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«IGOR SIKORSKY KYIV POLYTECHNIC INSTITUTE»
Educational and scientific Institute of energy saving and energy management
Department of Geoengineering

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________ Natalya ZUIEVSKA
«22nd» of December 2025

Master`s thesis for the degree of Master

Professional educational programme *«Ecologically efficient post-war restoration of polluted territories»*

Specialty *183 Environmental protection technology*

Topic *«Improvement of technologies for the restoration of soils affected by military activities»*

A student of group ГТ-41мп — Yelyzaveta FEDCHENKO ________

Supervisor — Tetiana HREBENIUK, Candidate of Technical Sciences, Docent ________

Reviewer — Olha FEDCHENKO, Expert in environmental activities, research and experimental development in the field of natural and technical sciences, Director of LLC «ECO LIGHTNESS» ________

I certify that this Master's thesis does not contain any material borrowed from the works of other authors without appropriate acknowledgment
Student ____________

Kyiv – 2025

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Educational and scientific Institute of energy saving and energy management
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Level of higher education – *the second (master's) according to the educational and professional programme)*

Specialty (specialization) - *183 Environmental protection technology*

APPROVE
Head of Department
________ Natalia ZUIEVSKA
«___»____________ 2025.

TASK
for a Master`s thesis

Student *Yelyzaveta FEDCHENKO*

1. Topic «*Improvement of technologies for the restoration of soils affected by military activities*»

Supervisor *Tetiana HREBENIUK, Candidate of Technical Sciences, Docent*

Approved by the university order dated 03.11. 2025 № 4749-c

2. The submission date is 09.12.2025
3. Research object is the process of phytoremediation on soil contaminated by military activities to remove pollutants from it
4. Research subject is the empirical study of the effectiveness of phytoremediation with the aim of achieving established MPC levels for heavy metals in soil
5. List of tasks to be developed :

1. Conduct physical and chemical studies of soil samples taken from the crater before and after the detonation of the explosive device.
2. Conduct a literature review of phytoremediation technology and select phytoremediation plants for the current case.
3. Test the sample taken after the detonation of the explosive device for phytotoxicity, make the calculations and analyse the results of the acute toxicity test.
5. Calculate the parameters necessary to assess the effectiveness of the phytoremediation and predict the time required to achieve the MPC levels approved by current regulatory documents.

6. List of publications:

1. T. Hrebeniuk, N.Remez, Y. Fedchenko. Application of monitoring to substantiate the biological method of soil restoration due to military operations. Energy, economy, technology, ecology. Scientific journal № 4(82), c. 157-165, 2025.
2. Hrebeniuk T. V., Fedchenko Y. P., Remez N. S., Bronitsky V. O. Monitoring and ecotoxicological assessment of the risks of soil degradation affected by military actions. Ecological Sciences. – 2026. – No. 4(62). – Publishing House «Helvetica».

8. Consultants for sections of the dissertation *

Section	Surname, initials and position	Signature, date	
		task published	task accepted

9. Issue date of task 01.09.2025.

Calendar plan

№	The name of the stages of the master`s degree thesis	Deadline for completion of project stages	Note
1	Conducting physical and chemical studies of selected samples	04.08-08.08	Done
2	Literature review of phytoremediation technology for soil safety restoration	30.07-11.08	Done
3	Conducting phytoremediation of contaminated soil	12.08-20.10	Done
4	Testing contaminated soil samples for phytotoxicity	09.10-27.10	Done
5	Evaluating the effectiveness of phytoremediation and performing the relevant calculations	10.11-16.11	Done
6	Analysing the results of acute toxicity testing of samples.	10.11-21.11	Done
7	Developing a start-up project	17.11-25.11	Done
8	Preparing an explanatory note	26.11-01.12	Done

Student ____________ Yelyzaveta FEDCHENKO
(signature)

Scientific supervisor _____________ Tetiana HREBENIUK
(signature)

ABSTRACT

The master's thesis consists of 119 pages, 44 illustrations, 19 tables and 53 sources in the list of references.

Relevance of the work. The problem of soil contamination with components contained in various military instruments, including heavy metals, requires a rapid response, as the threat of contamination of agricultural products and groundwater poses a danger to human health and ecosystems. A distinctive feature of the proposed method of soil remediation using phytoremediation is the low cost and accessibility of this technology, which in turn has proven effectiveness and is environmentally friendly

The study is based on the analysis of contaminated soil collected from an explosion crater after the detonation of an explosive device and its restoration through phytoremediation.

The aim of study is to apply phytoremediation technology for the remediation of soil affected by military operations and to determine its effectiveness.

The object of study is the process of restoring soil contaminated by military operations.

The subject of study is the phytoremediation of contaminated soil and the determination of its toxicity.

Approval of results. Based on the results of the research, two articles were published in the scientific journals «Energy, Economy, Technology, Ecology» and «Ecological Sciences».

Research objectives

1. Conduct appropriate analyses and tests to determine the physical, chemical, and toxic characteristics of the soil sample.
2. Investigate existing cases of soil phytoremediation and review scientific research on this topic.
3. Based on the results obtained and literature data, select the optimal phytoremediation plant and carry out soil remediation.

4. Calculate the parameters necessary to assess the effectiveness of the phytoremediation process and calculate the time required to achieve metal concentrations in the soil at maximum permissible concentration (MPC) levels..

Practical significance. Based on this study, new opportunities are opening up in the field of post-war restoration of territories, as well as new challenges for scientific research aimed at improving and optimising this technology.

Keywords: impact of military operations, environmental safety, soil contamination, public safety, agricultural product safety, land reclamation, post-war restoration, biological cleaning methods, phytoremediation.

ANNOTASJON

Masteroppgaven består av 119 sider, 44 illustrasjoner, 19 tabeller og 53 kilder i referanselisten.

Aktualitet. Problemet med forurensning av jord med komponenter som finnes i ulike militære innretninger, blant annet tungmetaller, krever rask respons, ettersom trusselen mot forurensning av landbruksprodukter og grunnvann utgjør en fare for befolkningens helse og økosystemer. En særegenhet ved den foreslåtte metoden for jordrestaurering ved hjelp av fytoremediering er at teknologien er billig, tilgjengelig for ulike samfunnslag, og samtidig dokumentert effektiv og miljøvennlig.

Studien er basert på analyse av forurenset jord hentet fra et eksplosjonskrater etter detonasjon av en eksplosiv gjenstand, samt gjennomføring av jordrestaureringen ved hjelp av fytoremediering.

Formålet med forskningen – å anvende fytoremedieringsteknologi for rekultivering av jord som er skadet av militære handlinger, og å fastslå dens effektivitet.

Forskningsobjektet – prosessen med jordforurensning forårsaket av militære handlinge.

Forskningens emne – gjennomføring av fytoremediering av forurenset jord og vurdering av dens toksisitet.

Godkjenning av resultater. Basert på resultatene ble to artikler publisert i de vitenskapelige tidsskriftene «Energetika. økonomi, teknologi, økologi» og «Økologiske vitenskaper».

Forskningsoppgaver

1. Utføre relevante analyser og tester for å bestemme de fysisk-kjemiske og toksiske egenskapene til jordprøven.
2. Undersøke eksisterende tilfeller av fytoremediering av jord og gjennomføre en gjennomgang av vitenskapelig litteratur om dette temaet.
3. Basert på oppnådde resultater og litteraturdata velge en optimal fytoremedierende plante og gjennomføre jordremediering.

4. Beregne parametere som er nødvendige for å vurdere effektiviteten av fytoremedieringsprosessen og beregne tiden det tar å oppnå konsentrasjoner av metaller i jorden tilsvarende grenseverdiene.

Praktisk betydning. Denne studien åpner nye muligheter innen etterkrigs restaurering av territorier, samt nye utfordringer for vitenskapelig forskning med mål om å forbedre og optimalisere denne teknologien.

Nøkkelord: påvirkning av militære handlinger, økologisk sikkerhet, jordforurensning, befolkningssikkerhet, matsikkerhet, jordrekultivering, etterkrigs gjenoppbygging, biologiske rensemetoder, fytoremediering.

ЗМІСТ

INTRODUCTION

Today, Ukraine faces an acute environmental safety issue caused by military actions. Warfare has a negative impact on biota, the atmosphere, water and soil, which requires the development of comprehensive strategies for environmental restoration and protection right now. A separate problem is the damage to agricultural land, which includes physical impact due to compression from explosions or the passage of heavy military equipment, and chemical contamination with heavy metals, petroleum products, and other components that may be contained in various military instruments. Chemical contamination poses a potential threat to ecosystems and human health, while physical impact destroys fertility and makes it impossible to grow crops effectively.

The use of biological remediation methods is promising for soil restoration. When combined, these methods can ensure high efficiency in the removal or immobilisation of pollutants, which in turn will allow safe concentration levels in the soil to be achieved. Phytoremediation technology, which is accessible to different segments of the population, is particularly promising for Ukraine. This method is easy to use, effective and eco-friendly.

The study proposes this technology for use in post-war territories, and its characteristics and effectiveness were investigated on soils contaminated by the detonation of explosive devices. Additionally, the toxicity of this soil was studied, which is an important aspect for agriculture.

1 ANALYSIS OF THE PROBLEM OF SOIL CONTAMINATION AS A RESULT OF MILITARY ACTION AND WAYS TO SOLVE IT

1.1 The impact of war on the natural environment

Wars and armed conflicts cause devastating consequences for the natural environment, which often have long-term and sometimes irreversible effects. These consequences extend to geological, hydrological, atmospheric and soil systems, which can lead to a number of environmental crises.

One of the most significant consequences is the destruction of biodiversity and mass migration of species, which is a key factor in the change or destruction of ecosystems. Shell explosions, artillery fire, air strikes and military manoeuvres destroy plant and animal life. Birds and mammals are killed by shelling and shock waves, which also kill insects and reptiles and destroy the underground habitats of many species.

Attacks with various types of long-range weapons often cause forest and steppe fires, which destroy vast areas of ecosystems. According to a study [1], 8096 km^2 of territory burned down in Ukraine during the war in 2022-2024. Of this area, 1047 km^2 is accounted for by forests that burned down as a result of hostilities and the inability to extinguish the fires. Figure 1.1 shows the areas that were completely burned down in the Black Sea Biosphere Reserve and the Biloberezhzhya Sviatoslav National Nature Park [1].

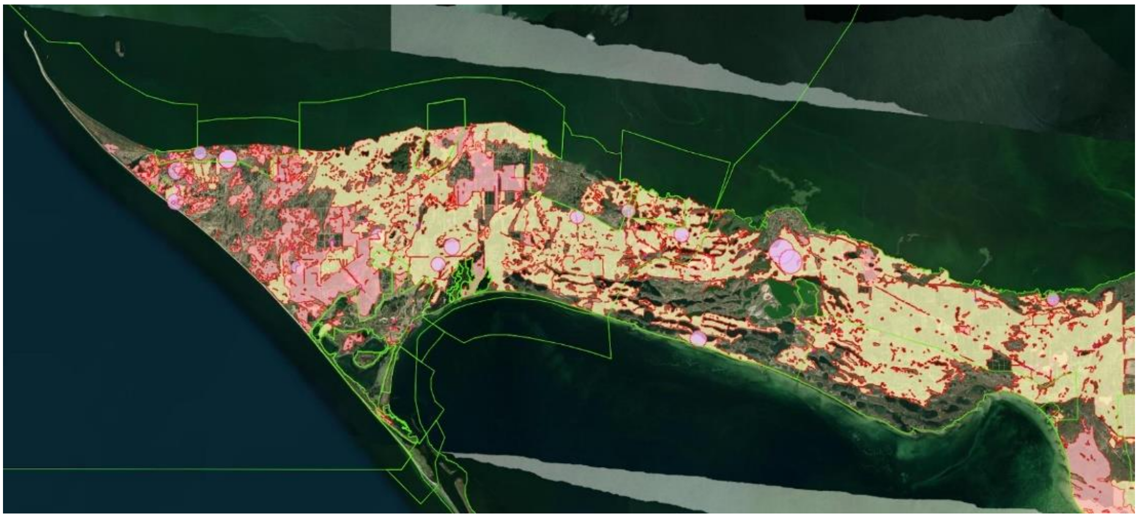

Figure 1.1 – Fire-affected nature conservation areas of the Black Sea Biosphere Reserve and the Biloberezhzhya Svyatoslav National Nature Park. Source: WebMap by csdeant2

Another extremely destructive process for ecosystems is mechanical landscape change and soil degradation. Armoured vehicles, such as tanks or infantry fighting vehicles, create deep compressed tracks when moving across open terrain, which destroy the fertile soil layer and subsequently become centres of soil erosion. Soil compaction also occurs as a result of explosions caused by various types of explosive devices, including mines and long-range weapons.

Military operations cause additional vibration loads, which may affect geological activity.

Among atmospheric pollution, we can highlight emissions from fuel combustion (both diesel and rocket fuel) and emissions resulting from shell explosions (including carbon dioxide and carbon monoxide, sulphur dioxide, and nitrogen oxides) [2].

Destroyed military equipment leaves thousands of tonnes of metal, rubber and plastic, creating mechanical pollution of the territory. In addition, oil leaks from destroyed military equipment, causing toxic effects on biota. In the event of a spill on land, the toxic effects of oils and other petroleum products will be localised, while a similar spill in a water body poses a much greater threat due to its rapid and uncontrolled spread.

In addition to direct environmental pollution from military operations and basic military equipment, Ukraine faces the problem of dealing with waste from the destruction of urban and industrial infrastructure as a result of military operations, which is currently hardly recycled at all and is transported to landfills, which, in line with the scale of the destruction, are expanding, increasing the negative impact on the habitats of various species. In addition, there is additional pollution from hazardous chemicals as a result of the destruction of oil depots, chemical plants and any production facilities where hazardous substances are stored as part of the technological process.

Considering that 70% of Ukraine's territory consists of agricultural land [3], the issue of monitoring the quality of soil and products grown on damaged areas is extremely important. There are no legal requirements for mandatory monitoring of the quality of soil damaged by military action, but landowners must be held responsible for the potential risks of contamination of agricultural products [4].

The largest impact on agricultural land is in frontline areas, as the density of explosion craters only increases over time due to regular shelling with various types of weapons of different calibres and chemical compositions [2]. Strategic mining of territories is also used. According to data from the State Emergency Service of Ukraine, approximately 156000 km^2 of Ukrainian territory had been mined as of 2024. Often, to ensure maximum efficiency or in specific cases, demining takes place at the location of the explosive object by means of a controlled detonation by an operator using a projectile with known characteristics and composition. Such cases have an additional negative impact on the soil cover.

Figures 1.2-1.7 show images of agricultural land attacked by various types of weapons (source: Google Maps). Soil across Ukraine is also suffering from long-range missile and drone strikes.

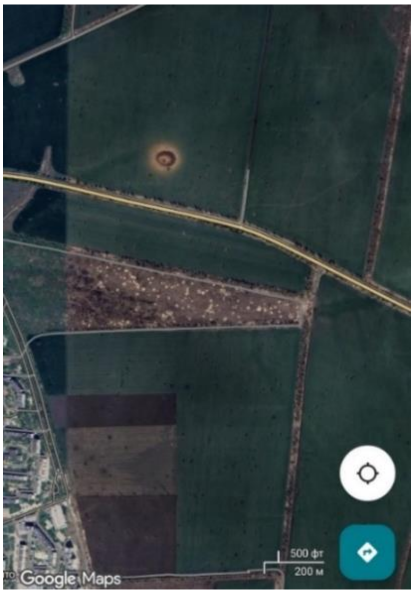

Figure 1.2 – Agricultural land near Mariupol, 47.1295758, 37.7001700

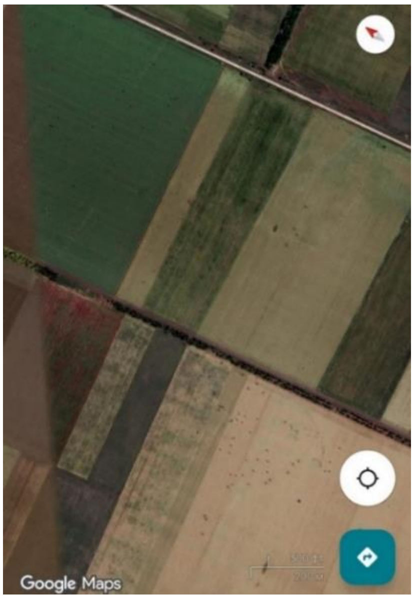

Figure 1.3 – Agricultural land near the village of Ternovi Pody, Mykolaiv Oblast, 46.8523664, 32.3503878

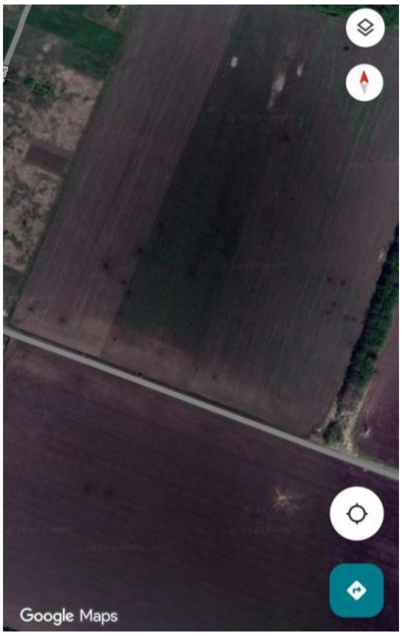

Figure 1.4 – Agricultural land near the village of Tsyrkuny, Kharkiv region, 50.080362,36.404144

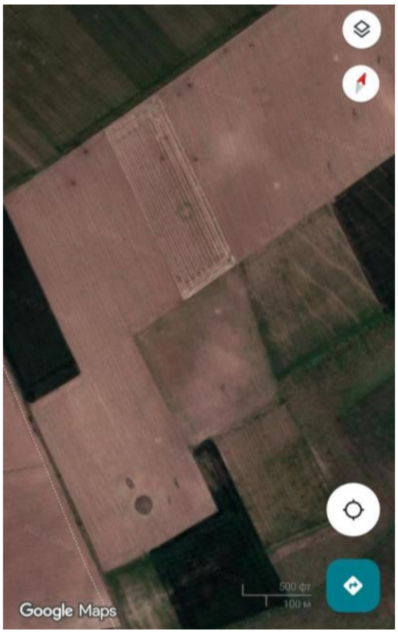

Figure 1.5 – Agricultural land near the village of Synetskyi, Donetsk region, 48.945392,38.419409

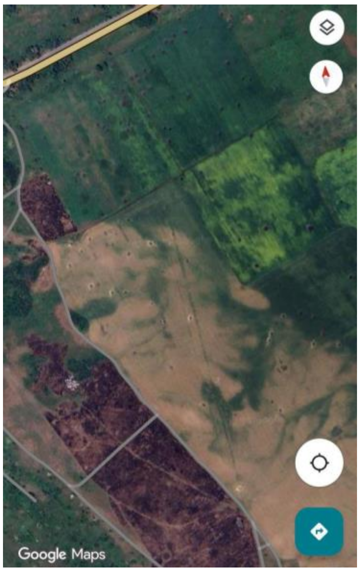

Figure 1.6 – Agricultural land near the village of Davydiv Brid, Kherson Region, 47.250720,33.173254

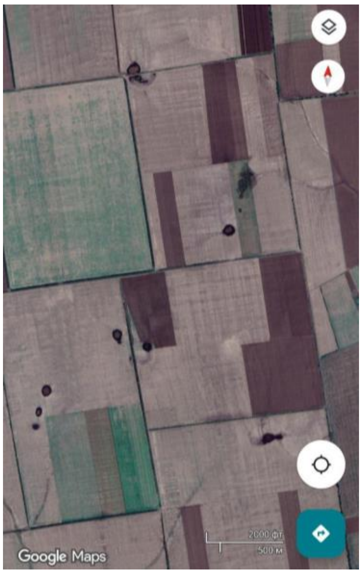

Figure 1.7 – Agricultural land near the village of Avydivka, Odessa region, 46.032858,30.186393

The environmental consequences of war are not just visible destruction, but also hidden long-term processes, including the poisoning of land and water bodies, disruption and contamination of food chains, the onset of erosion processes, changes in the microclimate due to fires or changes in the water regime, and even the complete disappearance of water bodies, as happened with the Kakhovka Reservoir.

1.2 The most common explosive items used in Ukraine

On Ukrainian territory russia mainly uses old Soviet mines, but there are also several new modifications: types MON, OZM, PMN, TM, POM, PFM, PTM [5]. Depending on the type, the purpose, the explosive power and the mechanism of operation of the mines themselves vary.

MON – directional fragmentation mine (anti-personnel), contains PVV-5A plastic explosive together with fragments of crushed steel in varying quantities depending on the model (400-2000 fragments). Modifications MON-50, MON-90, MON-100, MON-200 are used: the index indicates the lethal range (50 m, 100 m, 200 m, respectively). A photo of the MON-100 mine is shown in Fig. 1.8.

Figure 1.8 – MON-100 anti-personnel fragmentation mine

OZM – fragmentation barrier mine with circular coverage; explosive – TNT. The OZM-72 modification is used, which is usually activated by a tripwire via a mechanical detonator, but sometimes an electric detonator is also used.

PMN – anti-personnel high-explosive pressure mine, the most widely used type. There are modifications PMN-2 and PMN-4.

The most widely used anti-tank mine in Ukraine is the **TM-62M** (Fig. 1.9). This type of mine is activated by removing the safety pin from the cocking button; the warhead contains 7500 g of TNT. There is a modification, the TM-62P3, in which the warhead contains 6500 g of TNT. The TM-83 series, which is defined as anti-tank side mines, is characterised by a TG-40 composition – hexogen (RDX)/TNT 60/40; a special feature is activation by a BT-01 infrared sensor or a BT-02 seismic sensor.

Figure 1.9 – TM-62 anti-tank mine

There is a separate category of mines for remote scattering. The most common example is the **PFM-1** (known as the 'petal') – an anti-personnel high-explosive mine; it can be scattered using artillery systems, rocket systems, dropped from aircraft or installed by ground forces. The mine body is made of plastic, and the explosive (VS-6D) is liquid, volatile and toxic, posing a risk to the safety of the surrounding environment. The PFM-1 mine is shown in Fig. 1.10.

Figure 1.10 – PFM-1 anti-personnel high-explosive mine («petal»)

POM-2 mines (anti-personnel fragmentation mines; explosive - TNT) are also used for remote mining. They are delivered to targets by aircraft or multiple launch rocket systems. The successor to the POM-2 is the POM-3 series, which is a new type of anti-personnel mine for remote mining, activated by a seismic sensor; explosive – A-IX-1 (hexogen + aluminium powder).

PTM-type mines are used as anti-vehicle/anti-tank mines with remote mining. PTM-1 is delivered using multiple launch rocket systems, while PTM-3 and PTM-4 are delivered using KPT-3/4 containers, respectively. A modified version of the PTM-3 with motion and magnetic sensors is widely used on unmanned aerial vehicles.

1.3 Methods of demining

Thanks to modern technology, three main types of demining can be distinguished: manual, mechanical, and using modern technology (robots and drones) [6].

Manual demining is a traditional method of detecting and destroying explosive objects, which involves operators and sappers searching the area for mines using metal detectors. This process can be lengthy, as it is carried out by humans and, in order to ensure the safety of sappers and operators, the areas must be searched extremely thoroughly. When an explosive device is found, a specialist defuses the mine, and if this is not possible, carries out a controlled explosion (usually a standard charge containing 400 g of TNT). There are also cases where specialists remove the detonator from some explosive devices, allowing the mines to be reused.

