heavy metals phytoextraction as energy crops. Biomass and Bioenergy, 37, 106–113.

Sytar, O., Ghosh, S., Malinska, H., Zivcak, M., & Brestic, M. (2021). Physiological and molecular mechanisms of metal accumulation in hyperaccumulator plants. Physiologia Plantarum, 173(1), 148–166.

Tkachuk, O., Gucol, G., Mazur, O., Verhelis, V., & Titarenko, O. (2024). Ecological safety of sunflower seeds in the conditions of agricultural intensification. Scientific Horizons, 27(1), 71–79.

Tykhenko, O., Martyn, A., Tykhenko, R., & Openko, I. (2025). Cadastral accounting of land polluted as a result of military operations in Ukraine. Papers of International Scientific Conference Engineering for Rural Development, Jelgava, 21–23.05.2025. Pp. 257–261.

Tzvetkova, N., Miladinova, K., Ivanova, K., Georgieva, T., Geneva, M., & Markovska, Y. (2015). Possibility for using of two *Paulownia* lines as a tool for remediation of heavy metal contaminated soil. Journal of Environmental Biology, 36(1), 145.

Ueno, D., Iwashita, T., Zhao, F. J., & Ma, J. F. (2008). Characterization of Cd translocation and identification of the Cd form in xylem sap of the Cd-hyperaccumulator *Arabidopsis halleri*. Plant and Cell Physiology, 49(4), 540–548.

van der Ent, A., Baker, A. J. M., Reeves, R. D., Pollard, A. J., Schat, H. (2013). Hyperaccumulators of metal and metalloid trace elements: Facts and fiction. Plant and Soil, 362, 319–334.

Van Ginneken, L., Meers, E., Guisson, R., Ruttens, A., Elst, K., Tack, F. M., Vangronsveld, J., Diels, L., & Dejonghe, W. (2007). Phytoremediation for heavy metal contaminated soils combined with bioenergy production. Journal of Environmental Engineering and Landscape Management, 15(4), 227–236.

Van Nevel, L., Mertens, J., Oorts, K., & Verheyen, K. (2007). Phytoextraction of metals from soils: how far from practice? Environmental Pollution, 150(1), 34–40.

Van Nevel, L., Mertens, J., Staelens, J., De Schrijver, A., Tack, F. M., De Neve, S., Meers, E., & Verheyen, K. (2011). Elevated Cd and Zn uptake by aspen limits the phytostabilization potential compared to five other tree species. Ecological Engineering, 37(7), 1072–1080.

Vázquez, S., Agha, R., Granado, A., Sarro, M. J., Esteban, E., Peñalosa, J. M., & Carpena, R. O. (2006). Use of white lupin plant for phytostabilization of Cd and As polluted acid soil. Water, Air, and Soil Pollution, 177, 349–365.

Venegas-Rioseco, J., Ginocchio, R., & Ortiz-Calderón, C. (2021). Increase in phytoextraction potential by genome editing and transformation: A review. Plants, 11(1), 86.

Visconti, D., Álvarez-Robles, M. J., Fiorentino, N., Fagnano, M., & Clemente, R. (2020). Use of *Brassica juncea* and *Dactylis glomerata* for the phytostabilization of mine soils amended with compost or biochar. Chemosphere, 260, 127661.

Wang, C. Y., Zhou, X., Guo, D., Zhao, J. H., Yan, L., Feng, G. Z., Gao Q., Yu, H., & Zhao, L. P. (2019). Soil pH is the primary factor driving the distribution and function of microorganisms in farmland soils in Northeastern China. Annals of Microbiology, 69(13), 1461–1473.

Wang, X., Chen, C., & Wang, J. (2017). Cadmium phytoextraction from loam soil in tropical Southern China by *Sorghum bicolor*. International Journal of Phytoremediation, 19(6), 572–578.

Wieshammer, G., Unterbrunner, R., García, T. B., Zivkovic, M. F., Puschenreiter, M., & Wenzel, W. W. (2007). Phytoextraction of Cd and Zn from agricultural soils by *Salix* ssp. and intercropping of *Salix caprea* and *Arabidopsis halleri*. Plant and Soil, 298(1–2), 255–264.

Willey, N., & Collins, C. (2007). Phytoremediation of soils contaminated with radionuclides. Radioactivity in the Environment, 10, 43–69.

Yan, L., Van Le, Q., Sonne, C., Yang, Y., Yang, H., Gu, H., Ma, N. L., Lam, S. S., & Peng, W. (2021). Phytoremediation of radionuclides in soil, sediments and water. Journal of Hazardous Materials, 407, 124771.

Yang, M. J., & Lee, M. H. (2008). Rhizofiltration process with *Helianthus annuss* L., *Phaseolus vulgaris* var., and *Brassica juncea* (L.) Czern. to remediate uranium contaminated groundwater. Journal of Soil and Groundwater Environment, 13(4), 30–39.

Yang, X., Feng, Y., He, Z., & Stoffella, P. J. (2005). Molecular mechanisms of heavy metal hyperaccumulation and phytoremediation. Journal of Trace Elements in Medicine and Biology, 18(4), 339–353.

Yang-Guang, G., Qin, L., & Yan-Peng, G. (2016). Metals in exposed-lawn soils from 18 urban parks and its human health implications in Southern China’s largest city, Guangzhou. Journal of Cleaner Production, 115, 122–129.

Yu, G., Liu, J., Long, Y., Chen, Z., Sunahara, G. I., Jiang, P., You, S., Lin, H., & Xiao, H. (2020). Phytoextraction of cadmium-contaminated soils: Comparison of plant species and low molecular weight organic acids. International Journal of Phytoremediation, 22(4), 383–391.

Zaier, H., Ghnaya, T., Rejeb, K. B., Lakhdar, A., Rejeb, S., & Jemal, F. (2010). Effects of EDTA on phytoextraction of heavy metals (Zn, Mn and Pb) from sludge-amended soil with *Brassica napus*. Bioresource Technology, 101(11), 3978–3983.

Zgorelec, Z., Bilandzija, N., Knez, K., Galic, M., & Zuzul, S. (2020). Cadmium and mercury phytostabilization from soil using *Miscanthus*× *giganteus*. Scientific Reports, 10(1), 6685.

Zhang, J., Xie, S., Wei, Y., & Liang, Y. (2023). Physiological responses and uptake of heavy metals by *Miscanthus sacchariflorus* (Maxim.) Benth., an energy plant species, under multiple heavy metals stress. Archives of Agronomy and Soil Science, 69(2), 259–274.

Zhang, J., Yang, J., Wang, R., Hou, H., Du, X., Fan, S., Liu, J., & Dai, J. (2013). Effects of pollution sources and soil properties on distribution of polycyclic aromatic hydrocarbons and risk assessment. Science of the Total Environment, 463–464, 1–10.

Zhao, F. J., Jiang, R. F., Dunham, S. J., & McGrath, S. P. (2006). Cadmium uptake, translocation and tolerance in the hyperaccumulator *Arabidopsis halleri*. New Phytologist, 172(4), 646–654.

Zheljazkov, V. D., Craker, L. E., & Xing, B. (2006). Effects of Cd, Pb, and Cu on growth and essential oil contents in dill, peppermint, and basil. Environmental and Experimental Botany, 58(1–3), 9–16.

Zheljazkov, V. D., Jeliazkova, E. A., Kovacheva, N., & Dzhurmanski, A. (2008). Metal uptake by medicinal plant species grown in soils contaminated by a smelter. Environmental and Experimental Botany, 64(3), 207–216.