Today, in addition to classic controlled detonation with explosives, a metal burning tool (MBT) shown in Fig. 1.11, the so-called ‘pencil’, is actively used. It is designed for burning carbon and alloy steels, non-ferrous metals and cast iron, after which the explosives inside the projectile burn out without exploding. The advantage of this method is that it can be used underwater due to the high temperatures, after which the safe metal casing can be removed from the water. This technology was approved for use in humanitarian demining at the end of 2022.

Figure 1.11 – Metal burning tool («pencil»)

Another new method in the field of demining is the use of a water cannon, which destroys the body of the explosive device with a jet of water or a ballistic mixture at ultra-high pressure and wets the explosive substance, rendering it unusable. After the casing is destroyed, the moistened explosive can be collected and sent for disposal. This cannon is operated by a robot, which is an additional advantage, as operators are not exposed to danger. An example of such a water cannon in operation is shown in Fig. 1.12.

Figure 1.12 – Mortar mine destroyed using a water cannon

Mechanical demining is very effective over large areas, which is extremely important for Ukraine. Demining machines are usually equipped with metal detectors or ground-penetrating radars to locate mines. The machines are equipped with flails, which are metal bar systems with forged chain or cable suspensions. The flail moves over the mined area and the metal chains or cables strike the mines with a rotating drum, bringing them into combat position. This causes detonation and the mine is neutralised. The advantage is safety for people, but among the disadvantages is the inability to work on steep slopes.

Robots or FPV-drones are increasingly being used for demining, which also helps to ensure the safety of specialists by avoiding direct contact with unexploded ordnance (UXO). However, damage to robots and drones containing batteries causes additional contamination of the area with lead or lithium and acidic electrolytes.

1.4 Environmental consequences of demining

The detonation of any explosive device, whether a grenade or a ballistic missile, has devastating consequences for the soil. First of all, the landscape changes, which can be critical for some ecosystems. The explosion changes the structure of the soil: it becomes compacted, which will affect its physical and, in the future, even chemical characteristics, as geochemical barriers may potentially form in these areas.

When a shell explodes, depending on the composition of the explosive, the temperature in the explosion cloud can vary from 2000K to 4000K [7, 8]. At such temperatures, all organic matter that makes the soil fertile, along with all microorganisms, burns out. The absence of microorganisms in the soil will potentially have a negative impact on plant growth efficiency. In addition, such temperature effects cause the soil to «bake», making it unsuitable for effective agriculture for some time.

Many unexploded ordnance are fragmentary, which means that when they are defused using conventional methods or when they explode as intended, the environment is contaminated with metal particles hundreds of metres from the epicentre. The advantage of using «pencils» or water cannons is that there is no explosion, which means there is no impact on the soil structure and no associated contamination with metal fragments.

In addition to pollution, shell explosions have a significant impact on the behaviour and migration of animals and birds, which will also lead to significant ecosystem changes.

When shells explode, carbon dioxide and carbon monoxide, sulphur dioxide and nitrogen oxides are released into the air. In the event of detonation in open space, these gases disperse and do not have such a negative effect as, for example, detonation in a water body. Some UXOs cannot be removed from the water, so the only option for disposal is detonation, which causes these gases to dissolve in the water and have a negative impact on local hydrobiota. The explosion itself can also be fatal to aquatic life. As mentioned above, «pencils» and water cannons can be used underwater, which avoids explosions, but when using a water cannon, it is impossible to remove the explosives – they will end up in the aquatic environment and also have a toxic effect on the hydrobiota. Therefore, the most environmentally friendly method in this case would be to use a «pencil», which, thanks to its extremely high temperature, can burn underwater.

A separate category of pollution caused by military operations can be identified as the single use of various sizes of drones (reconnaissance or explosive), all of which have *batteries*. The toxicity of the battery in the environment is due to the presence of lead, lithium, cadmium and acids, which enter the environment as a result of the drone being blown up.

In addition to the direct impact of UXOs and the destruction of batteries, abandoned or destroyed special equipment (armoured personnel carriers, tanks, aircraft, remnants of missiles and military transport), from which fuel and lubricants leak, causing toxic effects on microorganisms and plants, as well as on fish, mammals, birds and humans if the spill occurs in a water body. In the event of a spill onto the ground, there is a risk of toxicants seeping into groundwater, which also poses a threat to humans. In the environment, under the influence of ultraviolet radiation, water, possibly acid rain, and mechanical damage, the hulls of specialised equipment and various types of military equipment corrode, which can release various metals, including heavy metals, as well as microplastics, paints/anti-corrosion coatings and explosives into the environment.

1.5 The impact of heavy metals on living organisms

Heavy metals are capable of bioaccumulation and can accumulate along the food chain. Although some of them are important trace elements, in excessive concentrations they can have many negative effects and cause various diseases in plants, animals and humans, respectively. The presence of heavy metals in soils poses a risk of contamination of agricultural products, so research on affected fields requires additional attention, as it raises the issue of human health safety.

In the context of war and pollution caused by military operations, lead pollution is of greatest concern because, due to its bioavailability, it bioaccumulates and biomagnifies in living organisms. **Lead (Pb)** affects the central and peripheral nervous systems, as the nervous system is the most sensitive organ to lead exposure [9]. Lead from the soil surface can infiltrate groundwater, which is the main source of drinking water for a significant part of Ukraine's population. This is especially dangerous for owners of private wells that are not equipped with specialised purification systems. Lead negatively affects growth, reproduction, metabolism, the nervous system, development and behaviour [9]. Lead mimics calcium, which allows it to quickly cross the blood-brain barrier and accumulate in brain cells. Even low concentrations can cause learning problems, impaired neural development and a decrease in IQ in children: by 1-5 points for every 0,1 mg/dm^3 increase in blood lead levels. High concentrations can lead to encephalopathy (brain swelling), with symptoms including memory loss, headaches and hallucinations [9].

Lead directly affects the haematological system even at very low levels in the blood (0,03-0,1 μg/dm^3), as it inhibits haemoglobin synthesis, leading to anaemia.

Lead can also cause kidney dysfunction: acute renal failure and chronic nephropathy. Lead levels above 0,05 mg/dm^3 in the blood can increase the risk of stroke, ischaemic heart disease and other cardiovascular diseases [10].

The maximum permissible concentration of lead in drinking water, in accordance with the Hygienic Standards for Water Quality in Water Bodies for Drinking, Domestic and Other Needs of the Population, approved by order of the Ministry of Health of Ukraine on 2 May 2022, shall not exceed 0,03 mg/dm^3. The hazard class of lead according to the standards is 2. For soil, the MPC is 32 mg/kg of soil for the gross form.

In plants, lead leads to reduced root growth, decreased photosynthesis due to the cessation of chlorophyll synthesis, affects the Calvin cycle and causes CO_2 deficiency, which leads to the closure of stomata [11]. Lead mainly accumulates in the roots, which is why root crops can have a high lead content. Therefore, in agricultural areas affected by military operations, it is advisable *to avoid growing carrots, beets, radishes, and other root crops*. It has also been proven that plants absorb more lead from acidic soils than from neutral or alkaline soils [11], which is generally characteristic of other metals due to their increased bioavailability.

Copper (Cu) is a vital trace element necessary for cellular functions, but it is dangerous in high concentrations: it can accumulate in the liver and cause cirrhosis, and it also affects the kidneys, brain, and other organs. Chronic toxicity is associated with neurological and mental disorders (anxiety, depression, headaches) and endocrine disorders (hypothyroidism, diabetes) [12]. The MPC for copper in accordance with hygiene standards for drinking water is 1,0 mg/dm^3. The hazard class of copper is 2. For the mobile form, the MPC in soil is 3 mg/kg of soil.

For plants, elevated concentrations pose a risk of growth inhibition, oxidative stress, effects on photosynthesis, and reduced absorption of other minerals necessary for plant growth [12]. Since copper is immobile, it accumulates mainly in the roots, similar to lead.

Cadmium (Cd) is extremely bio-persistent and can accumulate and remain in the body for many years after entering the body (biological half-life – 10-30 years). This metal may be a potential risk factor for lung, kidney or prostate cancer. High concentrations of cadmium are characterised by nephrotoxicity, accompanied by damage to the renal tubules, kidney stones and glucosuria. Chronic cadmium poisoning can reduce calcium absorption in the body, leading to skeletal demineralisation and osteoporosis. Prolonged exposure also causes neurodegenerative disorders [13].

Cadmium has negative effects on the central nervous system and can affect the cardiovascular system. This metal binds to the sulphhydryl groups of proteins, resulting in protein denaturation and DNA damage [14, 15]. Cadmium also interferes with the absorption of vitamin D and the absorption of phosphates by bones. The MPC for cadmium in drinking water is 0,001 mg/dm^3, and for soil – 3 mg/kg of soil. Hazard class – 2.

In plants, cadmium causes growth, morphology and development disorders: inhibition of root formation and development, inhibition of photosynthesis and oxidative damage to cells (membranes, biomolecules and cell organelles) [16].

Chromium (Cr) can cause mutations and cancer due to its high oxidative capacity. Hexavalent chromium is particularly dangerous because it penetrates cells more easily than trivalent chromium and is mostly associated with carcinogenic activity.

Hexavalent chromium does not have a direct toxic effect on genes; when it enters the sulphate transport system, it is reduced to trivalent chromium, and the intermediate products formed during reduction cause DNA damage. Reduced chromium reacts with phosphate groups in DNA and interferes with normal replication and transcription, causing mutagenesis, and also interacts with certain enzyme groups [17].

The MPC for trivalent chromium in drinking water is 0,5 mg/dm^3, and for hexavalent chromium – 0,05 mg/dm^3. For soil, the MPC for chromium in mobile form is 6 mg/kg of soil, and for hexavalent chromium – 0,05 mg/kg of soil.

Toxic effects on plants are mainly manifested by the inhibition of shoot and root growth, which disrupts water exchange due to a decrease in the active area. The effect of high chromium concentrations is even manifested in the inhibition of seed germination. In plants, chromium inhibits chlorophyll, which disrupts photosynthesis, cell cycle, mineral balance, enzyme activity and nitrogen assimilation. Chromium is also characterised by oxidative stress and disruption of the absorption of essential nutrients, which is typical for other heavy metals [18].

Nickel (Ni) compounds are classified by the International Agency for Research on Cancer (IARC) as carcinogenic (Group 1) under chronic exposure. Nickel in the body can cause neurotoxic effects, cardiovascular and kidney diseases. It is the toxicity and carcinogenicity of nickel that are associated with mitochondrial dysfunction and oxidative stress [19]. At excessive concentrations, it inhibits growth and interferes with the activity of RISCs enzymes (sulfite oxidase and sulfur dioxygenase) [20]. In addition, nickel can cause certain epigenetic changes: DNA hypermethylation and histone modification, which disrupt the genome and can potentially lead to the development of tumours [19]. The MPC for drinking water is 0,1 mg/dm^3, and for soil in mobile form – 4 mg/kg of soil.

Despite the importance of nickel for nitrogen metabolism in plants, excessive concentrations have a strong phytotoxic effect. The symptoms are similar to those caused by other heavy metals in high concentrations: growth inhibition, induction of chlorosis (yellowing), necrosis and wilting, disruption of photosynthesis, oxidative stress, disruption of mineral nutrition and impact on water balance, as nickel causes dehydration in plants [21].

Zinc (Zn) can also cause toxic effects in excessive concentrations, covering a wide range of metabolic disorders in both humans and plants.

For humans, toxic effects can vary depending on how the substance enters the body: it can be a short-term exposure to high doses or long-term exposure to low doses (as can potentially occur as a result of contamination of food or drinking water). Excessive zinc concentrations can have a neurotoxic effect: synaptically released zinc causes neuron death, which impairs cellular energy production by disrupting mitochondrial function. High zinc levels can cause neurological symptoms: lethargy, dizziness, anxiety and even depression. Excess zinc may also contribute to the onset and development of Alzheimer's disease.

The maximum permissible concentration of zinc in drinking water is 1 mg/dm^3; hazard class – 3. The maximum permissible concentration for soil in mobile form is 23 mg/kg of soil.

Chronic exposure to elevated zinc concentrations in the human body can cause copper deficiency and competitive interaction with iron, which can lead to a decrease in serum ferritin and haematocrit [22].

For plants, the danger of high zinc content in the soil lies in the inhibition of root growth, reduced germination energy and overall biomass. This may be due to the fact that excess zinc interferes with the absorption of other ions necessary for life, disrupts the plant's water balance, hinders photosynthesis and causes oxidative stress and cell damage [23].

The toxic effect of manganese (Mn) in excessive concentrations mainly affects the brain, causing manganism, a disease that resembles Parkinson's disease in its general symptoms: speech disorders, specific gait, ataxia, fine motor skills disorders, and dopaminergic dysfunction. The danger lies in the irreversibility of the neurotoxic effects caused by manganese. Excess manganese in the body can also cause changes in cardiovascular function, especially after acute exposure [24]. The

MPC for manganese in drinking water is 0,1 mg/dm^3; hazard class – 3; for soil, the MPC is 1500 mg/kg of soil for gross content and 140 mg/kg for mobile form.

1.6 Toxic effects of petroleum products on living organisms

The toxic effects of oil and its by-products, such as diesel fuel and petrol, are mainly caused by hydrocarbons and their physical properties (volatility, viscosity, surface tension).

Hydrocarbon poisoning can affect various organs and systems of the body. Toxic effects on the respiratory and central nervous systems are usually caused by inhalation of petroleum product vapours. In the context of poisoning due to direct entry into the body, symptoms may include nausea and haematemesis (vomiting blood). Cardiovascular symptoms and arrhythmias may also occur. Halogenated hydrocarbons can lead to necrosis of the liver and kidney tubules, causing renal and hepatic failure [25].

Among the components of petroleum and petroleum products, aromatic compounds are the most toxic. This is especially true for polycyclic aromatic hydrocarbons (PAHs), which are highly mutagenic and carcinogenic. The group of monocyclic aromatic hydrocarbons, known as BTEX (benzene, toluene, ethylbenzene and xylenes), are also highly toxic pollutants. In most cases, petroleum substances are highly toxic, strongly inhibit the growth of microorganisms and, as a result, reduce the enzymatic activity of soils.

Contamination with petroleum products affects the growth and development of plants growing on contaminated soil. More than 1 kg of oil per m^2 of soil can lead to plant necrosis. This occurs due to the creation of anaerobic, hydrophobic conditions that disrupt the soil-plant-water relationship. Severe contamination can lead to complete degradation or disappearance of vegetation cover. Hydrocarbons can create an oily film on the above-ground parts of plants, which reduces transpiration and respiration, decreases the permeability of plant membranes and causes metabolic disorders. Petroleum substances slow down plant growth in proportion to the degree of contamination. They can cause delays in germination and root growth. High doses of petrol (e.g., 10 cm³/kg of soil) can completely stop germination, while identical doses of diesel fuel severely inhibit this process. In general, diesel fuel often has a stronger toxic effect than petrol.

Even if soil contamination does not impair vegetative development, it can lead to the accumulation of hydrocarbons in plants, calling into question the sanitary quality of the harvest [26].

1.7 Restoration of soil contaminated by military operations

1.7.1 Methods of biological restoration of contaminated soils

One of the most promising methods of soil restoration for Ukraine is bioremediation. Biological restoration methods are environmentally friendly technologies for cleaning water, soil and even air from pollutants of various nature and origin. [27]. This approach involves the use of natural processes to remove various components from contaminated sites, which does not require significant financial costs.

Bioremediation involves the use of biological agents (mainly microorganisms: bacteria, fungi, algae) to decompose or remove unwanted components from the environment. The article «Bioremediation an eco-friendly method for administration of environmental contaminants» [28] provides a comprehensive description of bioremediation techniques, including: bioaugmentation (the introduction of microorganisms to decompose pollutants), bioventing (the stimulation of aerobic microorganisms by pumping air), biosparging, biocomposting (mixing contaminated soil with organic waste to accelerate the decomposition of pesticides and petroleum products), and biopiles (aerated piles of contaminated soil). Biocomposting is the most promising and cost-effective method for soil remediation in Ukraine, especially due to the localised negative impact of events such as the explosion of a shell on a private plot of land used for agriculture.

The above methods of bioremediation can be combined with phytoremediation, which in turn involves the use of plants and associated soil microorganisms to reduce the environmental impact of pollutants. The term phytoremediation itself comes from the Latin *phyto*, meaning plant, and *remedium*, meaning to cure[29].

Some of the advantages of using phytoremediation as a method of soil restoration compared to traditional methods are increased biodiversity and fertility, prevention of erosion [28], which are extremely important aspects, especially in the context of soil structure destruction and the extermination of microbial species diversity after an explosion.

In general, there are five main mechanisms for cleaning environments of unwanted components [30]:

- *phytoextraction* – absorption of pollutants by roots and accumulation in the above-ground parts of plants (effective for metals);
- *phytostabilisation* – immobilisation of pollutants in the soil through sorption, precipitation or complex formation in the inter-root space;
- *phytodegradation* – enzymatic decomposition of certain organic compounds (herbicides, pesticides, petroleum products) into simpler compounds, followed by their absorption by plants;
- *rhizofiltration* – purification of water from metals by absorption through roots (effective for aquatic systems with low pollution);
- *phytovolatisation* – the transformation of pollutants (such as mercury or arsenic) into volatile compounds and their removal through transpiration.

Table 1.1 below lists the strengths and weaknesses of bioremediation and phytoremediation in the context of Ukraine.

Table 1.1 – Strengths and weaknesses of biological soil remediation methods

Method	Strengths	Weaknesses	Prospects for application
Bioremediation	Environmentally friendly, relatively inexpensive, can be used for organic contaminants	Duration of the process, need for monitoring	Restoration of small volumes of soil in local areas, including the private sector
Phytoreme-diation	Availability of plants, proven effectiveness, resistance to various types of pollutants	Duration, disposal of contaminated biomass, need for maintenance, need for soil quality monitoring during the remediation process	Widespread use in agricultural areas

1.7.2 Plant species used for phytoremediation

Returning to issues relevant to Ukraine, namely the safety of agricultural soils, the most effective and economically acceptable mechanism would be classic phytoextraction. Sunflower (*Helianthus annuus L.*) is one of the most researched species for this process. It has high potential for phytoremediation, which has been confirmed in studies on the remediation of soils contaminated with nickel, lead, chromium and cadmium [31]. Studies have shown that sunflower accumulates a higher concentration in its leaves, accounting for 55% of the total metal content compared to the stems. Another effective species is brown mustard or Indian mustard (*Brassica juncea*), which shows high potential for decontaminating lead-polluted soils, especially when using adjuvants such as EDTA, which chelate heavy metals, making them more available for absorption by plants [32]. In addition to these species, hybrid poplar (*Populus*) and dandelion (*Taraxacum officinale*) can be used for the phytoextraction of heavy metals such as chromium [33].

Phytoremediation allows plants to be used for the degradation of hydrocarbons, particularly due to their well-developed root system, which creates a favourable environment for symbiotic microorganisms in the rhizosphere. The uptake and absorption of organic chemical compounds depends on their physical and chemical properties, in particular on the logarithm of the octanol-water partition coefficient ($logK_{ow}$). Chemicals with moderate hydrophobicity ($logK_{ow}$=1.0 – 3.5) are the most bioavailable to root vascular plants. However, some hydrophilic compounds, such as methyl tert-butyl ether, can also be absorbed by plants through water flow [34].

For phytoremediation of petroleum-contaminated soils, *Bassia scoparia* is effective due to its associated rhizosphere microorganisms [35]. Alfalfa (*Medicago sativa*) can also significantly reduce the concentration of petroleum products in the soil [36]. Some ornamental plants, such as tall fescue (*Festuca arundinacea*) and birdsfoot trefoil (*Lotus corniculatus*), can be used to clean up oil-contaminated soils [37].

Hybrid poplar (*Populus*) can also be used to cleanse soil of explosives, in particular 2,4,6-trinitrotoluene (TNT), which is one of the main explosive components of most shells fired at Ukraine [38]. Studies have shown that poplars are capable of absorbing TNT from the soil, with most of the TNT being bound and transformed in the plant's root system. Summary Table 1.2 with plants for phytoremediation and corresponding pollutants is provided below.

Table 1.2 – Phytoremediation agents and pollutants against which they are effective

Plant	Type of pollutant	Features of use
*Helianthus annuu*s (sunflower)	Lead, cadmium, chromium, nickel	High accumulation capacity in leaves and stems
Brassica juncea (Indian mustard)	Lead (using chelates, in particular EDTA)	High level of Pb removal thanks to chelation
Populus spp. (hybrid poplar)	Heavy metals (Cr, Zn), explosives (TNT)	Active transformation of explosives in the root system
Taraxacum officinale (dandelion)	Chromium and other heavy metals	High adaptability in different conditions
Bassia scoparia (summer cypress)	Petroleum products, surfactants	Symbiosis with microorganisms increases the degradation of carbohydrates
Medicago sativa (alfalfa)	Petroleum products	Reduces the concentration of hydrocarbons in the soil
Festuca arundinacea (tall fescue)	Petroleum products	Used for decorative recultivation
Lotus corniculatus (bird`s-foot trefoil)	Petroleum products	Suitable for long-term ecosystem restoration

Fig. 1.13 shows the efficiency of metal absorption by various hyperaccumulator plants, including Indian mustard (*Brassica juncea*), Chinese brake fern (*Pteris vittata*), poplar (*Populus spp.*), common sunflower (*Helianthus annuus*), Alpine pennycress (*Thlaspi caerulescens*), according to the article 'Exploring Phytoremediation And Plants As Natural Cleaners Of Polluted Environments', Deborah Paripuranam et. al, 2025 [27].

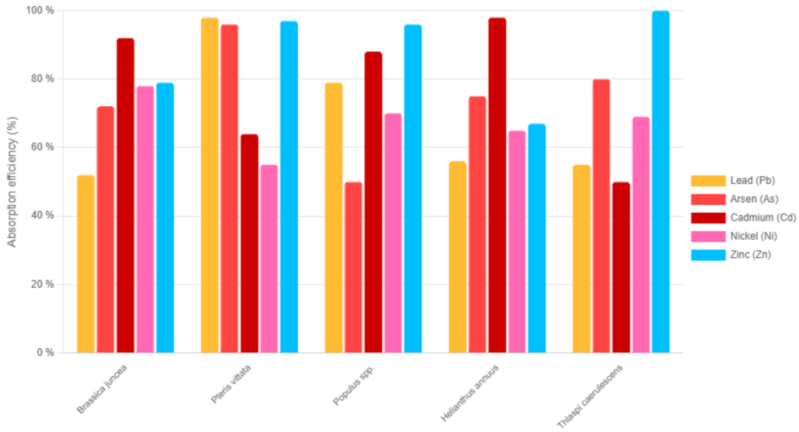

Figure 1.13 – Metal absorption efficiency, Deborah Paripuranam, 2025 [27].

1.7.3 International experience in the use of phytoremediation

In the field of heavy metals, phytostabilisation technology has been proven and is successfully used in both Europe and the United States [39]. For example, Belgium has conducted successful large-scale trials of zinc (Zn) and cadmium (Cd) immobilisation using additives and recultivation, while the US Environmental Protection Agency (EPA) has supported the use of biosludge for the recultivation of mining sites. A new direction is phytomining (extraction by plants) of valuable metals such as nickel, thallium and gold, where the main goal is cost-effective extraction, not just decontamination. However, the efficiency of phytoextraction of heavy metals, especially for meeting strict regulatory standards, remains low, as confirmed by studies in Denmark [40]. In a heavily contaminated site in Valby (Denmark) using willow (*Salix sp.*) and poplar (*Populus sp.*), the efficiency of Cd removal by willow was less than 0.5% over 10 years, and for other heavy metals — less than 1‰ over 10 years. Calculations have shown that it could take more than 178360 years for poplar to meet the standards for nickel (Ni). Despite this, planting trees on contaminated sites is still recommended due to additional benefits: reduced leaching, CO_2 fixation and habitat creation [40].

In Japan, *Thlaspi caerulescens* (Gang ecotype) has significant potential for phytoremediation of cadmium (Cd)-contaminated soils [41]. Compared to the slow extraction observed in Denmark, studies on representative soils in Japan (fluvisol and andosol) have shown that only about 2 harvests for fluvisol and about 6 harvests for andosol may be needed to reduce the total Cd concentration by 50%. To increase the effectiveness of Cd phytoremediation in Japan, it is recommended to use short rotation (repeated harvesting and planting), as this increases the availability of Cd and utilises new rhizosphere volume. Fig. 1.14 shows the decreasing dependence of the total cadmium content in the soil on the number of harvests [41].

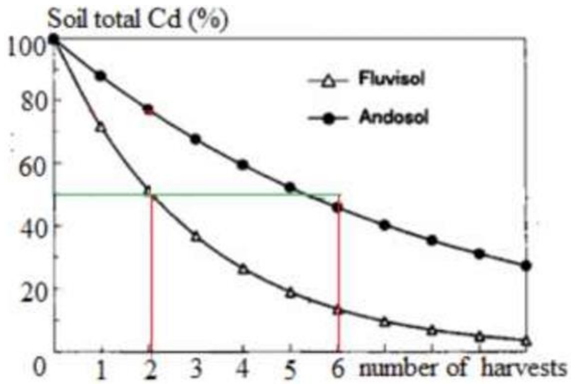

Figure 1.14 – Determined degree of cadmium removal depending on the number of planting cycles using *Thluspi cuerulescens*, Yuko Nishiyama, 2010 [41]

In Italy (Treccate), following an oil well spill, agricultural crops such as maize (*Zea mays*) and *Sorghum* were significantly more effective in removing petroleum hydrocarbons than agronomic methods or natural attenuation [39]. In addition, pilot studies have shown that the reclamation of soil contaminated with petroleum hydrocarbons (PHC) using plants *(L. sativum, M. sativa, H. annus*) and additional microorganisms and earthworms, demonstrated a reduction in PHC content by 80% and metals by 20% after 17 months [42].

The Baltic Phytoremediation concept, implemented as a cross-border project between Sweden, Poland and Lithuania, aims to use phytoextraction in combination with biomass generation and its subsequent use as an energy resource. Thus, after burning contaminated plant biomass, valuable ash ('bio-ore') can be recovered for further use. This approach increases energy efficiency and is an alternative energy source that reduces CO_2 emissions. Pilot cases for this project include reducing the level of nutrients (nitrogen and phosphorus) in landfill layers in Sweden, assessing the potential of energy crops to accumulate heavy metals (Zn, Cu, Cr, Pb, Ni and Cd) using sewage sludge as fertiliser in Lithuania, and phytoremediation of landfill leachate and soil remediation from heavy metals and organic pollutants (surfactants, dioxins, PCBs) in Poland [42].

Regarding radionuclides, although this area is less documented, Phytotech conducted a field trial in the Chernobyl Nuclear Power Plant zone (Ukraine) using sunflowers on rafts to reduce 137Cs levels in surface water over a period of 4–8 weeks. In addition, laboratory studies in the United States have shown that willow, *Kochia scoparia* and *Brassica napus* can remove 40–60% of 137Cs from soil under greenhouse conditions [39].

In addition to scientific research results, there are quite a few patents for phytoremediation technology under various conditions for the purpose of removing specific pollutants. The vast majority belong to the Chinese scientific community. For example, in order to achieve maximum efficiency, one Chinese company registered a patent (CN101947539B) [43] that combined processes such as chemical leaching, rainworm recultivation, and phytoremediation.

Another noteworthy patent, also registered by a Chinese company (CN105950502B) [44], involves the use of endogenous bacterial microbiological inoculum in combination with phytoremediation for soils contaminated with heavy metals. The composite bacterial agent consists of *Acinetobacter calcoaceticus*, *Pseudomonas fluorescens*, *Bacillus megaterium*, *Stenotrophomonas maltophilia*, *Bacillus pumilus* and *Pseudomonas putida*, which have been proven to increase the absorption of heavy metals by phytoremediation plants.

Another progressive approach has been patented in China (CN107138511B) [45], which involves the deliberate migration of cadmium from the upper soil layers to deeper ones, where it is then immobilised by iron compounds to prevent migration to groundwater; next, willow (*Salix spp*.) is planted, which ensures the removal of cadmium, thus ensuring the phytoextraction of cadmium by a hyperaccumulator from deeper soil horizons, while the arable layer becomes safe for use in growing agricultural crops.

1.7.4 Management of contaminated biomass of phytoremediation agents

After successful phytoremediation of the soil, there is a critical task of safely handling the resulting biomass, which is contaminated with various compounds. Due to the presence of toxic pollutants, this biomass cannot be used as animal feed, compost or biofertiliser, as this would simply result in the transfer of pollutants in space with repeated contamination of the environment and potential toxic effects on animals and plants. Therefore, the development and implementation of a sustainable strategy for managing this biomass is a key final stage in the entire process of soil restoration by phytoremediation.

According to Santanu Mukherjee's article «Sustainable management of post-phytoremediation biomass» [46], this biomass is a ‘green concentrate of pollutants’ that requires careful planning for its disposal. One of the main classical approaches is thermal conversion, which includes incineration and pyrolysis. Incineration is a simple and effective way to reduce the volume of biomass and destroy organic pollutants. However, heavy metals will not disappear using this method, but will be concentrated in ash, which will require treatment and disposal. Pyrolysis allows the production of biochar, which in this case will still contain heavy metals, but this raw material can be used as a non-renewable filter in various technological processes due to its high adsorption capacity.

Chemical treatment methods can also be used to extract and stabilise contaminants. According to the study 'Sustainable management of post-phytoremediation biomass,' one of the most innovative areas is phyto-extraction, which involves the extraction of valuable metals from biomass. Chemical extraction of metals from biomass using acid solutions allows for the production of a concentrated solution from which metals can be recovered.

CONCLUSIONS TO SECTION 1

1. Soils in Ukraine are constantly exposed to various types of damage during military operations, including chemical contamination with heavy metals and petroleum products, which pose a threat to both ecosystems and human health, as these pollutants can have a direct toxic effect on plants, animals and humans through drinking water and contaminated food.
2. As a result of corrosion of explosive objects and their detonation, heavy metals such as lead, copper, cadmium, chromium, zinc, nickel and manganese can enter the soil, creating localised pollution problems on private land, agricultural land, forests and fields.
3. A promising method for restoring contaminated soils is phytoremediation, which involves the removal or immobilisation of undesirable compounds, thereby achieving safe soil quality. Given the natural characteristics of Ukraine's regions, Indian mustard (*Brassica juncea*) could serve as a potential hyperaccumulator, the effectiveness of which has been proven by numerous studies.

2 METHODS AND INSTRUMENTS

2.1 Soil sampling methodology

Soil samples were collected on 31 July 2025 in an agricultural area at coordinates 46°50'24.19‘N 32°21'16.62’E near the village of Ternovi Pody, Mykolaiv Oblast, by a mine action operator. Sampling was carried out in accordance with the guidelines of State Standard of Ukraine ISO 10381-4:2005 [47].

The demining area is located on the border between Mykolaiv and Kherson regions, less than 30 km from the front line and occupied territories, which are constantly under fire from Russia, mainly with rocket artillery. Two samples were taken using the classic soil sampling method – an «envelope» from an explosive crater formed when a shell hit an agricultural field, using a shovel. The envelope method involves taking five samples – four at the corners of a conditional square and one from the centre of this square, after which all five samples are averaged. The sampling depth was 0,3 m. The first sample was taken from a 4 m^2 area at the site of the munition impact without detonation. The second sample was taken using the envelope method on the same 4 m^2 area after the ordnance had been defused on site by controlled detonation. The samples were packed in plastic bags and sent for analysis to Kyiv.

2.2 Chemical analysis of soil samples

To assess the impact of military operations, it was decided to analyse the soil for the content of the most potential pollutants – heavy metals and petroleum products.

Physical and chemical studies of the soil were carried out by the Soil and Waste Hygiene Laboratory of the O.M. Marzieiev Institute of Public Health of the National Academy of Medical Sciences of Ukraine.

The atomic absorption method was used for analysis.

The list of techniques and the essence of the research methods that were used to conduct sanitary and chemical studies of samples are given below.

The pH value was determined using the Ecotest 2000 multi-parameter liquid analyser, calibration certificate No. 31.08.2023-50 dated 31 August 2023, in accordance with State Standard of Ukraine (DSTU) ISO 10390:2022 (ISO 10390:2021, IDT). Soil, treated biowaste and sludge. Measurement of pH level.

The heavy metal content was determined using the atomic absorption method on a KAS-120.1 spectrophotometer, calibration certificate registration No. K/21699/X dated 24 April 2023, in accordance with the methods:

- Measurement procedure (MP) №081/12-0009-01 Soils. Procedure for measuring **lead** using atomic absorption spectrophotometry;
- MP №081/12-0117-03 Soils. Methodology for measuring the mass fraction of mobile forms of **nickel and cobalt** using the atomic absorption method;
- MP № 081/12-0012-01 Soils. Methodology for measuring **chromium** using atomic absorption spectrometry (0,5-100 mg/kg);
- MP №081/12-0013-01 Soils, Methodology for measuring the mass fraction of **zinc** by atomic absorption spectrophotometry;
- MP №081/12-0576-08 Soils. Methodology for measuring the mass fraction of **manganese** using the photocolorimetric method;
- MP №081/12-0002-01. Soils. Methodology for measuring the mass fraction of **copper** using atomic absorption spectrophotometry;
- MP №081/12-0010-01. Soils. Methodology for measuring the mass fraction of **cadmium** by atomic absorption spectrophotometry.

The content of petroleum products was determined in accordance with the methodology of MP № 081/12-0116-03 Soils. Methodology for measuring the mass fraction of petroleum products by gravimetric method dated 28.11.03. Developed by the Ukrainian Research Institute of Environmental Problems of the Ministry of Environment of Ukraine, State Environmental Inspection of the Ministry of Environment of Ukraine. DSTU 4770.4:2007. Soil quality.

2.3 Methodology for phytotoxicity testing

The study used a method for assessing soil toxicity using a growth test in accordance with the methodological recommendations «Bioindication and biotesting of contaminated areas» [48].

The method involves observing the growth of a test culture in a contaminated environment compared to the growth of the same test culture in a control environment, which in this case was soil sampled from a potentially ecologically clean area, namely the Osokorky Ecopark (coordinates: 50°22'23.1‘N 30°37'51.1’E). Samples for the control sample were also selected using the envelope method.

According to the methodology, the experiment was conducted in three repetitions – with three parallel samples of the sample selected after the explosion of the UXO.

Before starting the experiment, the total soil moisture content was determined. A sample weighing m=40,45 g was taken and placed in an oven at a constant temperature of 100 °C for 1 hour and 30 minutes. After that, the dry mass of the soil was measured, which was 38,92 g. The sample was again placed in an oven at the same temperature for 1 hour, after which the mass of the soil was 38,38 g. The test sample was again placed in an oven at a temperature of 100 °C to achieve a constant mass by evaporating all moisture. After 1 hour, the dry mass was measured, which was 38,378 g.

Total moisture content was calculated using the standard formula:

$$W = \frac{m_{initial} - m_{dry}}{m_{initial}} * 100; \% \tag{2.1}$$

To prepare samples for phytotesting, 210,7 g of the soil under investigation was taken, dried for 5 hours to a constant mass of 200,4 g, and moistened to a moisture content of 26.877%.

The prepared substrate was distributed among 3 experimental containers with the following masses:

- Sample №1: m_1=52,51 g;
- Sample №2: m_2=50,85 g;
- Sample №3: m_3=52,22 g.

In the control substrate, a moisture content of 27% was achieved using a similar method. The mass of the substrate in the control sample was:

- Sample №4: m_4=47,05 g.

The prepared substrates were placed in experimental containers, namely clean plastic cups, and 15 healthy seeds of the test culture, identical in appearance, were sown. For the first 3 days, the containers were covered with glass and ventilated 3 times a day for 15 minutes.

On the fourth day, the samples were moved to the windowsill, where they received approximately 10 hours of natural light. Since the methodology requires 14 hours of continuous lighting, which is impossible to achieve with natural light in autumn, a phytolamp was used to provide 4-5 hours of light per day.

Under these conditions, the samples were kept for two full weeks with the following indicators recorded:

- Plant growth and quantity (daily);
- Ground length of shoots and their daily growth;
- Characteristic changes and visible phytotoxic effects (yellowing, thinning of shoots, wilting, death)
- Total number of seeds that sprouted at the end of the experiment.

During the experiment, photographs were taken of the condition of the sprouts and a report was compiled on the condition of the seeds, sprouts and substrate.

The last day of the experiment was 27 October 2025: the final observations were recorded, and the shoots from all samples were carefully removed along with their roots to measure the length of the shoot, sprout and root.

After collecting all the necessary data, the results of the growth test were processed.

The average length of the above-ground and root parts x±m, where m is the arithmetic mean error, which is determined by the following formula:

$$m_{error} = \sqrt{\frac{\sigma^2}{N}}, \tag{2.2}$$

where *N* – amount of results,

σ^2- dispersion, which is determined by the formula:

$$\sigma^2 = \frac{\sum_{i=1}^{N}(x - \bar{x})^2}{N} \; ; \tag{2.3}$$

where *x* – value of the indicator (selected bioparameter);

$\bar{x}$ - the arithmetic mean of the indicator in the studied variant.

The reliability of the difference between arithmetic means t is calculated using Fisher's Student's t-test.:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{m_1^2 - m_2^2}}; \tag{2.4}$$

where $\bar{x}_1$ – the arithmetic mean of the indicator in the control sample;

$\bar{x}_2$ – the arithmetic mean value of the indicator in the contaminated sample;

m_1 – error of the arithmetic mean in the control sample;

m_2 – error of the arithmetic mean in the contaminated sample.

If the empirical value of the t-criterion is equal to or higher than the critical (tabulated) value t_{st}, it can be concluded that there is a statistically significant difference between the arithmetic means in the experimental and control samples. If the empirical t is less than t_{st}, the difference between the arithmetic means is considered unreliable. The absence of a statistically significant difference between the mean values of the bioparameter in the control and test samples indicates that there are no significant changes in the growth processes of bioindicators compared to the control. This suggests that the soil in the experimental sample is of similar quality to the control and does not exhibit toxic properties, and vice versa – the presence of a statistically significant difference indicates the phytotoxic properties of the studied samples.

The phytotoxic effect is determined as a percentage based on a specific biometric parameter: in this experiment, the biometric parameters were the average height of shoots, root length and dry weight of plants. The phytotoxic effect is determined using the following formula:

$$PE = \frac{M_0 - M_x}{M_0} * 100, \% \qquad (2.5)$$

where M_0 – the value of a specific bioparameter in a container with a control sample;

M_x – the value of this same bioparameter in the container with the test (contaminated) sample.

2.4 Methodology for conducting acute toxicity testing

Acute toxicity studies of samples were conducted by the laboratory of the Department of Translational Medical Bioengineering, Faculty of Biomedical Engineering, Igor Sikorsky Kyiv Polytechnic Institute.

The study was conducted on *Danio rerio* (zebrafish) embryos in accordance with the international OECD Guideline 236 'Fish Embryo Acute Toxicity (FET) Test' (OECD, 2013). The methodology was adapted and validated for the laboratory conditions of the Department of Translational Medical Bioengineering of the Faculty of Biomedical Engineering, as confirmed by validation report №01/2025 dated 09.09.2025.

The validation results showed that the method ensures the reproducibility of embryo viability indicators in accordance with OECD 236 criteria. During the test, the reference compound 3,4-dichloroaniline (3,4-DCA) was used, for which the LC_{50} value (96 hours) = 2,4 mg/L was obtained, which corresponds to the recommended sensitivity range (2,0–4,0 mg/L).

Danio rerio embryos were obtained through natural spawning of healthy sexually mature fish. Selected fertilised eggs (no later than 2 hours after fertilisation) were washed in distilled water and placed 1 embryo per cell in a 24-well microplate. The volume of the exposure medium was 2 ml per well.

Water extracts of soil before and after detonation were used as test samples. To obtain extracts, 300 g of soil samples were mixed with 750 ml of distilled water in a 1:4 ratio and kept for 24 hours at 25 ± 2 °C in a BIOSAN ES-20/60 orbital shaker-incubator with stirring at 50 rpm, after which they were filtered through a paper filter. The resulting extracts were diluted to the required concentrations. Dilutions of 1:1 with water and 1:3 with water were used. Pure distilled water served as a negative control. A positive control with a fixed concentration of 4 mg/l of 3,4-dichloraniline was also used for comparison.

The embryos were exposed in test media for 96 hours at a temperature of 26±1°C and a light regime of 14:10 (light:darkness). The medium was replaced or supplemented daily. Observations were made 24, 48, 72 and 96 hours after the start of exposure.

The criteria for embryo viability according to OECD 236 were:

- embryo coagulation (clotting);
- absence of heartbeat;
- absence of separation of the tail section;
- absence of somite formation.

The proportion of non-viable embryos in each group was determined. Statistical processing of the results was performed using Microsoft Excel software and the R environment.

2.5 Methodology for phytoremediation

Phytoremediation technology is one of the simplest ways to restore contaminated soil, so the main task is to select the right phytoremediation plant for a specific type of contamination.

The first step is to conduct a physical and chemical analysis of the substrate from the affected area, determining the concentrations of potential contaminants in order to select an effective approach.

After determining the level of contamination, 1 kg of soil was taken from the affected area for laboratory testing and crushed with a hammer. After that, it was necessary to remove metal fragments from the explosive device. The soil was then placed in a 3 dm^3 container, in which holes had been drilled in the bottom to prevent water stagnation during watering.

The soil was watered three days before sowing to soften it and achieve a uniform structure, but due to complex damage, the substrate still remained mostly clumped together.

The selected phytoremediant was sown on the prepared substrate to a depth of 2-0 cm, and the container was placed in a location with direct access to daylight.

During the experiment, a report was kept on observations of plant development and substrate changes with photo documentation.

Two weeks after the start of the experiment, most of the sprouts had died and a musty smell was coming from the container, so the experiment had to be interrupted and a new one started.

Similarly, three containers with contaminated soil with a volume of 1,1 dm^3 were prepared. Two different crops were sown: peas were planted in one container, and Indian mustard with the addition of a mycorrhizal preparation and a mycorrhizal preparation with biohumus were planted in containers 2 and 3, respectively.

The experiment lasted two months, during which regular records were kept on the condition and changes in plant growth with photographic documentation.

On the last day of the experiment, the container with the highest biomass growth was selected for further study. The biomass was removed, cleaned of substrate and sent to the laboratory for chemical analysis of heavy metal content. Soil after phytoremediation was also sent for testing for heavy metal content.

Data processing

Based on the results of laboratory tests, we can calculate **the effectiveness** of phytoremediation using the following formula:

$$E = \frac{C_0 - C_f}{C_0} * 100, \% \qquad (2.6)$$

where C_0 – initial metal concentration in soil, mg/kg;

C_f – final concentration of metal in soil after phytoremediation, mg/kg.

We calculate **the amount of metal extracted from the soil** using the formula:

$$M_{ext} = (C_0 - C_f) * m_{sample} \qquad (2.7)$$

where C_0 – initial metal concentration in soil, mg/kg;

C_f – final concentration of metal in soil after phytoremediation, mg/kg;

m_{sample} – mass of soil on which phytoremediation was carried out, kg.

The absolute mass of metal in plant biomass is determined using the following formula:

$$M_{ab} = C_p * B_{dry} \qquad (2.8)$$

where C_p – metal concentration in dry biomass, mg/kg;

B_{dry} – dry plant biomass output, kg.

We calculate **the extraction balance**, which is the percentage of metal that has been extracted from the soil and actually absorbed by plants:

$$R = \frac{M_{ab}}{M_{ext}} * 100, \% \tag{2.9}$$

We calculate **the bioaccumulation coefficient**, which is one of the most important parameters for assessing the effectiveness of phytoremediation:

$$BAF = \frac{C_p}{C_f} \tag{2.10}$$

де C_p – metal concentration in dry biomass, mg/kg;

C_f – final concentration of metal in soil, mg/kg.

We calculate the remediation speed using the formula:

$$\tau = \frac{C_0 - C_f}{t} \tag{2.11}$$

where C_0 – initial metal concentration in soil, mg/kg;

C_f – final concentration of metal in soil, mg/kg;

t – duration of the experiment in years (2 months = 2/12 = 0,167 years).

To calculate the forecast for achieving the MPC, we use the following formula:

$$T = \frac{ln(C_0/C_t)}{k} \tag{2.12}$$

where T – restoration period;

k – first-order reaction rate constant;

C_t – target concentration (MPC), mg/kg.

The speed constant is calculated using the formula:

$$k = \frac{ln(C_0/C_f)}{t} \quad (2.13)$$

2.6 Research design

To visualise the sequence of research stages, Fig. 2.1 shows a diagram of how scientific research is conducted.

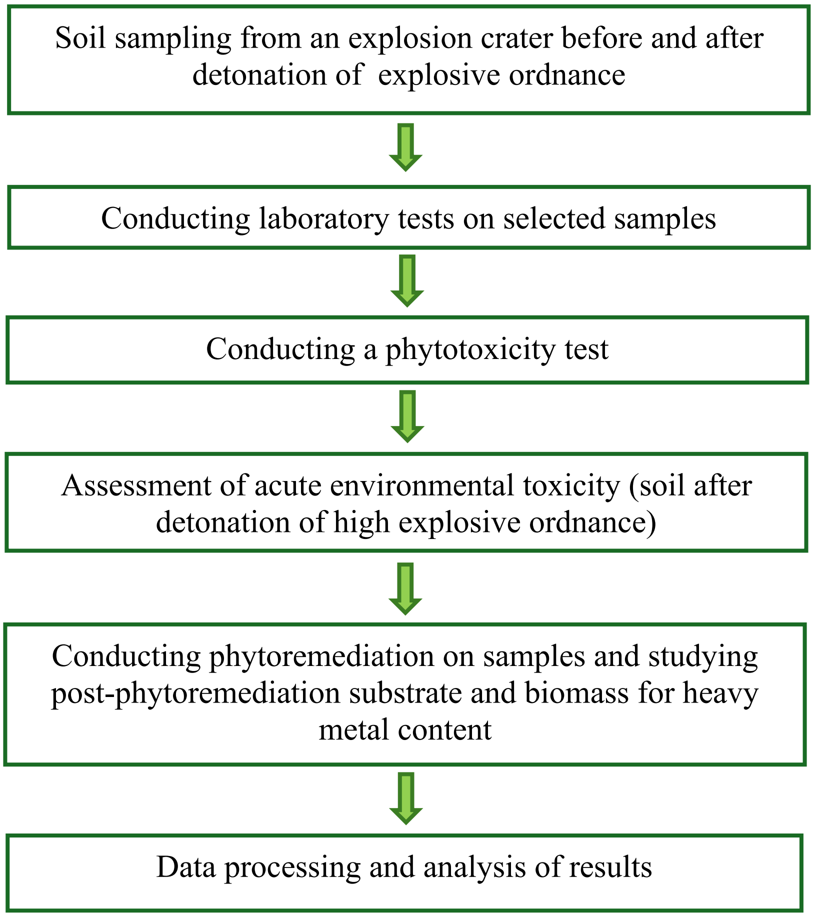

Figure 2.1 – Research design

CONCLUSIONS TO SECTION 2

1. To conduct a comprehensive study of the impact of detonation of UXO on soil, samples are taken before and after detonation of high-explosive ordnance in accordance with State Standard of Ukraine using the ‘envelope method».
2. To determine chemical contamination, both samples are analysed for heavy metals and petroleum products using approved methods. Analyses are also carried out on the substrate sample after phytoremediation and the biomass of the selected accumulator plant for heavy metals for further assessment of the effectiveness of phytoremediation.
3. To study the impact of pollution separately, a phytotoxicity test is conducted using garden cress (*Lepidium sativum*), which is standard for this method.
4. Phytoremediation is carried out over a specified period using Indian mustard (*Brassica juncea*) and field peas (*Pisum sativum*) with the addition of a complex mycorrhizal preparation, followed by chemical analysis of the soil sample with the best biomass growth for heavy metal content and corresponding calculations.

3 PHYTOREMEDIATION TECHNOLOGY FOR THE RESTORATION OF SOILS CONTAMINATED BY MILITARY ACTIVITIES

3.1 Analysis of soil samples from the explosion crater

For a comprehensive assessment of the degree of soil damage, both physical and chemical tests of the sample must be carried out. During attempts to perform compression tests on the soil, it was found that it was impossible to saturate the sample with moisture, since under the action of the explosive (shock) wave, the soil became as compact as possible. As a result of overcompaction, its pore space was significantly reduced, and it was impossible to re-saturate it with water under laboratory conditions.

Chemical soil tests were carried out by the Soil and Waste Hygiene Laboratory of the O.M. Marzieiev Institute of Public Health of the National Academy of Medical Sciences of Ukraine. The analysis was conducted for heavy metals (lead, copper, nickel, cadmium, chromium, zinc, and manganese) and petroleum products. Table 3.1 shows the results of soil sample tests taken before and after the detonation of the explosive device; the protocols are provided in Appendix 1.

Table 3.1 – Results of physical and chemical studies of soil samples affected by military operations

Indicator	**Sample №1**	**Sample №2**	**MPC, mg/kg**	**Clarks (background content)****
1	2	3	4	5
pH	5,37	5,44	-	-
Heavy metal content (gross content), mg/kg				
Pb	84,5	357,0	32,0	10,0
Cu	1,56	1,91	-	20,0
Ni	228,6	229,6	-	40,0
Cd	0,14	4,58	1,5	0,5

Table 3.1 Continued

Cr	10,6	36,6	-	200
Zn	189,1	331,6	-	50,0
Mn	129,8	255,4	100,0	100,0
Нафтопродукти, мг/кг	80,0	342,0	1000,0	

* - gross content, mg/kg (taking into account the background (clarification) in accordance with "Hygienic regulations for the permissible content of chemicalnsubstances in soil" (approved by order of the Ministry of Health of Ukraine dated 14 July 2020 No. 1595, registered by the Ministry of Justice on 31 July 2020 under No. 722/35005);

** - background content of chemical elements in soil according to A.P. Vinogradov.

The results show that the soil under study has an acidic environment with a pH of 5.37 in the first sample and a pH of 5.44 in the second sample. An acidic environment increases the solubility of metals, which in turn increases their bioavailability.

Comparing with the maximum permissible concentrations (MPC) specified in the «Standards for maximum permissible concentrations of hazardous substances in soils, as well as a list of such substances» approved by Resolution of the Cabinet of Ministers of Ukraine №1325 of 15 December 2021 [49], we can see that some of the components analysed exceed these limits. After the explosion, an increase in the concentrations of certain metals was detected: primarily lead – a 4,2-fold increase in lead content compared to sample № 1; cadmium – a 32,7-fold increase; chromium – a 3,5-fold increase; nickel – 1,75 times; manganese – 1,97 times; petroleum products – 4,3 times.

The results obtained indicate that some indicators in the soil cannot be interpreted unambiguously with an explanation of all the properties identified, since no study of background concentrations in the soil was conducted in accordance with DSTU [47].

Sample №1 cannot serve as a control sample because the soil cover has already been mechanically disturbed.

Table 3.2 shows the MPC values according to the Hygienic Regulations for the permissible content of chemicals in soil, approved by Order of the Ministry of Health of Ukraine №1595 of 14 July 2020 [50], and the Standards for Maximum

Permissible [49] Concentrations of Hazardous Substances in Soil, as well as a list of such substances, approved by Resolution of the Cabinet of Ministers of Ukraine №1325 of 15 December 2021, for comparison, as these two documents have different purposes. Hygiene regulations are aimed at protecting human health, while the Standards are aimed at protecting the environment. In the context of assessing the contamination of agricultural land, it is necessary to proceed from the Hygiene Regulations, since the contamination of products will have an impact on the health and safety of the population.

Table 3.2 – Maximum permissible concentrations of hazardous substances in soil according to regulatory documents

Name of substance	**CAS №**	**MPC value, mg/kg, taking into account background levels (clarification) according to Hygienic Regulations**	**MPC value, mg/kg, taking into account background (clarification) according to standards**	
			Gross content	**Mobile form**
Lead (Pb)	7439-92-1	32	32	6
Copper (Cu)	7440-50-8	3		3
Nickel (Ni)	7440-02-0	4		4
Cadmium (Cd)	8048-07-5	1,5	3	0,7
Hexavalent chromium (Cr)	18540-29-9	0,05	0,05	6
Zinc (Zn)	7440-66-6	23		23
Manganese (Mn)	7439-96-5	1500	1500	140
Petroleum products		1000	500	

The lead concentration in the first sample exceeds the MPC by 2,6 times, and in the second sample by 11,2 times. Since the type of explosive device is unknown, it can be assumed that the contamination with lead and petroleum products was caused by the explosion of a drone. However, if it was a conventional mortar shell, which excludes potential increases in the concentrations of certain heavy metals and petroleum products, it can also be assumed that the soil was previously contaminated, as agricultural soils in Ukraine are typically contaminated with lead due to the use of fuel for agricultural machinery with added tetraethyl lead, which was common practice in the last century. Over time, due to infiltration, the contamination reached deeper layers of soil, which were exposed during the detonation of the explosive device. Lead is classified as a carcinogen and mutagen, as well as a substance that exhibits reproductive toxicity in accordance with Hygienic Regulations.

The copper content in the sample is within the normal range.

We see a significant exceedance of the MPC for nickel: 57,25 times for the first and second samples. Since the values for both parallel samples are the same, it can be assumed that such contamination is caused not by an explosion from the VNP, but by previous man-made pollution. According to hygiene regulations, nickel is classified as a carcinogen and a strong sensitising chemical, so such a high content in the soil poses a danger to humans.

The cadmium concentration in the first sample is 0,14 mg/kg, which is within the normal range according to both regulatory documents. However, after detonation, the concentration increases 32,7 times and amounts to 4,58 mg/kg, which exceeds the environmental and hygienic safety levels.

The chromium level in sample № 1 exceeded the MPC (based on gross content) by 212 times, and in sample №2 by 732 times. Assumed origin – similar to the assumption regarding high cadmium concentrations.

The zinc concentration in the first sample is 189,1 mg/kg, which is 8,22 MPC, and in the second sample it is 331,6 mg/kg, which is 14,4 MPC. According to hygiene regulations, zinc is classified as a carcinogen.

The manganese content in sample №1 is 129,8 mg/kg (1,3 MPC), in sample № 2 – 255,4 mg/kg (2,6 MPC). According to Hygienic Regulations, manganese is classified as a mutagenic substance and one that exhibits reproductive toxicity.

It can be assumed that high concentrations of cadmium, chromium, zinc and manganese were caused by the explosion of the UXO, but potential contamination of deeper soil layers that were brought to the surface should not be ruled out.

Regardless of the hypotheses about the reasons for the increase in these components in the samples studied, it is a well-established fact that agricultural land is heavily polluted, which is an extremely acute problem that requires immediate solutions to ensure the safety of the population.

3.2 Conducting a phytotoxicity assessment on the soil samples

The phytotoxicity of the soil samples studied was calculated based on the results of the ‘growth test’ in accordance with the methodology [48].

To assess soil phytotoxicity, soil moisture was first determined using formula 2.1:

$$W = \frac{40{,}35 - 38{,}378}{40{,}35} = 4{,}88\%$$

The analysed sample weighing 210.7 g was also dried to a constant weight of 200,4 g, after which it was moistened to 27%. According to the methodology, the soil must be moistened to 70% humidity, but given the physical and chemical properties of the soil, which were altered as a result of the explosion, it is almost impossible to saturate the soil with water. The most optimal humidity level for this sample is approximately 27%.

The prepared sample of the analysed soil has a light chestnut colour, an oily texture at 27% moisture content and a specific persistent odour reminiscent of burnt nails. The control substrate is black-brown in colour, and its total mass consists mainly of loose lumps.

For each sowing sample, 15 healthy seeds of garden cress (*Lepidium sativum*) were selected, all of the same size, colour and hardness. Clean plastic cups were used for sowing. Sowing was carried out on 9 October 2025.

It was noted that the unpleasant odour from the affected soil samples became more concentrated and persisted until the end of the experiment. The control sample had the odour of normal soil.

The samples with contaminated soil are marked with numbers 1, 2 and 3; the control substrate is marked with sample number 4.

Observation

As of **11 October** (Fig. 3.1):

- In sample №1, 8 out of 15 seeds produced healthy roots based on external characteristics;
- In sample №2 – 7 out of 15;
- In sample №3 – 5 out of 15;
- In the control sample №4 – 6 out of 15 released the roots.

Plant development in contaminated soil was slightly faster than in the control substrate.

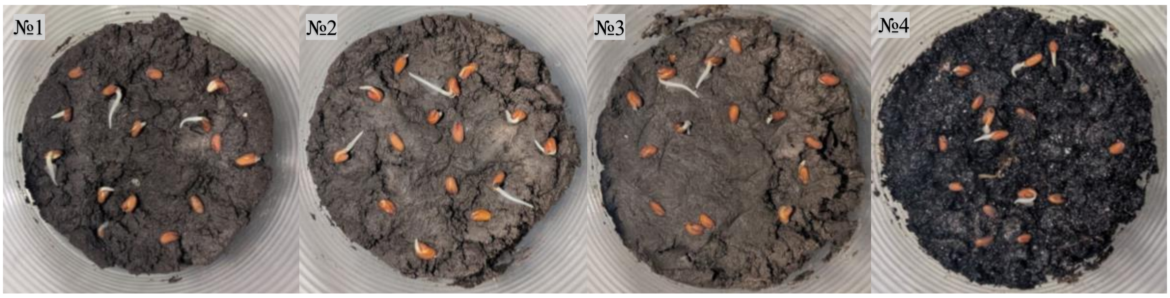

Figure 3.1 – Observation of samples №1-4 on 11 October

As of **13 October** (Fig. 3.2):

- In sample №1:
  - There are 5 healthy shoots with the following heights: h_1=12 mm, h_2=10 mm, h_3=10 mm, h_4=7 mm, h_5=3 mm;
  - 4 of them have sprouted leaves;
  - 2 are potentially dead..
- In sample №2:
  - There are 7 shoots with the following heights: h_1=14 mm, h_2=8 mm, h_3=10 mm, h_4=15 mm, $h_{5,6,7} < 3$ mm;
  - 1 shoot looks unhealthy: yellowed and wilted;
- In sample №3:

- Six shoots are observed with the following heights: h_1=14 mm, h_2=12 mm, h_3=9 mm, h_4=13 mm, h_5=4 mm, h_6 is difficult to determine because the shoot looks unhealthy – weak and thin;
- Roots have appeared in 2 seeds;
- 1 sprout is potentially diseased;

- In sample №4:
  - Six healthy shoots are observed with the following heights: h_1=9 mm, h_2=4 mm, h_3=6 mm, h_4=11 mm, h_5=8 mm, h_6=3 mm;
  - A rootlet has appeared in one seed;
  - One seed has opened.

Figure 3.2 – Observation of samples № 1-4 on 13 October

As of **14 October**, the soil of the samples studied appears to be overcompacted and waterlogged (Fig. 3.3), which could potentially cause the death of seedlings. Therefore, it was decided not to maintain the soil moisture at 27%, but to allow it to dry out in order to prevent the green mass of the plant from rotting and to increase the ability of the roots to penetrate the soil.

- In sample №1:
  - There are 5 healthy shoots with leaves (6 leaves per sprout) with the following shoot heights: h_1=13 mm, h_2=12 mm, h_3=12 mm, h_4=9 mm, h_5= 7 mm;
  - 1 shoot has significant thinning at the root and yellowed green mass;

- 3 seeds have opened: 2 of them look healthy, 1 is yellow and unhealthy;
- 1 shoot that has not straightened out has turned yellow and thinned out.

- In sample №2:
  - There are 7 sprouts with the following shoot heights: h_1=17 mm, h_2=8 mm, h_3=13 mm, h_4=15 mm, $h_{5,6,7}$ < 3 mm (5-7 have not yet unfolded, 1 of them has turned yellow);
  - 3 seeds have opened and look unhealthy.;
- In sample №3:
  - Six shoots are observed with the following heights: h_1=20 mm, h_2=11 mm, h_3=12 mm, h_4=14 mm, h_5=5 mm, h_6=7;
  - The tallest shoot with h1=20 mm is turning yellow, its root is weakening because it cannot penetrate the soil due to compaction.
  - 5 seeds have opened;
  - A root has appeared in 1 seed.
- In sample №4:
  - Six shoots are observed, two of which already have six leaves each, with the following heights: h_1=8 mm, h_2=7 mm, h_3=7 mm, h_4 = 5 mm, h_5=12 mm, h_6 =15 mm;
  - A rootlet has appeared in one seed.

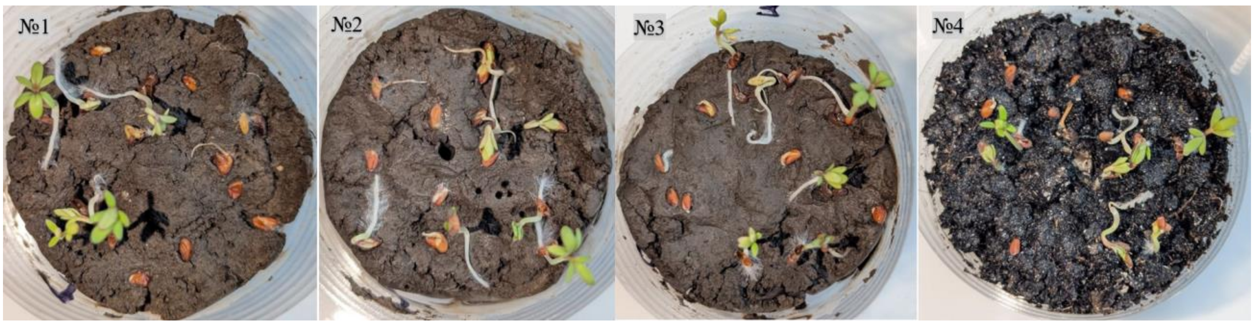

Figure 3.3 – Observation of samples №1-4 on 14 October

As of **15 October**, in samples №1-3, due to soil compaction, the substrate shrinks in volume as it dries, turning into a solid mass without air gaps, which makes it impossible for plant roots to penetrate the thickness of the sample. The observations are shown in Fig. 3.4.

- In sample №1:

- There are 4 healthy shoots with leaves (6 leaves per sprout) with the following shoot heights: h_1=13 mm, h_2=20 mm, h_3=14 mm, h_4=8 mm;
- 1 shoot has wilted;
- 2 shoots have fallen: the root collar and root show signs of drying out;
- 4 seeds appear non-viable;
- the shoot with h_4=8 mm has the longest root (more than $l_4 > 40$ mm), which can be seen through the transparent cup.

- In sample №2:

- 3 healthy shoots are observed: h_1=18 mm, h_2=15 mm, h_3=15 mm;
- 2 shoots have an unhealthy, withered appearance;
- 2 shoots have died;
- 2 seeds with roots have a yellowed, weak appearance;
- 2 roots are visible at the bottom – $l_{1,2} \approx 25$ mm, from which it is impossible to determine the origin of the sprouts.

- In sample №3:

- There are 5 shoots with leaves: h_1=20 mm, h_2=17 mm, h_3=7 mm, h_4=13 mm, h_5=7 mm (1 of the 6 leaves is completely yellow);
- 1 shoot is lying down, potentially healthy, leaves do not open;
- 4 seeds have roots (1 of them is yellow);
- 4 healthy roots are observed on the seedling;

- In sample №4:

- There are 7 shoots, 1 of which has unopened leaves: h_1=16 mm, h_2=17 mm, h_3=11 mm, h_4=7 mm, h_5= 16 mm, h_6=13 mm;
- h_7=5 mm – lying, with a thin root.

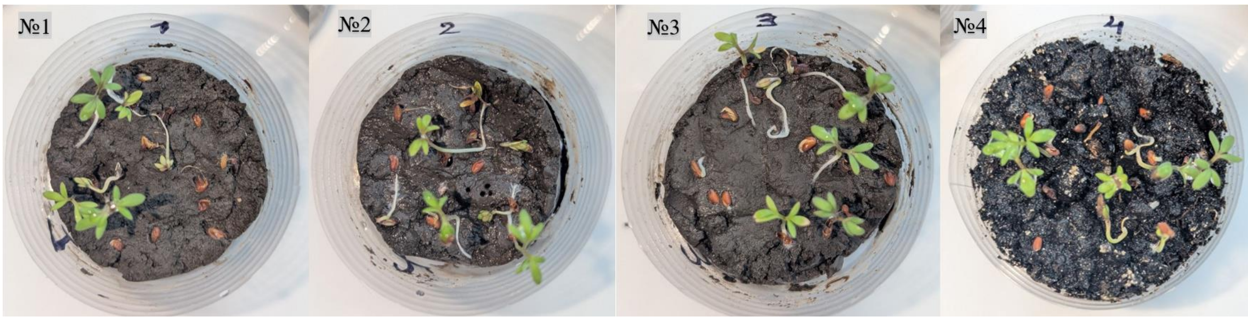

Figure 3.4 – Observation of samples № 1-4 on 15 October

As of **16 October** (Fig. 3.5):

- In sample №1:
  - There are 5 shoots, 3 of which are healthy with 6 leaves each: h_1=13 mm, h_2=15 mm, h_3=12 mm; 1 shoot looks unhealthy: h_4=9 mm; 1 shoot is lying down and has a thin root h_5=5 mm;
  - 1 shoot is withered, its root is dry;
  - 4 seeds appear to be non-viable;
  - 1 seed has sprouted a root.
- In sample №2:
  - 3 healthy shoots are observed: h_1=20 mm, h_2=15 mm, h_3=17 mm;
  - 3 seeds with dead roots;
  - 2 dead shoots;
  - 1 seed with a healthy root.
- In sample №3:
  - 5 shoots with the following heights are observed: h_1 =14 mm, h_2=15 mm, h_3 =9 mm (has the largest leaves), h_4 =11 mm, h_5 =4 mm;
  - 1 shoot with a slender root and unopened leaves;
  - 1 seed with a dead root;
- In sample №4:
  - There are 7 healthy shoots with the following heights: h1=11 mm, h2=13 mm, h3=15 mm, h4=11 mm, h5= 13 mm, h6= 4 mm, h7= 5 mm;

- 3 seeds with healthy roots;
- The soil in this sample is loose and loamy.

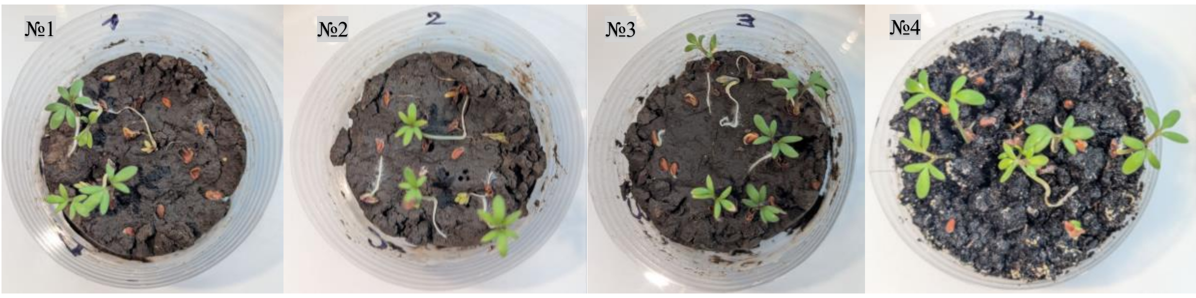

Figure 3.5 – Observation of samples №1-4 on 16 October

As of **17 October**, when watering the soil in samples № 1-3, water remains on the surface of the substrate with minimal saturation. The observations are shown in Fig. 3.6.

- In sample №1:
  - 4 sprouts are observed: h_1=17 mm, h2=10 mm, h_3=12 mm, h_4=5 mm;
  - 2 shoots have died;
  - 1 seed has produced a healthy-looking root.
- In sample №2:
  - 3 wilted sprouts are observed: h_1=17 mm, h_2=12 mm, h_3=14 mm;
  - The seeds appear unhealthy.
- In sample №3:
  - There are 5 shoots: h_1=12 mm, h_2=13 mm, h_3=7 mm, h_4=14 mm, h_5=8 mm;
  - 1 seed has a healthy-looking root;
  - 1 sprout is potentially diseased;
- In sample №4:
  - 7 healthy shoots are observed with the following heights: h_1 = 17 mm, h_2=12 mm, h_3=16 mm, h_4=5 mm, h_5=6 mm, h_6=17 mm, h_7=19 mm;
  - The roots appear healthy;

- Leaves are present on all shoots and are slightly larger in size compared to the leaves on all shoots from samples № 1-3 at the same shoot height.

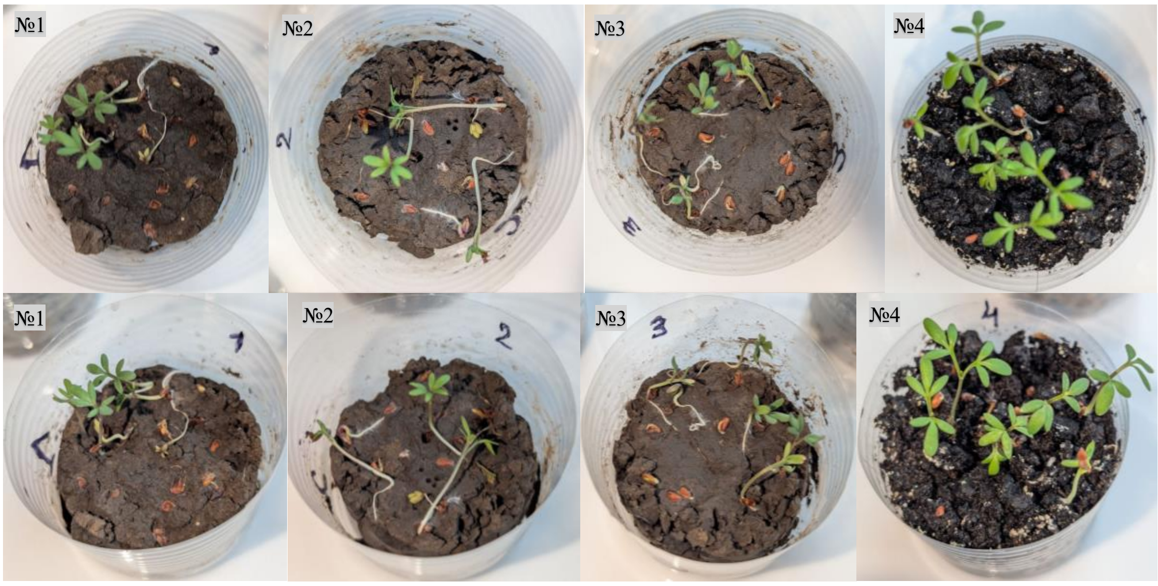

Figure 3.6 – Observation of samples №1-4 on 17 October

As of **18 October** (Fig. 3.7):

- In sample №1:
  - All 4 shoots are wilted and look unhealthy: h_1=5 mm, h_2=12 mm, h_3=17 mm, h_4=10 mm;
  - All seeds appear non-viable.
- In sample №2:
  - All sprouts have wilted;
  - No healthy seeds or roots are observed.
- In sample №3:
  - All shoots have wilted, characterised by thin roots and twisted leaves: h_1=10 mm, h_2=11.
- In sample №4:
  - There are 7 healthy shoots with the following heights: h_1=21 mm, h_2=22 mm, h_3=18 mm, h_4=9 mm, h_5=8 mm, h_6= 6 mm, h_7=19 mm

- The leaves are healthy and large compared to samples № 1-3;
- 2 seeds with healthy roots are observed.

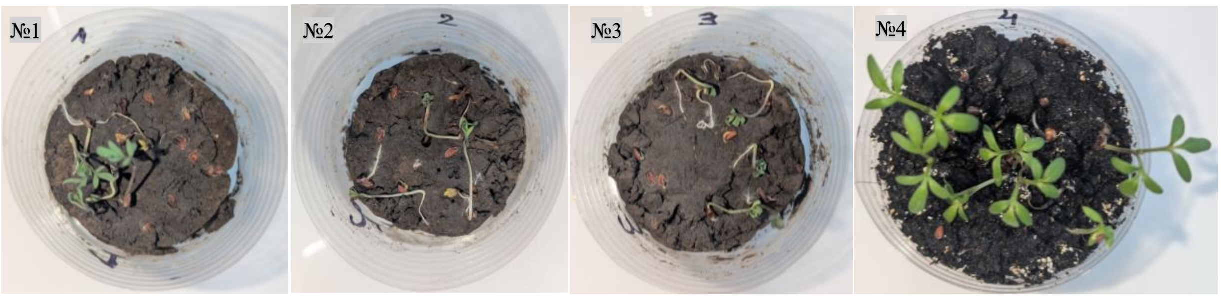

Figure 3.8 – Observation of samples № 1–4 on 18 October

As of **19 October**, watering was resumed (see Fig. 3.9):

- In sample №1:
  - After watering, the shoots rose back up: h_1=20 mm, h_2=9 mm, h_3=17 mm, h_4=5 mm;
  - One seed began to develop a root.
- In sample №2:
  - 3 sprouts have emerged: h1=16 mm, h2=19 mm, h3=12 mm.
- In sample №3:
  - 7 shoots have emerged and appear relatively healthy: h_1=16 mm, h_2=15 mm, h_3=6 mm, h_4=7 mm, h_5= 10 mm, h_6= 4 mm, h_7= 4 mm (new with unopened leaves).
- In sample №4:
  - There are 7 healthy shoots with the following heights: h_1=22 mm, h_2=22 mm, h_3=18 mm, h_4=24 mm, h_5= 12 mm, h_6= 7 mm, h_7= 20 mm;
  - All shoots are forming a second pair of leaves.

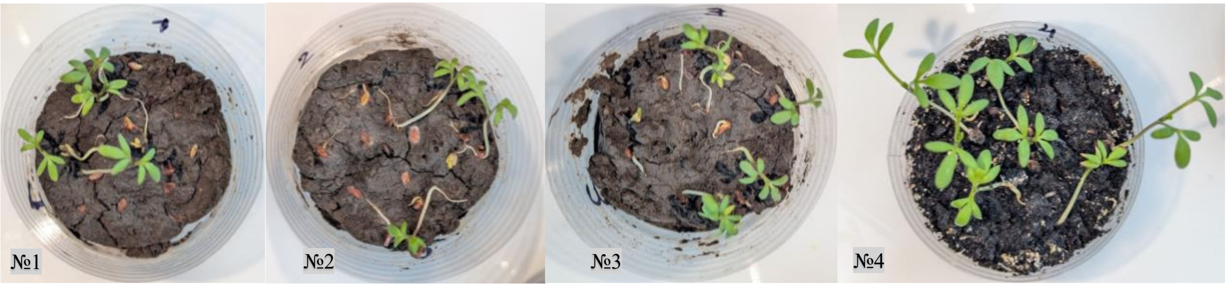

Figure 3.9 – Observation of samples № 1-4 on 19 October

As of **20 October** (Fig. 3.10):

- In sample №1:
  - 4 healthy shoots are observed: h_1=22 mm, h_2=13 mm, h_3=18 mm, h_4=6 mm;
  - 1 seed has a healthy root.
- In sample №2:
  - 4 healthy shoots are observed: h1=17 mm, h2=19 mm (second pair of leaves forming), h3=13 mm; h4=5 mm (has unopened leaves).
- In sample №3:
  - There are 7 shoots: h_1=14 mm, h_2=13 mm, h_3=6 mm, h_4=10 mm, h_5=8 mm, h_6=4 mm, h_7=4 mm (has yellowish leaves that have not opened).
  - 1 sprout has a yellowed leaf.
- In sample №4:
  - There are 7 healthy shoots with the following heights: h_1=22 mm, h_2=22 mm, h_3=15 mm, h_4=24 mm, h_5= 13 mm, h_6= 12 mm, h_7=7 mm;
  - 2 shoots sprout from the seed.

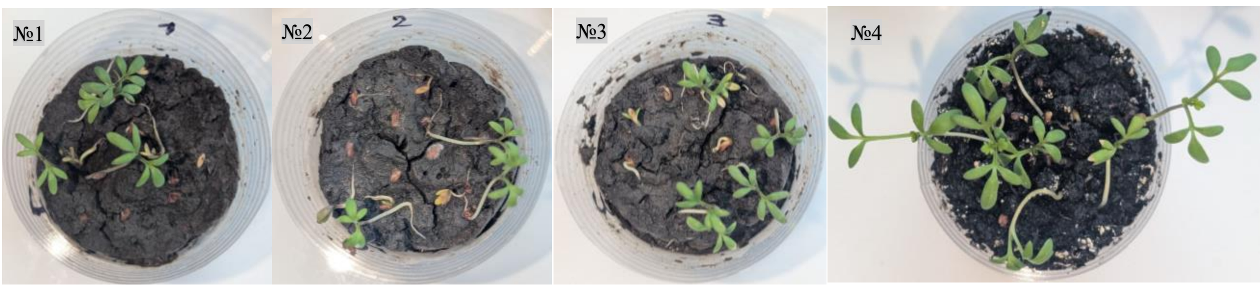

Figure 3.10 – Observation of samples № 1-4 on 20 October

As of **21 October** (Fig. 3.11):

- In sample №1:
  - 4 healthy shoots are observed: h_1=19 mm, h_2=14 mm, h_3=18 mm, h_4=10 mm;
- In sample №2:
  - 4 healthy shoots are observed: h_1=16 mm, h_2=18 mm, h_3=8 mm; h_4= 5 mm;
  - 1 seed has a fluff that is not characteristic of all other seeds.
- In sample №3:
  - 5 shoots are observed: h_1 =13 mm, h_2=15 mm, h_3=6 mm, h_4=12 mm, h_5=12 mm;
  - There are 2 developing shoots;
  - 1 seed has formed a rootlet.
- In sample №4:
  - There are 8 healthy shoots with the following heights: h_1=20 mm, h_2=19 mm, h_3=18 mm, h_4=18 mm, h_5= 15 mm, h_6= 6 mm, h_7= 20 mm; h_8= 4 mm (leaves are not opened).

Figure 3.11 – Observation of samples № 1-4 on 21 October

As of **22 October** (Fig. 3.12):

- In sample №1:
  - There are 4 shoots with the following heights: h_1=20 mm, h_2=10 mm, h_3=19 mm, h_4=1 mm.

- In sample №2:

  - 3 shoots are observed: h_1=12 mm, h_2=8 mm, h_3=8 mm;

- In sample №3:

  - There are 7 sprouts: h_1=6 mm, h_2=10 mm, h_3=13 mm, h_4=18 mm, h_5=12 mm, h_6=16 mm, h_7=5 mm.

- In sample №4:

  - There are 8 healthy shoots with the following heights: h_1=12 mm, h_2=15 mm, h_3=15 mm, h_4=14 mm, h_5= 5 mm, h_6= 5 mm, h_7= 12 mm; h_8= 19 mm.

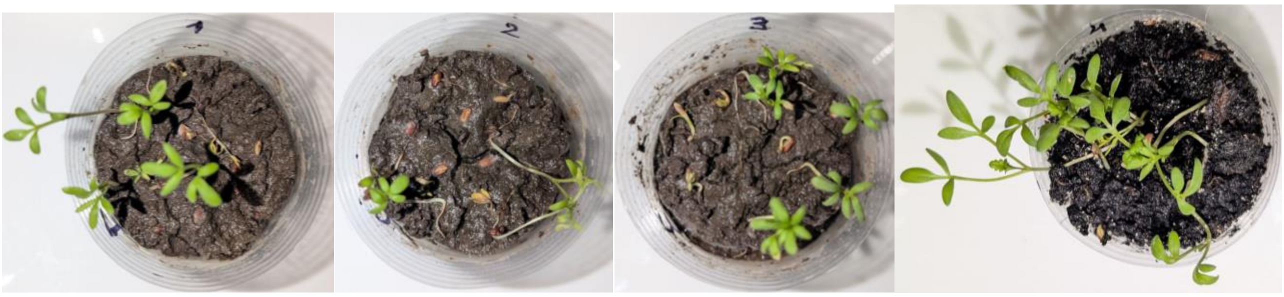

Figure 3.12 – Observation of samples № 1-4 on 22 October

As of 23 October (Fig. 3.13):

- In sample №1:

  - There are 4 healthy sprouts with leaves and shoot heights: h_1=22 mm, h_2=7 mm, h_3=20 mm, h_4=14 mm;
  - 1 sprout is unfolding from the seed;
  - 2 yellow withered sprouts are lying down.

- In sample №2:

  - Three shoots are observed: h_1=13 mm, h_2=16 mm, h_3=8 mm;
  - One sprout is wilted and lying down
  - One small sprout with open leaves is lying down;
  - 3 seeds with healthy roots are observed.

- In sample №3:

- 7 sprouts are observed: h_1=7 mm, h_2=10 mm, h_3=14 mm, h_4=18 mm, h_5= 13 mm, h_6= 16 mm, h_7= 4 mm;
- 3 sprouts are forming;
- 1 seed with a rootlet.

- In sample №4:
  - There are 8 healthy shoots with the following heights: h1=13 mm, h2=16 mm, h3=15 mm, h4=14 mm, h5= 7 mm, h6= 5 mm, h7= 14 mm; h7= 21 mm;
  - One shoot is forming;
  - One seed has a root.

№1 №2 №3 №4

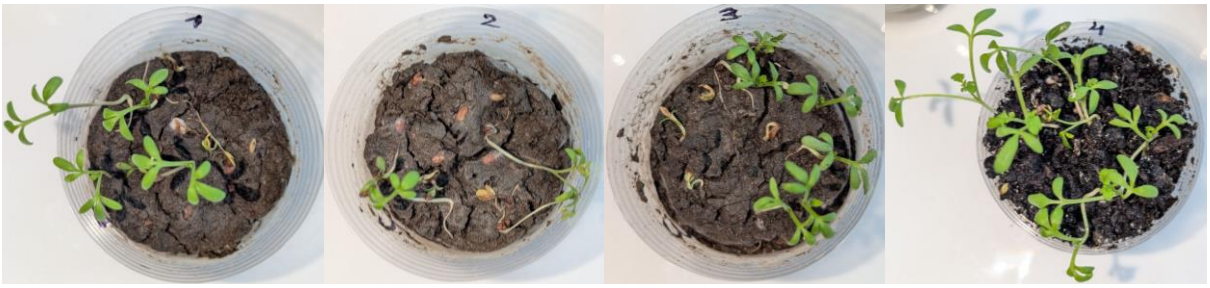

Figure 3.13 – Observation of samples №1-4 on 23 October

As of **24 October** (Fig. 3.14):

- In sample №1:
  - There are 4 shoots with leaves and shoot heights: h_1=20 mm, h_2=14 mm, h_3=20 mm, h_4=8 mm;
  - 1 shoot is developing.
- In sample №2:
  - 3 shoots are observed, two of which are severely wilted with significant thinning of the shoot and roots: h_1 =11 mm, h_2=7 mm, h_3=13 mm;
- In sample №3:

- 7 shoots are observed: h_1=8 mm, h_2=11 mm, h_3=14 mm, h_4=18 mm, h_5= 14 mm, h_6= 15 mm, h_7= 5 mm;
- 4 shoots are forming.

- In sample №4:
  - There are 8 healthy shoots with the following heights: h_1=13 mm, h_2=16 mm, h_3=15 mm, h_4=14 mm, h_5= 7 mm, h_6= 5 mm, h_7= 14 mm; h_7= 21 mm;
  - One shoot unfolds;
  - Two shoots develop from seeds.

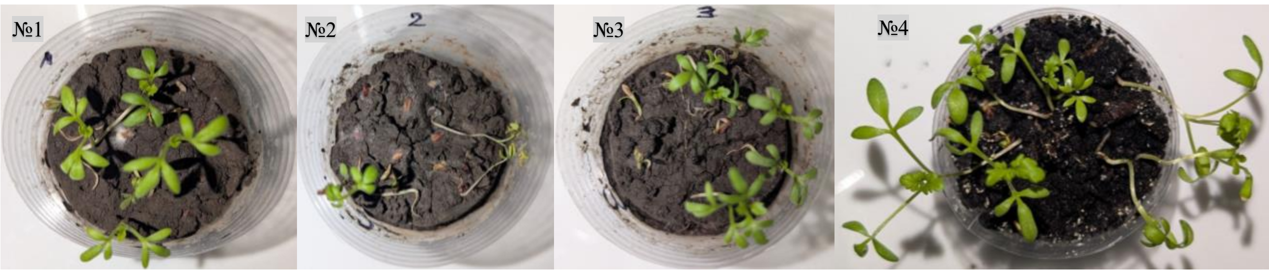

Figure 3.14 – Observation of samples №1-4 on 24 October

As of **25 October** (Fig. 3.15):

- In sample №1:
  - There are 4 shoots with leaves and a height of shoots up to the first pair of leaves: h1=21 mm, h2=14 mm, h3=10 mm, h4=18 mm;
  - All 4 have formed a second pair of leaves;
  - 1 sprout lies on the surface with an unrooted root, which looks unhealthy and shows signs of stunted growth..
- In sample №2:
  - Two shoots appear unhealthy: h_1=7 mm, h_2=21 mm (show signs of previous root growth inhibition and necrosis of the root lying on the surface);
  - Two shoots are wilted and lying on the soil surface.
  - One shoot is observed developing from a seed..

- In sample №3:

- There are 7 sprouts: h_1=17 mm, h_2=15 mm, h_3=10 mm, h_4=12 mm, h_5= 4 mm, h_6= 6 mm, h_7= 10 mm;
- 4 sprouts develop from seeds;
- 1 developing sprout has a dead unrooted root, the growth of which was previously suppressed.

- In sample №4:

- There are 8 healthy shoots with the following heights: h_1=16 mm, h_2=17 mm, h_3=17 mm, h_4=20 mm (has the most leaves), h_5= 18 mm, h_6= 15 mm, h_7= 7 mm; h_8= 8 mm;
- Together with the leaves, the height of the shoots increases by an average of 18 mm from the height of the shoots;
- 3 shoots develop from the seed;
- 7 of the 8 shoots have a second pair of leaves;
- The second pair of leaves has a different shape compared to the first pair.

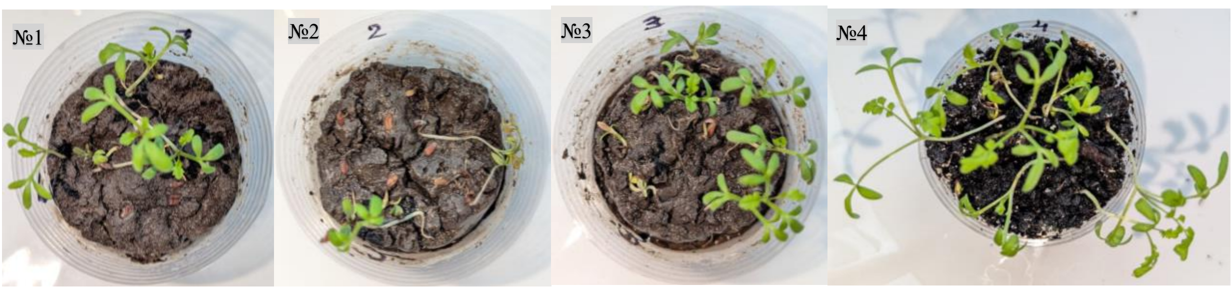

Figure 3.15 – Observation of samples №1-4 on 25 October

As of **26 October** (Fig. 3.16):

- In sample №1:

- Six shoots with leaves are observed, with shoot heights up to the first pair of leaves: h_1=10 mm, h_2=4 mm (has unopened leaves and a yellowish shoot), h_3=20 mm, h_4=22 mm, h_5=14 mm, h_6=3 mm.

- One sprout lies on the surface with an unrooted root, which looks unhealthy and shows signs of stunted growth..

- In sample №2:
  - 2 shoots appear unhealthy: h_1=7 mm, h_2=22 mm (shows signs of previous root growth inhibition and necrosis of the root lying on the surface);
  - 1 sprout developing from the seed is observed.

- In sample №3:
  - 8 sprouts are observed: h_1=15 mm, h_2=18 mm, h_3=9 mm, h_4=7 mm, h_5=10 mm, h_6=11 mm, h_7=12 mm, h_8=2 mm;
  - Sprouts and roots are developing from 2 seeds;
  - There are 2 shoots, which have not yet levelled out.

- In sample №4:
  - 9 healthy shoots are observed with the following heights: h1 = 16 mm, h_2 =15 mm, h_3 =10 mm, h_4 =8 mm, h_5 =7 mm, h_6 =16 mm, h_7 =20 mm; h_8 =19 mm, h_9 =19 mm;
  - The sprouts have strong shoots compared to samples № 1-3, with healthy large leaves; 3 sprouts are developing from seeds.

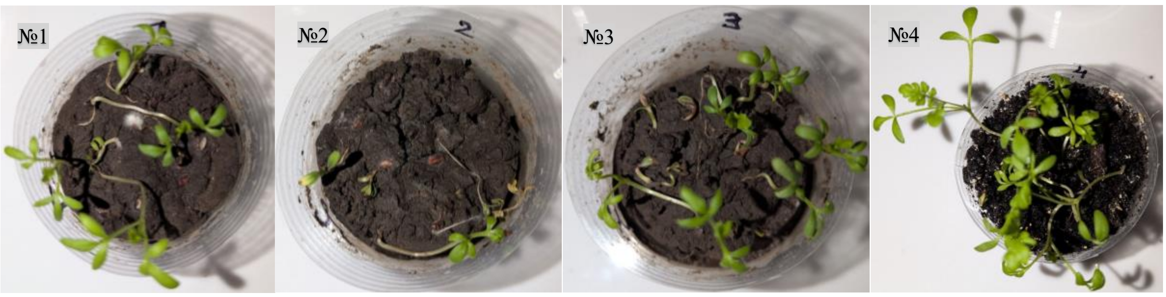

Figure 3.16 – Observation of samples №1-4 on 26 October

The last day of the experiment was **27 October 2025** (14 days after removing the glass and beginning to observe the growth of sprouts).

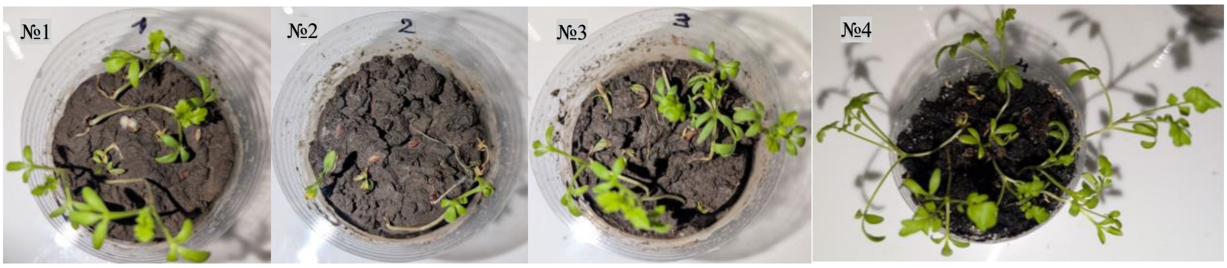

Figure 3.17 – Monitoring of samples No. 1-4 on 27 October

As of **27 October**:

- In sample №1:

  - There are 6 shoots with leaves (Fig. 3.18);
  - 4 shoots have 2 pairs of formed leaves each;
  - Four seedlings have very thin roots, dried out in places, completely unbranched, which is potentially the result of exposure to heavy metals, which inhibit root development and branching.
  - Two seedlings have roots < 1 mm, which is completely disproportionate to the level of green mass development, which is also a consequence of exposure to heavy metals.

Figure 3.18 - Plants removed from sample № 1

- In sample №2:

  - There are 3 shoots (Fig. 3.19);
  - The roots are thin and unbranched;
  - The root of the smallest shoot is not formed;

- The leaves are slightly wilted, one leaf on the rightmost shoot is yellow.

Figure 3.19 - Plants removed from sample № 2

- In sample №3 (рис. 3.20):

- There are 7 sprouts that look healthy;
- 4 out of 7 have a second pair of leaves;
- There are 4 sprout embryos with leaf buds and roots <1 mm (2 are blackened, 2 are yellowish);
- Root branching is present in only 1 sprout (5th from right to left);
- The leaves of all sprouts are very easy to tear off, and the shoots and roots are also easily damaged.

Figure 3.20 - Plants removed from sample №3

- In sample №4:

- There are 9 healthy shoots with leaves (Fig. 3.21);
- The roots are well branched in all shoots and look healthy;
- In 4 of the 9 shoots, a third pair of leaves is forming;
- In 3 of the 9, there are two pairs of leaves;
- One of the nine (the smallest) has a second pair of leaves forming;
- The leaves and shoots are fleshy and strong;
- The leaves are large.

Figure 3.21 - Plants removed from sample № 4

We can clearly see that the sprouts in control soil sample No. 4 are significantly more developed in terms of green mass and roots: we see larger leaves compared to samples No. 1-3, in greater numbers per sprout, and healthy, proportionate roots with branched lateral roots. For comparison, Figures 3.22 and 3.23 show images of the roots of sprouts from samples No. 1 and No. 4, respectively, which clearly show that the development of lateral roots of plants in contaminated substrate was inhibited by heavy metals. It is also possible to note slower growth and development compared to samples № 1-3; faster growth in contaminated samples may be due to the presence of petroleum products, which could act as growth stimulants.

Figure 3.22 - Roots of a sprout from sample № 1

Figure 3.23 - Roots of a sprout from sample №4

General data necessary for assessing the phytotoxic effect, namely the total length of shoots in the sample, the length of shoots and the length of roots, are given in Table 3.3.

Table 3.3 – Phytotesting results

	Sample №1			**Sample №2**			**Sample №3**			**Control sample №4**		
Sprout, №	Plant height, H, mm	Root length, l, mm	Sprout height, h,mm	Plant height, H,mm	Root length, l, mm	Sprout height, h, mm	Plant height, H, mm	Root length, l, mm	Sprout height, h, mm	Plant height, H, mm	Root length, l, mm	Sprout height, h, mm
1	35,00	22	21,00	12	8	6,00	17,00	4	11,00	13,00	14	3,00
2	27,00	23	17,00	29	19	20,00	19,00	19	9,00	20,00	26	6,00
3	23,00	36	11,00	11	1	7,00	29,00	22	18,00	51,00	25	20,00
4	38,00	21	25,00	0	0	0	33,00	34	22,00	36,00	21	19,00
5	7,00	0,5	5,00	0	0	0	16,00	21	10,00	49,00	29	24,00
6	7,50	2	3,50	0	0	0	18,00	16	11,00	29,00	12	17,00
7	0	0	0	0	0	0	30,00	24	18,00	25,00	36	15,00
8	0	0	0	0	0	0	0	0	0	45,00	24	19,00
9	0	0	0	0	0	0	0	0	0	26,00	28	6,00
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
x̄	**9,17**	**6,97**	**13,75**	**3,47**	**1,87**	**11,00**	**11,57**	**10,00**	**14,14**	**19,60**	**14,33**	**14,33**
Dry weight of sprouts												
m,g	**0,0217**			**0,0085**			**0,0352**			**0,053**		

The visualization of the dynamics of changes in the heights of shoots in each sample is shown in Fig. 3.24

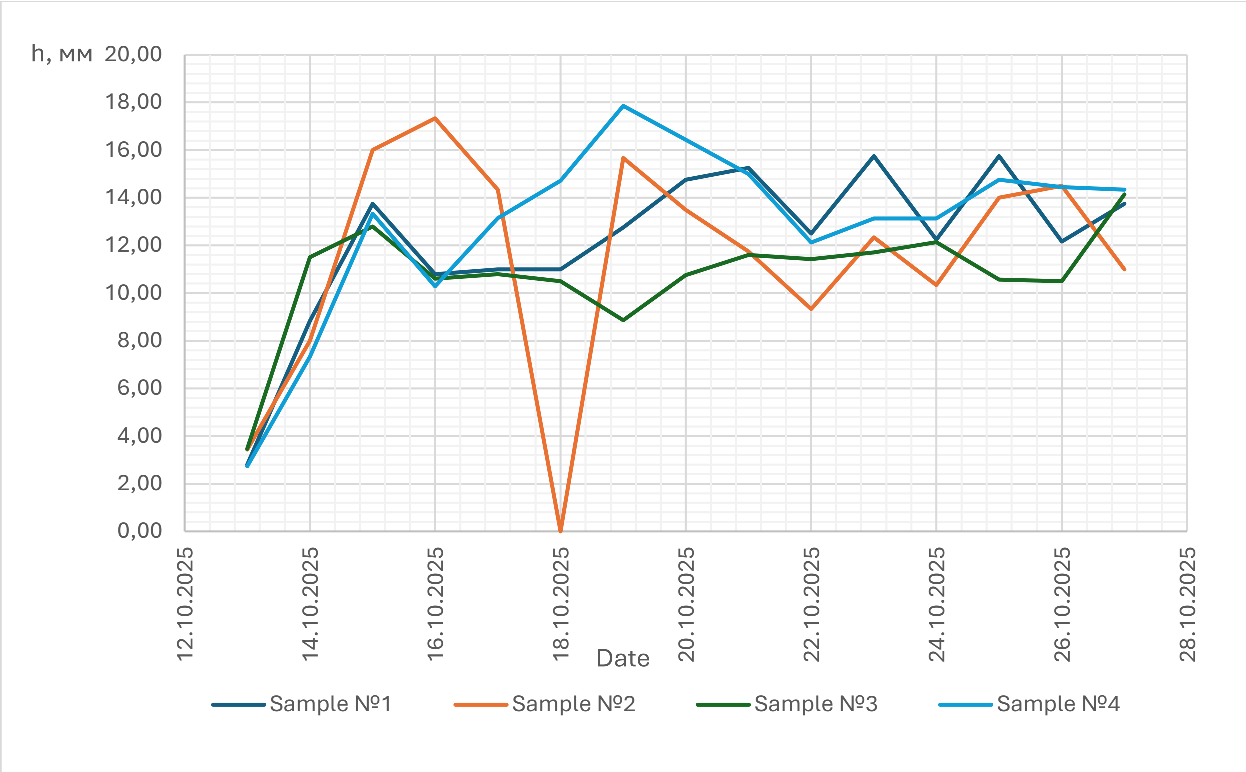

Figure 3.24 – Change in shoot height in samples № 1-4 during the experiment between 13 and 27 October

The height of the shoots is not an accurate indicator during the experiment, since the visible above-ground part of the plant is measured before the leaves grow, but based on the dynamics, we can say that the plants from samples № 3 and №. 4 behaved most stably. We also see that as of 16 October, all curves were sharply downward, which coincides with the moment of substrate oversaturation with moisture, which had a negative effect on the plants. The sharp drops in samples № 1-3 are associated with the appearance of new shoots or the death of existing ones. We can also note the lack of dynamic change in shoot height for samples 3 and 4 after 20 October, which is most likely due to the reduction in daylight hours, since other conditions did not change.

We can see that the curve representing the height of shoots in sample № 2 does not show stable development. It is important to note that sample №. 2 showed the most growth in the first days of the experiment, which may have been caused by the influence of the pollutants under study, which caused excessive activity. In general, the heights of healthy plants in this sample changed daily, which is associated with the toxic effect of pollutants, as the plants often wilted and died. A similar trend is observed in sample № 1.

Such a significant difference between the three samples may be caused by insufficient averaging of samples during selection, since in this case it was almost impossible to mix the selected samples for homogenisation due to the 'baked' nature of the soil clumps, which potentially have different chemical compositions on their surface and inside the clump.

For additional visualisation of plant growth dynamics, Fig. 3.25 shows the number of sprouts in each sample on a given day.

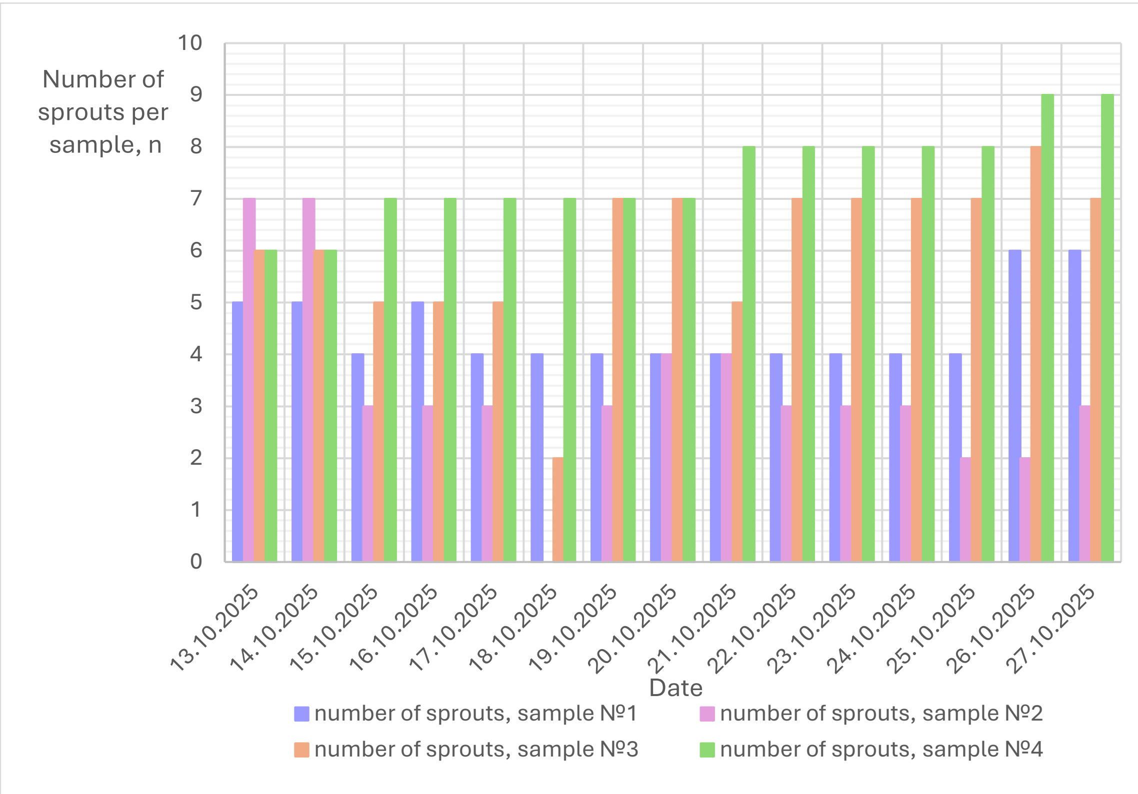

Figure 3.25 – Dynamics of changes in the number of sprouts in each sample during the experiment between 13 and 27 October

The figure shows that stable biomass growth is characteristic of sample № 4, while for plants planted in affected soil, mortality among seedlings is clearly visible. According to the graph, the highest mortality is characteristic of sample № 2. Comparing the graphs in Figures 3.24 and 3.25, we can conclude that the highest concentrations of pollutants were found in sample № 2, which caused the greatest phytotoxic effects.

Data processing

For each experimental sample, the variance σ^2 was calculated using formula 2.3, the arithmetic mean error using formula 2.2, and the reliability of the difference between arithmetic means t using Fisher's Student's t-test using formula 2.4. This calculation was performed based on the height of the shoots and the length of the roots in each experimental container.

The results are presented in Table 3.4.

Table 3.4 – Results of calculating parameters for assessing phytotoxic effects

Sample, №	**Parameter**	**Dispersion, σ^2**	**Average $\bar{x}$+m**	**t-test**	
1	*Sprout height*	184,789	9,17±3,51	3,6105	m_1= 3,509880234
	Root length	135,082	6,97±3,00	2,9274	m_2= 3,000913441
2	*Sprout height*	61,716	3,47±2,03	6,1557	m_3= 2,028391079
	Root length	24,916	1,87±1,29	5,7998	m_4= 1,288812258
3	*Sprout height*	154,622	11,57±3,21	2,8295	m_5= 3,210625782
	Root length	132,667	10,00±2,97	1,7257	m_6= 2,97396107
4	*Sprout height*	351,440	19,60±4,84	-	m_7= 4,84038566
	Root length	166,489	14,33±3,33	-	m_8= 3,331555081

All calculated values are $t > t_{st}$ (∞;0,05)=1,96, which indicates a significant difference from the control result. However, for sample №3, the root length t=1,7257, which is below the critical value of 1,96 at a significance level of 0,05. This indicates a statistically insignificant difference between the studied bioparameter in the contaminated and control samples. However, biological inhibition of germination was observed, indicating a possible toxic effect of the soil sample, which was not statistically confirmed due to the small number of repetitions and the rather high variability of the results..

The phytotoxic effect was determined according to three bioparameters using formula 2.5 for all three samples with contaminated soil:

Sample №1:

- Based on plant height:

$$PE_1 = \frac{19,6 - 9,17}{19,6} * 100 = 53,23\%$$

- Based on root length:

$$PE_2 = \frac{14,33 - 6,97}{14,33} * 100 = 51,39\%$$

- Based on dry mass:

$$PE_3 = \frac{0,053 - 0,0217}{0,053} * 100 = 59,057\%$$

Sample №2:

- Based on plant height:

$$PE_1 = \frac{19,6 - 3,47}{19,6} * 100 = 82,31\%$$

- Based on root length:

$$PE_2 = \frac{14,33 - 1,87}{14,33} * 100 = 86,98\%$$

- Based on dry mass:

$$PE_3 = \frac{0,053 - 0,0085}{0,053} * 100 = 83,96\%$$

Sample №3:

- Based on plant height:

$$PE_1 = \frac{19,6 - 11,57}{19,6} * 100 = 40,96\%$$

- Based on root length:

$$PE_2 = \frac{14,33 - 10,0}{14,33} * 100 = 30,23\%$$

- Based on dry mass:

$$PE_3 = \frac{0,053 - 0,0352}{0,053} * 100 = 33,58\%$$

The average phytotoxic effect for each sample according to three bioparameters is:

Sample №1: $PE_{average}$ =54,56%

Sample №2: $PE_{average} = 84,42\%$

Sample №3: $PE_{average} = 34,93\%$

The average *PE* for three samples is 57,97%.

Since the control substrate was soil taken from a potentially ecologically clean area, we assume that its phytotoxicity is 0%. However, no physical and chemical analysis of the control soil was conducted, so the results obtained may be more positive.

In comparison, we see that the results of phytotests conducted in the affected substrate are extremely high, which indicates the inevitable negative impact of hostilities. The issue of such significant pollution requires an urgent response in order to prevent the further spread of pollutants.

3.3 Study of acute toxicity of the soil environment

The results of the experiment showed that the survival rate of *Danio rerio* embryos depends on the concentration of soil extracts and the duration of exposure. In the group with soil extract after explosion (Soil_after) at the lowest concentration of 0,25, there was no embryo mortality during the first 72 hours, and it was 20% at 96 hours, and by 120 hours, all embryos had died. At a concentration of 0,5, embryo death began as early as the 24th hour (20%) and gradually increased to 60% at the 120th hour. The native extract (1) caused moderate mortality, which was 50–55% by the end of exposure.

In the soil group before the explosion (Soil_before), a similar dose- and time-dependent dynamic was observed, but the overall mortality at the same concentrations was slightly lower. Thus, for a concentration of 0,25, mortality reached 65% at 96 hours and 100% at 120 hours. For a concentration of 0,5, mortality ranged from 20% at 24 hours to 60% at 120 hours. The native extract (1) caused mortality of 25–35% during exposure.

The negative control (water) showed high embryo survival: 90% remained alive until the end of the 120-hour observation period. The positive control (3,4-dichloraniline, 4 mg/L) confirmed the sensitivity of the system: embryo mortality increased from 45% at 24 hours to 65% at 96 and 120 hours.

The results of embryo mortality are shown in Fig. 3.26.

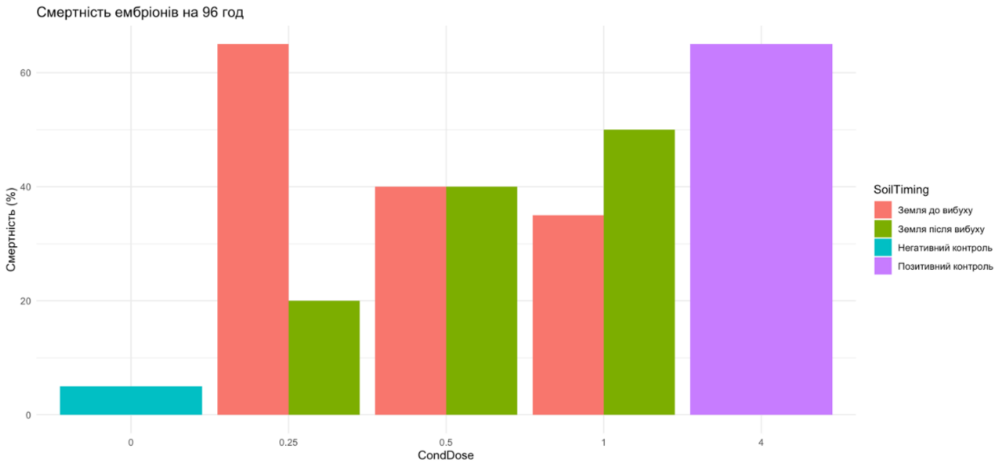

Figure 3.26 - Embryo mortality in controls and test samples throughout the experiment

The study also assessed the effect of aqueous soil extracts on the development of *Danio rerio* embryos, paying particular attention to heart rate (HeartRate), oedema (Edema) and other morphological signs (Other_sign). The study included a negative control, native extract, its dilution (1:1; 1:3) and a positive control (3,4-dichloraniline, 4 mg/dm^3).

The results showed a clearly pronounced dose-dependent toxic effect. Low concentrations of the extract did not cause significant deviations from the control values. The native extract caused isolated cases of cardiac arrhythmia, the appearance of oedema and isolated morphogenetic defects. The positive control caused pronounced cardiotoxic effects, damage to the fins and jaw, immobility of the tail, eye pigmentation disorders and combined morphological changes.

The toxicological effect obtained indicates a potential danger to terrestrial and aquatic ecosystems, as well as to human health in the event of migration of toxicants to aquifers and their entry into food chains.

For visual demonstration, Figures 3.27 and 3.28 show live and dead *Danio rerio* embryos in negative control and native extract.

Figure 3.27 – Healthy *Danio Rerio* embryo in negative control (water)

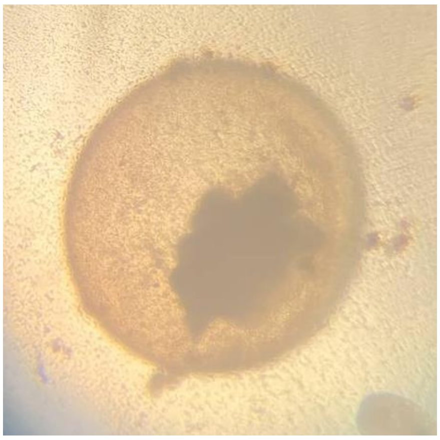

Figure 3.28 – Dead *Danio Rerio* embryo in native control

3.4 Phytoremediation of contaminated soil

Based on a literature review, Indian mustard was selected for phytoremediation of this soil. The first sowing was carried out **on 12 August 2025**: to a depth of 0,5-2 cm and on the soil surface.

General data on sowing:

Soil weghts m_{soil} = 740 g

Seed weight m_{seed}= 15 g

Moisture content W= 25%

The seeds were planted in a transparent container for further observation of the root system. The containers were placed in a room with a constant supply of fresh air, with an average temperature close to the outside air temperature. Lighting was natural – daylight, averaging 10 hours per day. Watering was carried out as the soil dried out to avoid over-watering.

Below are periodic observations of a sample taken from the crater after the detonation of an explosive projectile.

As of **14 August**, approximately one-third of the seeds had opened and begun to sprout roots, and the following day, 15 August, the first leaves were observed.

On **18 August**, formed roots were observed, but some roots were yellowish and brownish in colour, indicating stunted growth. Also, shoots formed from seeds that were planted deeper could not break through to the surface due to soil compaction. In addition, due to compaction, moisture evaporation from the soil did not occur properly, which caused stagnation and rotting of green mass in the soil (Fig. 3.29).

a b

Figure 3.29 – Observation of the phytoremediation process, 18 August

a – general view; b – visible signs of root and green mass decay

On **19 August**, condensation was observed inside the container (Fig. 3.30) and an unpleasant musty odour; watering was stopped. The beginning of decomposition of the green mass is clearly visible, as well as the formation of healthy roots reaching the bottom of the container.

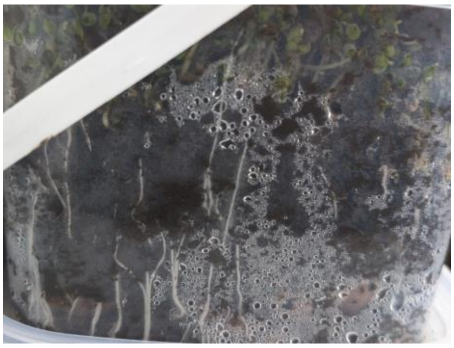

Figure 3.30 – Observation of the phytoremediation process, 19 August

As of **22 August**, wilting and drying of green mass was observed, as well as significant thinning of roots (Fig. 3.31).

Figure 3.31 - Observation of the phytoremediation process, 22 August

It was decided to start a new experiment on 3 samples:

- Container № 1 with contaminated soil with the addition of 3 g of mycorrhizal agent; phytoremediant – Indian mustard (*Brassica juncea*);
- Container № 2: 1/4 biohumus + 3/4 sample with the addition of 10 g of mycorrhiza; phytoremediant – Indian mustard (*Brassica juncea*);
- Container № 3: 1/4 vermicompost + 3/4 sample with the addition of 10 g of mycorrhiza; phytoremediant – field peas (*Pisum sativum*) planted in the amount of 15 seeds pre-soaked in water for 2 hours.

In all subsequent figures showing observations of three samples, the samples are arranged in order 1-3 from left to right.

Composition of the mycorrhiza-forming preparation: *Glomus, Trichoderma harzianum, Pseudomonas fluorescens, Streptomyces sp., Bacillus subtilis, Bacillus megaterium var. phosphaticum, Bacillus muciloginosus, Enterobacter sp*.

On **25 August**, a growth test was conducted on pea seeds – growth was normal: out of 52 seeds, 45 sprouted within 2 days (germination efficiency: 86,53%).

Compared to the samples in which mustard was planted, the development of peas is very slow: as of 31 August, only 2 sprouts had formed, while in the containers with mustard, almost a quarter of the area was covered with green mass.

Figure 3.32 - Observation of the phytoremediation process, 25 August

As of 29 September, the most effective development is observed in container № 2. In container No. 1, the vast majority of seeds have died, but only this container has sprouts with large leaves compared to container № 2. There is slight growth of 4 pea shoots, the other seeds have died; dead roots are observed throughout the soil layer.

Figure 3.33 - Observation of the phytoremediation process, 20 September

On **6 October**, a significant increase in biomass was observed in containers № 1 and № 2.

The last day of the experiment was **20 October** (Fig. 3.34):

In container № 1, we see mustard sprouts with large leaves compared to container № 2; there are 21 sprouts at various stages of development. Compared to the first attempt to plant phytoremediation in contaminated soil, we can conclude that with the use of a mycorrhiza-forming agent, plant growth and development was relatively healthy.

In container № 2, we can see dense biomass from Indian mustard sprouts, which is the result of adding biohumus and a mycorrhiza-forming agent to the contaminated substrate.

In container № 3, there are only 6 pea sprouts at different stages of development, which indicates the unsuitability of using field peas (*Pisum sativum*) as a phytoremediation agent for soils affected by the combined effects of military operations.

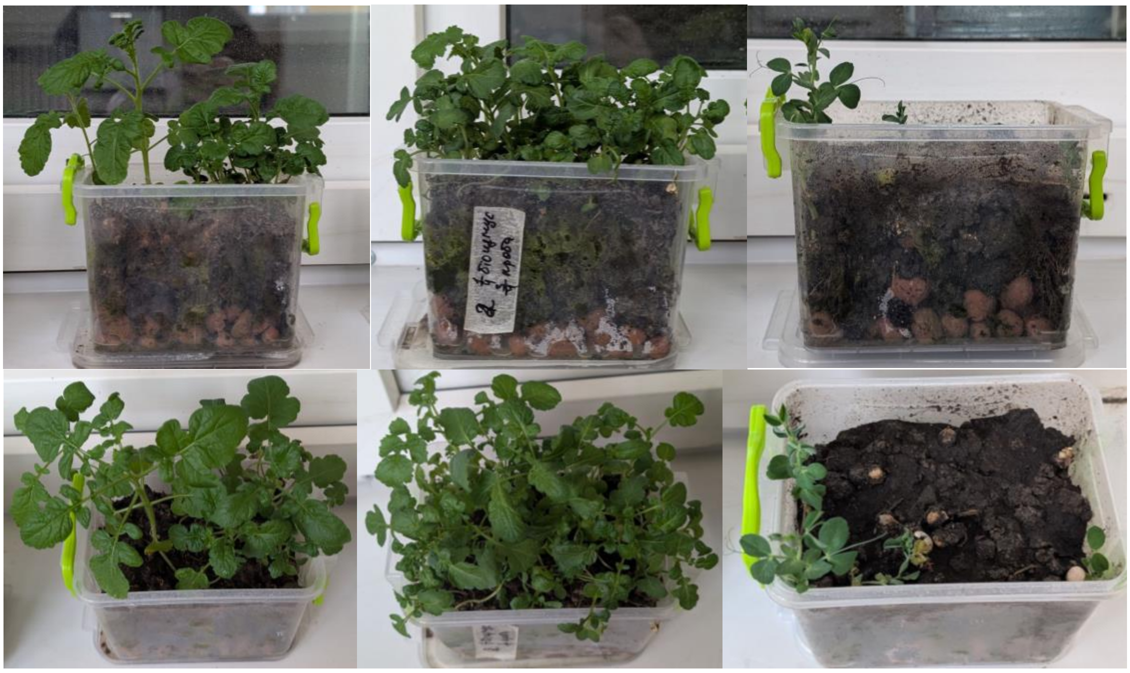

Figure 3.34 - Observation of the phytoremediation process, 20 October

To study the effectiveness of phytoremediation, biomass from container № 2 was sent to the laboratory, as it showed the highest biomass growth during the experiment.

Analysis of restored soil and biomass

Table 3.5 shows the results of soil testing for heavy metal content after two months of phytoremediation and dry biomass of phytoremediation agents. The research protocol provided by an accredited laboratory is given in Appendix 2.

Table 3.5 – Results of chemical analysis for heavy metal content in soil restored by phytoremediation and in the biomass of phytoremediation plants

Heavy metal	**Concentration in soil, mg/kg**	**Concentration in dry biomass of phytoremediation agent, mg/kg**
Lead	15,54	0,53
Copper	5,72	1,10
Nickel	15,99	9,67
Cadmium	0,48	0,17
Chromium	31,69	0,42
Zinc	52,64	3,92
Manganese	1762,7	103,2

To visualize the results and effectiveness of heavy metal removal from the soil, the bar charts below show the concentrations of heavy metals in the soil before phytoremediation, after phytoremediation, and the maximum permissible concentrations in the soil in accordance with the Hygienic Regulations.

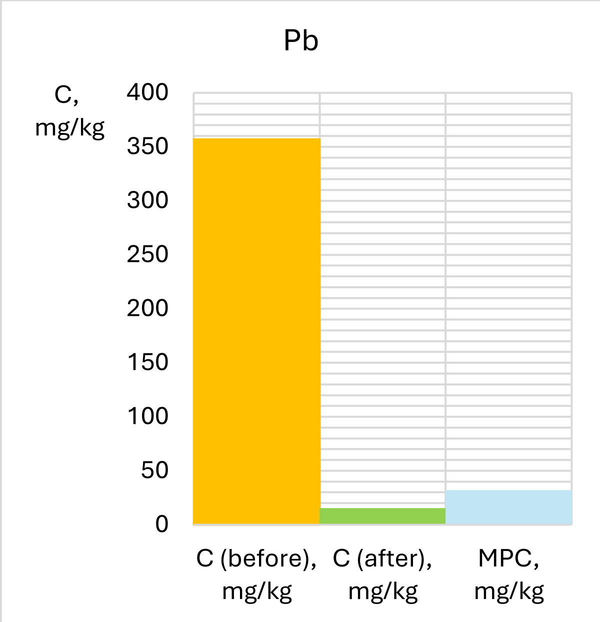

Figure 3.35 – Comparison of lead concentrations in soil before and after phytoremediation with MPC

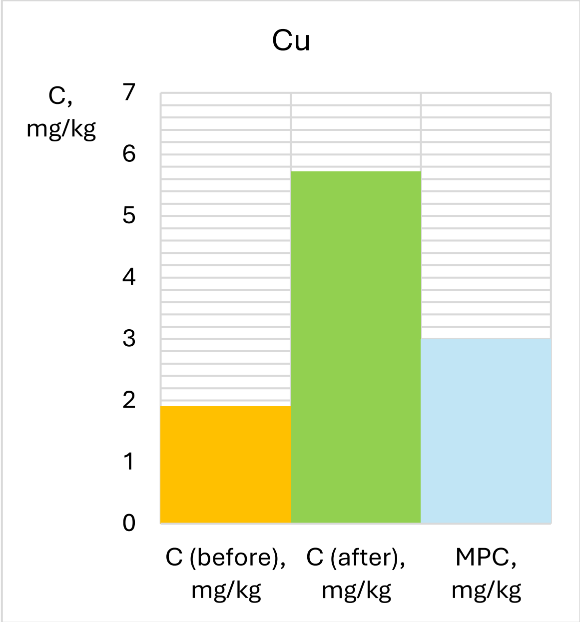

Figure 3.36– Comparison of copper concentrations in soil before and after phytoremediation with MPC

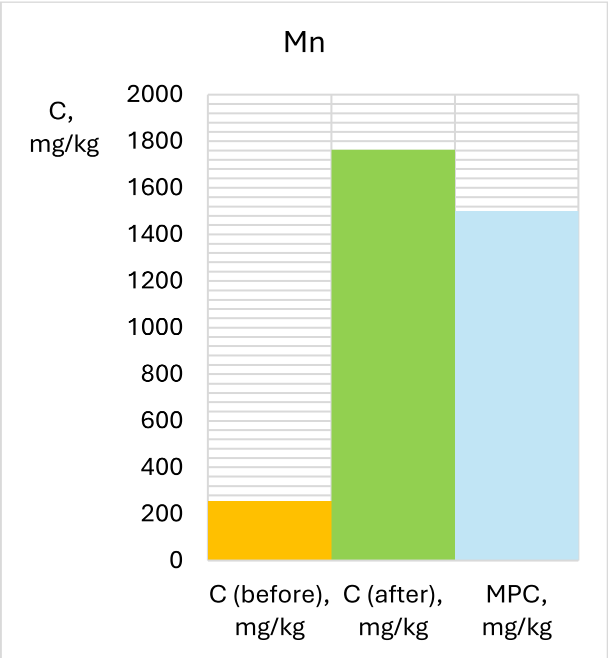

Figure 3.37 – Comparison of manganese concentrations in soil before and after phytoremediation with MPC

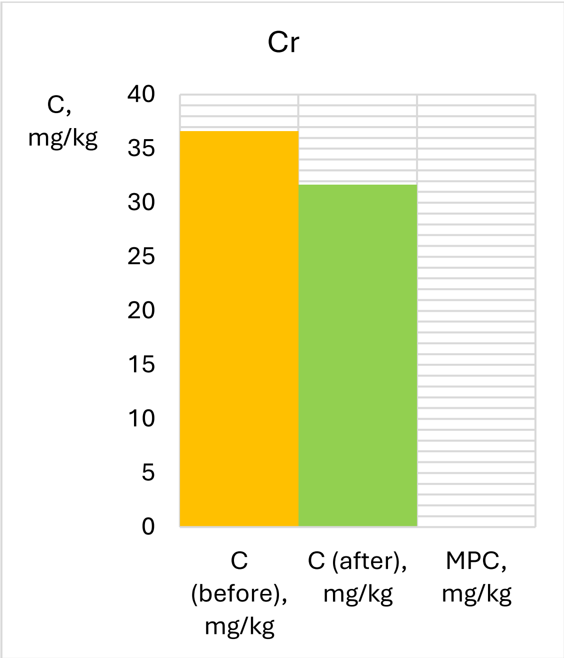

Figure 3.38 – Comparison of chromium concentrations in soil before and after phytoremediation with MPC

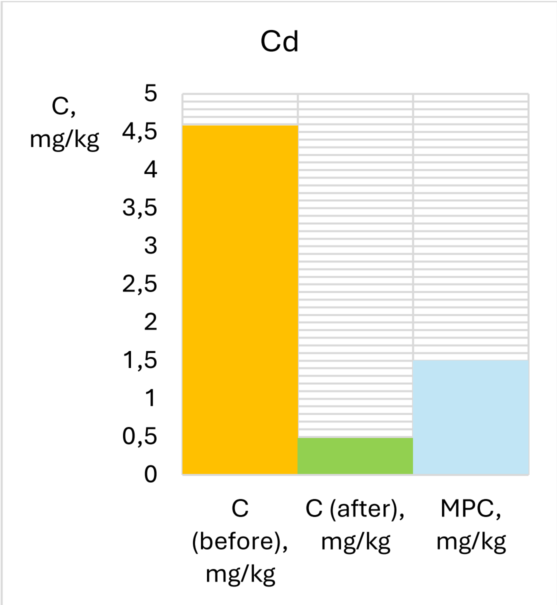

Figure 3.39 – Comparison of cadmium concentrations in soil before and after phytoremediation with MPC

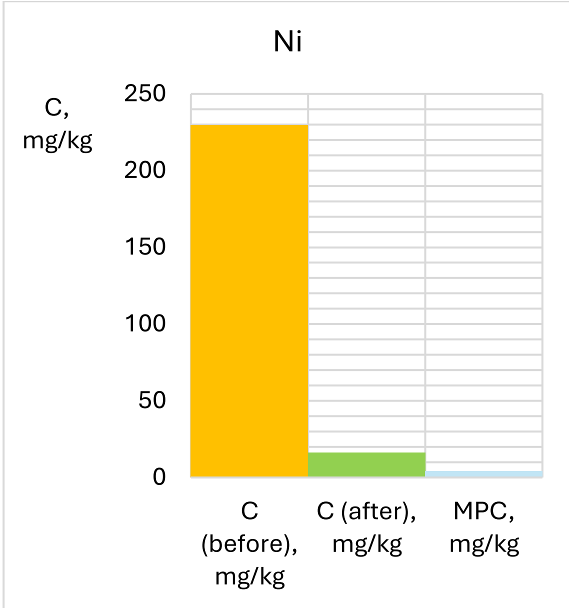

Figure 3.40 – Comparison of nickel concentrations in soil before and after phytoremediation with MPC

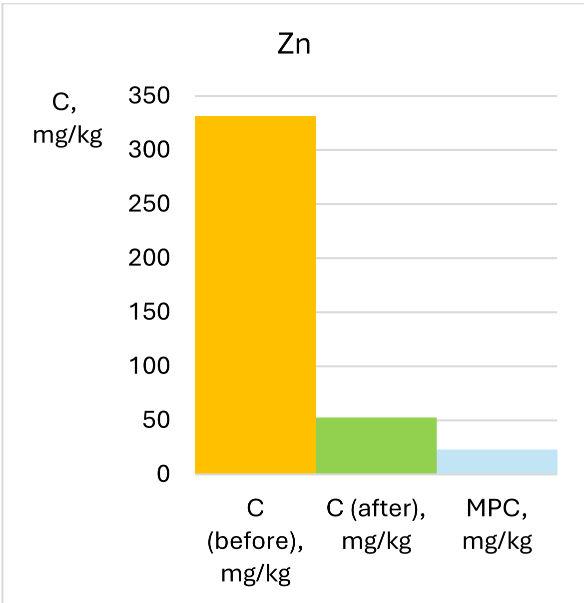

Figure 3.35 – Comparison of zinc concentrations in soil before and after phytoremediation with MPC

The results show that the standardised level of heavy metals in the soil, in accordance with the Hygienic Regulations, was achieved only for lead and cadmium. Phytoremediation for zinc and nickel also showed high efficiency in a single vegetation cycle, so MPC levels can be achieved through several cycles of planting phytoremediation plants. The complex restoration process was not effective enough to reduce chromium concentrations in the soil in one cycle, so a strategy for removing or immobilising this metal needs to be developed in order to return agricultural land to use as quickly as possible.

The results obtained for copper and manganese show that their concentration in the soil after phytoremediation has increased significantly. This may be due to several factors: the heterogeneity of the chemical composition of the samples during the initial determination of the content, since the homogenisation of the sample was insufficient due to mechanical and thermal damage to the substrate, while the soil characteristics were changed during the experiment due to the work of the plant root system, the addition of a mycorrhizal preparation and regular watering, which allowed the soil structure to become more homogeneous.

Based on the results obtained, the effectiveness of the phytoremediation, the amount of metal removed from the soil, the absolute mass of metal in the plant, the metal removal balance, and the bioaccumulation coefficient were calculated using formulas 2.6-2.13. The calculation results are shown in Table 3.6

Table 3.6 – Calculation of parameters for assessing the effectiveness of phytoremediation and predicting further metal removal from soil

Parameter/Metal	Pb	Cu	Ni	Cr	Cd	Zn	Mn
E, %	95,647	-199,476	93,036	13,415	89,520	84,128	-590,184
M_{ext}, mg/kg	252,680	-	158,071	3,633	3,034	206,475	-
M_{ab}, mg	0,007	-	0,135	0,006	0,002	0,055	-
R, %	0,003	-	0,086	0,162	0,078	0,027	-
BAF	0,034	-	0,605	0,013	0,354	0,074	-
τ, mg/(kg*year)	2048,760	-	1281,660	29,460	24,600	1674,120	-
k	18,806	-	15,986	0,864	13,534	11,044	-
T, months	1,539	-	3,040	34,731	4,005	2,900	-
T_{total}, months	3,539	-	5,040	36,731	6,005	4,900	-

where *E* – the efficiency of heavy metal removal from contaminated soil during phytoremediation, %;

M_{ext} – the amount of metal removed from the soil relative to the initial concentration, mg;

M_{ab} – absolute mass of metal absorbed by plants, mg;

R – removal balance, representing the percentage of metal that was removed from the soil and actually absorbed by plants, %;

BAF – bioaccumulation factor;

τ – remediation rate, mg/(kg*year);

k – remediation rate constant;

T – predicted period of metal removal from the soil, months;

T_{total} – total time to reach MPC, months.

The plant species under study, namely Indian mustard, demonstrated high efficiency in reducing the mobile fractions of most heavy metals in soil affected by the explosion of the UXO. The highest efficiency, 95,65%, was observed for lead removal from the soil: the initial lead concentration of 357 mg/kg was reduced to 15,54 mg/kg, resulting in a level within the MPC. Nickel is next in terms of removal efficiency – 93,04% with a reduction in the initial concentration from 229,6 mg/kg to 15,00 mg/kg, while cadmium and zinc were removed with efficiencies of 89,52% and 84,13%, respectively. Chromium showed the lowest efficiency (13,41%) due to its high mobility in the soil environment. Calculating the efficiency and other parameters for copper and manganese is meaningless due to the error of the experiment.

The bioaccumulation coefficients for all metals ranged from 0,013 (for cadmium) to 0,605 (for nickel), confirming that the selected plant acts as an excluder for all heavy metals analysed in a certain way. The proportion of metal removed from the soil that actually transferred to the phytoremediation biomass was insignificant for each metal. This proves that phytoextraction played almost no role, while phytostabilisation in the rhizosphere was likely the dominant mechanism in this experiment.

The phytoremediation plant achieved such a significant reduction thanks to several processes in the rhizosphere, which proved to be effective in soils that had been compacted as a result of the explosion. The change in pH and redox potential caused by root activity contributed to the precipitation of insoluble metal-containing compounds. It is also necessary to take into account the addition of a mycorrhizal agent, which probably had a significant impact on the behaviour of metals in the studied soil, since a single vegetation cycle lasting two months could not ensure such high efficiency in the removal of individual metals.

The mycorrhiza-forming preparation contained the following microorganisms, which perform a specific function that, in combination, affects the efficiency of plant growth and development, as well as the behaviour of elements in the substrate: *Glomus, Trichoderma harzianum, Pseudomonas fluorescens, Streptomyces sp., Bacillus subtilis, Bacillus megaterium var. phosphaticum, Bacillus muciloginosus, Enterobacter sp*.

Arbuscular mycorrhiza (*Glomus*) could play a leading role in phytostabilisation, as the hyphae of the fungus increased the absorbing surface of the root system. On the surface of the hyphae and inside them, metals were adsorbed and precipitated in the form of poorly soluble compounds [51, 52], which significantly reduced their bioavailability and generally explains the low bioaccumulation coefficients and almost zero extraction balance..

Trichoderma harzianum probably contributed to metal immobilisation due to its high adsorption capacity [53] and bioprecipitation.

In other words, the use of mycorrhizal preparations is a promising method for fixing heavy metals in contaminated soil when it is impossible to remove them by extraction. The use of microorganisms can prevent the bioaccumulation of heavy metals in agricultural products and avoid their migration through the soil profile, which will ensure the safety of groundwater and, accordingly, the safety of the population for whom groundwater is the main source of water supply.

CONCLUSIONS TO SECTION 3

1. Chemical analysis of soil samples taken before and after the detonation of the explosive device showed that metal concentrations in the soil increased 4,2 times for lead; 32,7 times for cadmium; 3,5 times for chromium; 1,75 times for nickel; 1,97 times for manganese; and 4,3 times for petroleum products.
2. The average phytotoxic effect for the sample taken after detonation of the explosive device is 57,97%.
3. During phytoremediation, the largest increase in biomass was observed in sample № 2, which contained 1/4 biohumus and 3/4 of the studied affected substrate with the addition of 10 g of mycorrhiza; Indian mustard (*Brassica juncea*) acted as a phytoremediant.
4. After conducting chemical studies of post-phytoremediation soil and spent biomass, it was found that in this experiment, the process of immobilisation of heavy metals prevails over the process of phytoextraction, since the BAF coefficients for each metal are <0,1. This is probably explained by the mechanisms of adsorption of heavy metals on the formed mycorrhizae, which prevented heavy metals from translocating into the biomass of the phytoremediant.

4 DEVELOPMENT OF A START-UP PROJECT

4.1 Using phytoremediation to recover contaminated soils

The studies conducted clearly demonstrate the negative impact of war, accompanied by soil contamination, posing a danger to the health of the population and living organisms.

The use of biological methods to cleanse the soil of various types of pollutants is economically attractive in the context of the financial situation in Ukraine, and there are numerous studies confirming the effectiveness of removing or degrading unwanted compounds in soil or water ecosystems.

The main purpose of phytoremediation is to effectively clean the soil layer in order to achieve an optimal level of safety that meets the soil quality requirements established by regulatory documents, which is especially important for agricultural areas.

The main stages of implementing phytoremediation technology to restore contaminated areas:

1. Collection of soil samples for physical and chemical analysis by an accredited laboratory owned by the landowner (interested party).
2. Conducting physical and chemical analysis of samples to determine the content of the main pollutants that could have entered the environment as a result of military actions (heavy metals, petroleum products, explosives).
3. Analysis of the results by a specialist competent in soil remediation and individual selection of a set of biological methods and a restoration period.
4. Consulting and assisting the client in implementing phytoremediation on their territory.
5. Repeated physical and chemical analysis of the soil for the content of pollutants after phytoremediation.

For a general understanding of the implementation of phytoremediation technology, a description of the start-up is given in Table 4.1.

Table 4.1 – Project description

Concept	Areas of application	Benefits for users
Implementation of phytoremediation technology in order to achieve safe levels of compounds in soils	Restoration of war-damaged soils, particularly on agricultural land	Achieving safe concentrations of pollutants in soils to ensure the safety of ecosystems and the population, in particular the safety of agricultural products to comply with state standards

For the successful implementation of phytoremediation technology, it is necessary to assess the potential threats that may arise during the implementation of the start-up, which are summarised in Table 4.2.

Table 4.2 – Potential threats

№	Factor	Threat content	Potential reaction of the company
1	Long recovery period	Low probability of investing in long capital return cycles	Negative
2	Climate	Limited time frame during the year; unpredictable long-term weather conditions (rain or drought) may affect the effectiveness of phytoremediation	Negative
3	Low predictability of results	It is difficult to guarantee a certain percentage of effectiveness within a specified time frame, as various environmental factors may affect the growth of phytoremediation plants and the effectiveness of removal	Negative
4	Issues surrounding the handling of spent biomass	Disposing of contaminated biomass or recovering metals from it is an expensive process	Negative
5	Market mistrust	Most customers are prejudiced against the effectiveness of biological methods	Negative
6	Competition with traditional methods	In comparison, removing or burying contaminated soil cover is cheaper	Negative

Table 4.3 lists the opportunities created by the introduction of phytoremediation technology.

Table 4.3 – Start-up opportunity factors

№	Factor	Contents of opportunities	Potential reaction of the company
1	Investments from international donors	International companies investing in Ukraine's recovery will be interested in «green methods»	Positive
2	Development of biological soil remediation methods	Improving the effectiveness of phytoremediation in certain cases by combining it with other biological soil remediation methods based on empirical experience	Positive
3	Development of technology for recovering metals from biomass	Approaching sustainable development through the full use of available resources	Positive (in the long term)
4	Obtaining biomass for energy purposes	If it is impossible to recover metals from phytoremediation agents, their biomass can be used as raw material for combustion, after which the contaminated ash can be disposed of, thus adding a useful link in the life of contaminated biomass	Positive
5	Massive return of territories to use	Agricultural companies will be interested in «green recovery» to enter the European market	Positive

As with any start-up, it is necessary to conduct a SWOT analysis for phytoremediation technology in order to determine future directions for development.

Table 4.4 – SWOT analysis of technology

Strengths	Weaknesses
1. The cheapest method for clearing large areas with high efficiency	1. A long purification cycle may be necessary
2. Can be used on mined areas with the use of drones for sowing	2. Impact of seasonality and climate in Ukraine
3. Simultaneous restoration and production of energy biomass	3. Need for disposal when using biomass as an energy resource due to metal contamination
4. High demand from European donors interested in implementing ‘green methods’ of restoration	4. Expensive recovery of metals from biomass
5. Easy implementation (self-sowing by the client or by a team using drones)	5. Low market awareness of biological recovery methods (prejudice against them)
66. Positive PR for large companies at the state level and for the state on the world stage	6. Lack of legislation on the status and treatment of contaminated biomass

Opportunities	Threats
1. Interest from foreign investors and capital investment in 'green recovery'	1. Change in donor priorities in post-war reconstruction
2. Return of large areas of agricultural land to use, which will further contribute to the country's economic development	2. Complication of the licensing system for work with reclaimed land and spent biomass
3. Carbon credits secured by planting perennial plants	3. Emergence of cheaper chemical or microbiological alternatives
4. Export of the model to other post-war territories	4. Prolonged war and expansion of the combat zone, which will make phytoremediation unfeasible
5. Implementation in other industries: use of phytoremediation on land contaminated by industrial processes	5. Negative publicity in the event of an unsuccessful pilot project (low efficiency, unused biomass)

Therefore, the following strategic conclusions can be drawn from the SWOT analysis:

- Be the first to find and take on donor projects and showcase successful cases;
- Develop a clear plan for handling contaminated biomass (disposal or use as an energy resource with subsequent disposal) with partner companies;
- Implement training programmes for civil servants and large agricultural holdings to promote the idea and prove the effectiveness and feasibility of the method;
- Start work in areas where traditional methods are clearly impossible (in mined areas or large areas).

For the comprehensive implementation of the start-up, it is necessary to conduct an analysis of competition in the market. The results of this analysis are presented in Table 4.5.

Table 4.5 – Analysis of competition in the market for the selected technology

Features of the competitive environment	How this characteristic manifests itself	Impact on business operations (possible actions by the company to remain competitive)
Competitive environment of developments	Use of combined restoration methods; phytoremediation with the integration of drones for sowing and monitoring; a small number of companies providing such services	Increased accuracy and speed of cleaning large areas; increased technology costs; investment in research to develop adaptive varieties.

Competitive environment of goods	Preference for inexpensive phytoremediation plants as an alternative to other remediation methods	Lowering barriers to entry for new companies, leading to dumping from donor investments.
Competitive environment of services	Reclamation services with an emphasis on «green remediation»	To remain competitive, it is necessary to certify your model and offer comprehensive package services.

4.2 Development of a model for phytoremediation

The proposed model consists of the following stages:

1. Chemical analysis, initial mapping and zoning to create a pollution map.
2. Selection of plant species and varieties for a specific level and type of pollution.
3. Sowing or planting plants.
4. Periodic monitoring and implementation of appropriate measures to regulate phytoremediation.
5. Collection of biomass and its further use or disposal.

4.3 Start-up graphics and analytics tools

The purpose of the developed tools is to ensure maximum transparency and clarity for all customers – government agencies, international donors and agricultural holdings. The information is presented in a format that allows for a quick assessment of the initial state of contamination, current progress and the projected date for achieving safe indicators.

The main tools are:

1. An interactive web map 'Before/After' implemented on the basis of QGIS, which allows users to switch between certain layers (e.g. current year or forecast years), with the overlay of NDVI layers, plant stress indices, and areas of accumulation of specific pollutants (determined by biomass activity).

2. Collection of information on the dynamics of vegetation indices (NDVI, EVI, Red Edge), which is automatically provided through Google Earth Engine and exported to software developed by the company, which creates graphs of the dynamics of the vegetation period.
3. A calculator of removed pollutants, which, based on laboratory analyses of biomass and accumulation models, calculates the actual and predicted volume of removed heavy metals.
4. A standard report for the client (15–20 pages in two languages: Ukrainian and the language of the interested party), which contains ‘before’ and ‘after’ satellite images, graphs of dynamics, laboratory protocols, calculation of removed pollutants, and a forecast of the time required to achieve MPC.
5. Mobile access via a web application, allowing the customer to obtain up-to-date information on the status of the process..

6. Infographics on economic efficiency, demonstrating savings, the volume of biomass obtained for energy, and the potential volume of carbon credits.

Internal analytical tools used only by the project team include:

- Pollutant accumulation model;
- Crop rotation and crop selection optimiser for specific cases;
- Logistical model for biomass collection and utilisation.

This set of tools ensures a high level of customer confidence in long-term projects and creates a significant competitive advantage in the market.

In addition, for effective positioning of a start-up in the market, it is necessary to take into account the main requirements of the target audience for the result and form appropriate development strategies. The results of determining the main strategies are presented in Table 4.6.

Table 4.6 – Project development strategies

№	Requirements for goods for the target audience	Basic development strategy	Key competitive advantages of our start-up project	Selection of associations that should form a comprehensive position for your own project (three key ones)
1	International donors and sponsors require high compliance with green criteria, transparency of results, and readiness for audits	Cost and innovation leadership strategy	The most affordable solution for large volumes, a complete turnkey cycle, a ready-made monitoring and research system, and established relationships with partner companies	Green standard. The cheapest way to quality. Ecological and natural
2	Agricultural holdings and landowners want the land to be returned to work as soon as possible, a guarantee that MPC levels will be achieved, and the opportunity to earn money from biomass (as a resource)	Niche specialisation strategy	The fastest among plant-based methods (combination of hyperaccumulators + phytoextraction), official protocols accepted by the Ministry of Environment	Reliability. Proven. Profitability.
3	International funds and export require a proven case in the combat zone, a ready-made franchise, and experience working with UN and World Bank donors	Internationalisation strategy	The first Ukrainian case of large-scale phytoremediation after the war, a complete set of reports in English, ready-made contracts with donors	Reliability. Partnership and mutual assistance. The path to a clean future.

4.4 Technical and economic assessment of phytoremediation in post-war restoration

The technical and economic assessment of the implementation of phytoremediation in the post-war restoration of the country includes an analysis of the costs of research, equipment, software and disposal services.

The economic assessment is carried out taking into account that the most common request is the cleaning/restoration of craters after explosions. The average area of contamination from an explosive device varies from 80 to 120 m^2 depending on the type of explosive device, so the calculation was made for 100 m^2 = 0,01 ha.

Table 4.7 contains the results of the analysis of the cost of the phytoremediation process with optimisation for price limits for different consumers with their income levels and needs.

Table 4.7 – Determining price setting limits

№ п/п	Price level for substitute goods	Income level of the target consumer group	Upper and lower limits for setting the price for cleaning a 100 m^2 area
1	Removal of 50–120 m^3 of soil + disposal as hazardous waste: 420000–780000 UAH	Average (private farmers, small farms)	From 45000 to 85000 UAH
2	Chemical neutralisation/stabilisation on site: 180000–350000 UAH	Medium-high (agricultural holdings)	From 65000 to 110000 UAH
3	Simply plough and sow (risky option with no guarantee): 8000–18000 UAH	Low (farmers with small private land holdings)	From 35000 UAH
4	Donor/grant programmes: 0–50000 UAH	Large farmers	From 0 to 30000 UAH

Table 4.8 shows a detailed breakdown of costs for a specific area.

Table 4.8 – Detailed breakdown of costs per 100 m^2 plot

№	Cost components	What is included	Price, UAH
1	Initial survey	Team visit to collect samples, conduct chemical tests	15000
2	Planting/sowing material	1 kg of mustard/35 seedlings	60 – 3850
3	Planting/sowing	Manual (can be done independently by the customer or by the team)	0 - 6000
4	Equipment and fertilisers (2-3 seasons)	Biological fertilisers, mycorrhizal preparations	3500
5	Monitoring and laboratory testing	4 trips: 4 combined soil samples and 4 combined biomass samples	50000
6	Biomass harvesting (2-3 harvests)	Mowing + removal	500-2000
7	Disposal of contaminated biomass	Transportation and incineration	10000
8	Final report	Official report	2000
9	Logistics, insurance, company maintenance costs	Fuel, insurance, unforeseen expenses	4000-7500
Total for the entire cycle:			**99850**

At the lower end of the range, provided that certain actions are taken by the customer, the cost will be **85060 UAH**.

For successful development and effective implementation, a basic development strategy was developed, as shown in Table 4.9, a sales system, as shown in Table 4.10, and a project model structure, as shown in 4.11.

Table 4.9 – Basic development strategy of the company

№	Selected alternative for project development	Market coverage strategy	Key competitive positions according to the chosen alternative	Basic development strategy
1	Scaling up to large donor and government projects	Broad market coverage	The cheapest solution, compliance with green technologies	Partnership strategy
2	Launching our own hyperaccumulator nursery	Differentiated marketing	Own cultivation of seedlings, additional income from bioenergy and independence from imports	Vertical integration strategy
3	Exporting technology and franchises to other post-war and post-conflict countries	Internationalisation	The world's first case of large-scale phytoremediation after a full-scale long-term war	Cost leadership and export strategy

Table 4.10 – Formation of a service distribution system

№	Specifics of target customers' purchasing behaviour	Sales functions to be performed by the supplier of goods	Depth of the distribution channel	Optimal sales system
1	Large international donors	Full turnkey cycle, English reporting	Zero-level channel	Direct sales + tenders
2	Agricultural holdings and large landowners	Fixed price per hectare, guaranteed results, sale of biomass/credits	Zero-level channel	Direct sales
3	Farmers and village councils	Simple fixed price per crater, payment in instalments, minimal bureaucracy	First-level channel	Direct regional representatives, online orders
4	Ministry of Environment/Ministry of Defence, State Emergency Service	Work in mined areas, remote sowing	Zero-level channel	Direct contracts

Table 4.11 – Business model structure

Key resources	**Sales channels**
1. Our own team of phytoremediation experts and soil scientists	1. Direct sales to large customers
2. Drones for sowing and monitoring	2. Regional representatives for farmers
3. Accredited partner laboratory	3. Online platforms for orders and partnerships with resellers
Cost structure	**Revenue streams**
1. Survey, planting and consumables: 15060-24850 UAH	1. Customer payments
2. Agricultural technology and maintenance (2-3 seasons): 3500 UAH	2. Biomass sales
3. Biomass collection and disposal: 10500-12000 UAH	3. Carbon credits
4. Costs of planned activities: 4000-7500 UAH	4. Technology exports

The use of phytoremediation as a means of generating income is unacceptable, and this service should be provided free of charge to those who need it, because soil remediation from potentially hazardous contaminants is not a business opportunity, but a fundamental right of every person to a clean environment, safe food and clean water. Therefore, this right must be guaranteed to everyone without exception, regardless of status or financial capacity.

4.5 Assessment of the effectiveness of phytoremediation technology in post-war territories

The effectiveness of phytoremediation technology is assessed according to four main criteria: environmental, technical, economic and social.

Environmental effectiveness is determined by the ability of the selected phytoremediation agent to remove pollutants and restore fertility. According to the results of the study, a reduction in the concentrations of heavy metals such as lead, nickel, chromium and zinc of more than 95% can be achieved in a period of up to six months and three years separately for cadmium in one cycle, and faster if two cycles of phytoremediation are carried out during this period. Upon completion, the land plots will comply with the maximum permissible concentrations established by current legislation and will be suitable for agricultural use.

The technical efficiency lies in the possibility of applying this technology in mined or hard-to-reach areas. The sowing of herbaceous plants and monitoring are carried out using drones.

Economic efficiency is confirmed by the cost of remediation, which is slightly lower than traditional recultivation methods. Additional income from the sale of biomass for energy needs and carbon credits reduces the actual costs for the end customer.

Social efficiency consists in returning land to various uses, including agriculture, as well as ensuring environmental safety.

Each criterion is assessed on a 5-point scale: 1 – low efficiency, 5 – maximum efficiency. The results are presented in Table 4.12.

Table 4.12 – Assessment of the effectiveness of phytoremediation technology

Criterion	**Points**
Environmental efficiency.	4.8
Technical efficiency	4.5
Economic efficiency	4.2
Social efficiency	5.0
Average indicator	**4.63**

This technology has a high effectiveness rating of 4.63, which once again confirms its potential for use in military and post-war areas in Ukraine. This model and its technical and economic analysis may be useful for government agencies or international donors to provide free phytoremediation services to land users whose land has been affected by military operations.

CONCLUSIONS TO SECTION 4

1. A start-up project was proposed to introduce phytoremediation technology in post-war areas in Ukraine, for which a standard SWOT analysis was conducted and the threats and opportunities for the project's development were assessed.

2. Comprehensive graphic and analytical tools were developed for the start-up, as well as a development strategy, and price limits were set for individual components and service processes.

3. The phytoremediation technology as a project was assessed in terms of its environmental, technical, economic and social effectiveness. The average efficiency score is 4.63 out of a possible 5.

GENERAL CONCLUSIONS

1. In order to develop a phytoremediation plan and gain a general understanding of the impact of military operations on the soil environment, particularly chemical contamination, physical and chemical studies were conducted on soil samples taken from the crater before and after the explosion of the high-explosive ordnance. It was impossible to perform compression tests on the samples due to soil compaction, potentially caused by the explosion. According to the results of chemical analysis after the detonation of the UXO, compared to the soil sample before detonation, an increase in concentrations of lead by 4,2 times, cadmium by 32,7 times, chromium by 3,5 times, nickel – 1,75 times; manganese – 1,97 times; petroleum products – 4,3 times.
2. Taking into account the degree and type of contamination, based on scientific research, Indian mustard (*Brassica juncea*) was selected as the main hyperaccumulator for phytoremediation, and field peas (*Pisum sativum*) with the addition of a mycorrhiza-forming agent.
3. Phytotesting of soil samples was conducted after detonation of the explosive device: the calculated average phytotoxic effect based on three bioparameters (plant height, root length, and dry weight) was 57,97%, demonstrating the potential for an extremely negative impact on ecosystems. Acute toxicity was assessed on *Danio rerio* fish embryos: pronounced cardiotoxic effects, damage to fins and jaws, tail immobility, eye pigmentation disorders and combined morphological changes were observed, confirming the danger of the environment affected by military actions.
4. During the study of the phytoremediation process, it was found that the greatest increase in biomass was achieved by the sample of the studied soil in combination with biohumus in a ratio of 3:1 with the addition of a mycorrhiza-forming preparation. After conducting a chemical analysis of this sample and biomass for heavy metal content, it was found that the MPC levels for lead were achieved: the phytoremediation efficiency for this metal was 95,65%. High

efficiency rates are also characteristic of nickel (93,04%), cadmium (89,52%) and zinc (84,13%). It should also be noted that the bioaccumulation factor (BAF) for all metals is less than 0,7%, which indicates the absolute inefficiency of phytoextraction. The immobilisation of heavy metals due to the activity of the formed mycorrhiza, for which this process is characteristic, became a potentially dominant process.

5. The approximate period for soil remediation to safe levels is: for lead – 3,5 months of vegetation; for nickel – 5 months; for chromium – 36,7 months; cadmium – 6 months; zinc – 4,5 months; calculations for copper and manganese were not performed due to error.

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Appendix 1

Державна установа
«Інститут громадського здоров`я ім. О.М. Марзєєва НАМН України
02094, м. Київ-94, вул. Гетьмана П. Полуботка, 50, тел. 292-14-25
Свідоцтво з акредитації установ і організацій на проведення робіт з гігієнічної регламентації небезпечних факторів №06 від 10.11.2021 р.

ЛАБОРАТОРІЯ ГІГІЄНИ ҐРУНТУ ТА ВІДХОДІВ

Сертифікат визнання вимірювальних можливостей
№ ПТ-469/23 від 21.12.2023 р.

ПРОТОКОЛ ДОСЛІДЖЕНЬ № 67.25

Робота виконувалась в лабораторії гігієни грунту та відходів ДУ «ІГЗ НАМНУ» у відповідності до договору №981/10 від 08.08.2025 р. (договір про співпрацю), зразки ґрунту були відібрані та доставлені згідно акту відбору проб №01 від 30.07.2025 р.

Дата проведення досліджень: 01.08.2025 р. - 15.08.2025 р.

Найменування організації замовника: Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського» (КПІ ім. Ігоря Сікорського). Юридична адреса: просп. Берестейський, 37, м. Київ, 03056; ідентифікаційний код згідно з ЄДРПОУ: 02070921; тел.: (044) 204 82 82; e-mail:
Найменування досліджень: Фізико-хімічні дослідження 2 зразків ґрунту в Миколаївській області, забрудненого внаслідок бойових дій
Мета досліджень: Фізико-хімічні дослідження зразків ґрунту, забрудненого внаслідок бойових дій

Посада, прізвище, ім'я осіб, що проводять дослідження: м.н.с. Гуменнікова Н.М.; пров. інж. Мураш О.І.

Методи дослідження: атомно-абсорбційний.

Перелік методик та сутність методів дослідження, які були застосовані для проведення санітарно-хімічних досліджень наданих зразків.

- значення pH визначалося на аналізаторі рідинному багатопараметричному «Екотест-2000», сертифікат калібрування №31.08.2023-50 від 31.08.2023 р., згідно ДСТУ ISO 10390:2022 (ISO 10390:2021, IDT). Ґрунт, оброблені біовідходи та осад. Визначення pH;
- визначення вмісту важких металів виконувалось атомно-абсорбційним методом на спектрофотометрі типу КАС-120.1, свідоцтво про калібрування реєстраційний №К/21699/Х від 24.04.2023 р., згідно методик МВВ 081/12-0009-01 Ґрунти. Методика виконання вимірювань свинцю методом атомно-абсорбційної спектрофотометрії; МВВ № 081/12-0117-03 Ґрунти. Методика виконання вимірювань масової частки рухомих форм нікелю та кобальту атомно-абсорбційним методом; МВВ 081/12-0012-01 Грунти. Методика виконання вимірювань хрому методом атомно-абсорбційної спектрометрії (0,5-100 мг/кг); МВВ 081/12-0013-01 Грунти. Методика виконання вимірювань масової частки цинку методом атомно-абсорбційної спектрофотометрії; МВВ № 081/12-0576-08 Ґрунти. Методика виконання вимірювань масової частки марганцю фотоколориметричним методом; МВВ №081/12-0002-01. Грунти. Методика виконання вимірювань масової частки міді атомно-абсорбційної спектрофотометрії; МВВ №081/12-0010-01. Грунти. Методика виконання вимірювань масової частки кадмію методом атомно-абсорбційної спектрофотометрії. МВВ № 081/12-0116-03 Ґрунти. Методика виконання вимірювань масової частки нафтопродуктів гравіметричним методом від 28.11.03. Розроблена Українським науково-дослідним інститутом екологічних проблем Мінприроди України. Державною екологічною інспекцією Мінприроди України. ДСТУ 4770.4:2007. Якість грунту.

Ідентифікація зразків за візуальним оглядом:

- проба №1 – Миколаївська область, GPS координати: 46^{0}50'24.19"N 32^{0}21'16.62"E, вибуховий кратер до детонації снаряду;

- проба № 2 - Миколаївська область, GPS координати: 46^{0}50'24.19"N 32^{0}21'16.62"E, вибуховий кратер після детонації снаряду без зміни його локації;

РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ

Показник	Проба №1	Проба №2	ГДК	Кларки (фоновий вміст)**
pH	5,37	5,44		
Вміст важких металів (валовий вміст), мг/кг				
Pb	84,5	357,0	32,0	10,0
Cu	1,56	1,91	-	20,0
Ni	228,6	229,6	-	40,0
Cd	0,14	4,58	1,5	0,5
Cr	10,6	36,6	-	200
Zn	189,1	331,6	-	50,0
Mn	129,8	255,4	100,0	100,0
Нафтопродукти, мг/кг	80,0	342,0	1000,0	-

* - валовий вміст, мг/кг (з урахуванням фону (кларка) згідно з „Гігієнічні регламенти допустимого вмісту хімічних речовин у грунті" (затверджені наказом МОЗ України від 14.07.2020 р. №1595, зареєстрованим Мінюстом 31.07.2020 р. за №722/35005);

** - фоновий вміст хімічних елементів у грунті за А.П. Виноградовим.

Зав. лабораторії гігієни грунту та відходів, д.мед.н. Валерій СТАНКЕВИЧ

М. н.с. Наталія ГУМЕННІКОВА

Пров. інженер Олена МУРАШ

Appendix 2

Державна установа
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02094, м. Київ-94, вул. Гетьмана П. Полуботка, 50, тел. 292-14-25
Свідоцтво з акредитації установ і організацій на проведення робіт з гігієнічної регламентації небезпечних факторів №06 від 10.11.2021 р.

ЛАБОРАТОРІЯ ГІГІЄНИ ҐРУНТУ ТА ВІДХОДІВ

Сертифікат визнання вимірювальних можливостей
№ ПТ-469/23 від 21.12.2023 р.

ПРОТОКОЛ ДОСЛІДЖЕНЬ № 86.25

Робота виконувалась в лабораторії гігієни грунту та відходів ДУ «ІГЗ НАМНУ» у відповідності до договору №981/10 від 08.08.2025 р. (договір про співпрацю), зразки ґрунту були відібрані та доставлені згідно акту відбору проб №03 від 21.10.2025 р.

Дата проведення досліджень: 21.09.2025 р. - 29.09.2025 р.

Найменування організації замовника: Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського» (КПІ ім. Ігоря Сікорського). Юридична адреса: просп. Берестейський, 37, м. Київ, 03056; ідентифікаційний код згідно з ЄДРПОУ: 02070921; тел.: (044) 204 82 82; e-mail:

Найменування досліджень: Фізико-хімічні дослідження ураженого внаслідок вибуху грунту після відновлення методом фіторемедіації з використанням гірчиці індійської та біомаси гірчиці індійської, яка використовувалась для фіторемедіації забрудненого грунту
Мета досліджень: Фізико-хімічні дослідження зразків ґрунту та біомаси, забруднених внаслідок бойових дій

Посада, прізвище, ім'я осіб, що проводять дослідження: м.н.с. Гуменнікова Н.М.; пров. інж. Мураш О.І.

Методи дослідження: атомно-абсорбційний.

Перелік методик та сутність методів дослідження, які були застосовані для проведення санітарно-хімічних досліджень наданих зразків.

- значення pH визначалося на аналізаторі рідинному багатопараметричному «Екотест-2000», сертифікат калібрування №31.08.2023-50 від 31.08.2023 р., згідно ДСТУ ISO 10390:2022 (ISO 10390:2021, IDT). Ґрунт, оброблені біовідходи та осад. Визначення pH;
- визначення вмісту важких металів виконувалось атомно-абсорбційним методом на спектрофотометрі типу КАС-120.1, свідоцтво про калібрування реєстраційний №К/21699/Х від 24.04.2023 р., згідно методик МВВ 081/12-0009-01 Ґрунти. Методика виконання вимірювань свинцю методом атомно-абсорбційної спектрофотометрії; МВВ № 081/12-0117-03 Ґрунти. Методика виконання вимірювань масової частки рухомих форм нікелю та кобальту атомно-абсорбційним методом; МВВ 081/12-0012-01 Грунти. Методика виконання вимірювань хрому методом атомно-абсорбційної спектрометрії (0,5-100 мг/кг); МВВ 081/12-0013-01 Грунти. Методика виконання вимірювань масової частки цинку методом атомно-абсорбційної спектрофотометрії; МВВ № 081/12-0576-08 Ґрунти. Методика виконання вимірювань масової частки марганцю фотоколориметричним методом; МВВ №081/12-0002-01. Грунти. Методика виконання вимірювань масової частки міді атомно-абсорбційної спектрофотометрії; МВВ №081/12-0010-01. Грунти. Методика виконання вимірювань масової частки кадмію методом атомно-абсорбційної спектрофотометрії. МВВ № 081/12-0116-03 Ґрунти. Методика виконання вимірювань масової частки нафтопродуктів гравіметричним методом від 28.11.03. Розроблена

Українським науково-дослідним інститутом екологічних проблем Мінприроди України, Державною екологічною інспекцією Мінприроди України. ДСТУ 4770.4:2007. Якість грунту.

Ідентифікація зразків за візуальним оглядом:

- проба №1 – Миколаївська область, GPS координати: 46^{0}50'24.19"N 32^{0}21'16.62"E,уражений внаслідок вибуху грунт після відновлення методом фіторемедіації з використанням гірчиці індійської;

- проба № 2 - Миколаївська область, GPS координати: 46^{0}50'24.19"N 32^{0}21'16.62"E, біомаса гірчиці індійської, яка використовувалась для фіторемедіації забрудненого грунту.

РЕЗУЛЬТАТИ ДОСЛІДЖЕНЬ

Показник	Проба №1	Проба №2	ГДК у грунті	Кларки (фоновий вміст у грунті)**
Вміст важких металів (валовий вміст), мг/кг				
Pb	15,54	0,53	32,0	10,0
Cu	5,72	1,10	-	20,0
Ni	15,99	9,67	-	40,0
Cd	0,48	0,17	1,5	0,5
Cr	31,69	0,42	-	200
Zn	52,64	3,92	-	50,0
Mn	1762,7	103,2	100,0	100,0

* - валовий вміст, мг/кг (з урахуванням фону (кларка) згідно з „Гігієнічні регламенти допустимого вмісту хімічних речовин у грунті" (затверджені наказом МОЗ України від 14.07.2020 р. №1595, зареєстрованим Мінюстом 31.07.2020 р. за №722/35005);

** - фоновий вміст хімічних елементів у грунті за А.П. Виноградовим.

Зав. лабораторії гігієни
ґрунту та відходів,
д.мед.н. Валерій СТАНКЕВИЧ

М. н.с. Наталія ГУМЕННІКОВА

Пров. інженер Олена МУРАШ