

Changes in the dynamics of the content of nutrients, trace elements and heavy metals in the soils of southern Ukraine affected by hostilities

Oleksandr Babych*

Assistant

Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-4271-3629>

Mykhailo Fedorchuk

Doctor of Agricultural Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0001-7028-0915>

Abstract. From February through November 2022, intense combat operations took place in southern Ukraine, which affected the chemical properties of agricultural lands, raising concerns about soil contamination with heavy metals and explosive substances. The aim of the study was to determine the agroecological condition of soils affected by hostilities in southern Ukraine in 2024 and 2025 and to conduct a comparative analysis of changes in these indicators following the start of soil preparation and tomato planting by InAgro. The article presents a comparative analysis of the content of trace elements (Zn, Mn, Fe, Cu), nutrients (available nitrogen, phosphorus, and potassium), certain physicochemical (pH) and chemical parameters (chloride-anion content), and heavy metals (Cd, Pb) in 2024 and 2025 in the lands of the Snigurivska territorial community managed by InAgro. No agricultural crops were grown during the period from 2022 to 2024. On the soils under study, the farm applied an $N_{20}P_{20}K_{20}$ fertilizer regimen, which is optimal for tomatoes, and implemented drip irrigation using water from the Ingulets Irrigation System. The results showed a significant reduction in the content of heavy metals and trace elements compared to 2024 with high statistical significance (Pb – a decrease on average from 12.57 ppm to 0.13 ppm (100-fold reduction), Cd – from 0.26 ppm to values below 0.05 ppm (more than 5-fold decrease), Cu – from 4.19 ppm to values below the detection limit (<0.05 ppm), Mn – from 19.3 ppm to 11.09 ppm (a 42% decrease), Zn – from 10.23 ppm to 0.03 ppm (a 340-fold decrease), which is associated with the cultivation of *Solanum lycopersicum* L. and the intensive use of irrigation. The practical significance of these results lies in understanding the extent to which cultivated plants influence the content of heavy metals and trace elements in the soil and in determining the potential risk posed by the presence of these elements in the edible parts of cultivated plants

Keywords: remediation; tomatoes; irrigation; agroecological indicators; Ingulets Irrigation System

INTRODUCTION

Following the onset of a full-scale invasion, agricultural soils began to be contaminated by various types of shells, explosives, and fuel and lubricants. Southern

Ukraine was particularly affected by the hostilities, especially the lands of the Snigurivska Territorial Community and the Kherson region. The detonation of

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*Corresponding author (babichoa29@gmail.com)



projectile warheads causes significant changes in the physical, physicochemical, and chemical properties of agricultural soils, leading to a decline in their fertility and posing an environmental hazard due to contamination with heavy metals and explosive residues. Therefore, this study was conducted to prevent further negative impacts, understand the current state and trends of these indicators, and develop a strategy to mitigate the negative consequences.

According to researchers G. Kaplan *et al.* (2022), the issue of heavy metal content in agricultural soils is quite pressing and requires detailed study. The increase in heavy metal content in soils is caused by various anthropogenic factors: industrial emissions, landfills, and so on. V. Melnychenko (2024) noted that since the onset of the full-scale war, soils have suffered significant damage from various explosives, shell fragments, and other debris. As a result, concentrations of the trace elements Zn, Mn, and Cu, as well as the heavy metals Pb and Cd, have increased. The increase in heavy metal content in the soil ultimately leads to their accumulation in plant tissues, which can enter the human body and cause various disorders (such as inducing somatic cell mutations, leading to the development of cancerous tumors, etc.).

Researchers C. Müller *et al.* (2022) concluded that the main sources of soil contamination resulting from military actions include shell fragments, fuel leaks, explosive residues, and the like. M. Solokha *et al.* (2022) and O. Angurets *et al.* (2023) conducted detailed studies on the presence of explosives and heavy metals, as well as changes in the particle size distribution of soils in various regions, particularly the Kharkiv, Dnipro, Mykolaiv, and Kherson regions, which suffered the most damage as a result of hostilities. Researchers O. Krainiuk *et al.* (2025) investigated the level of soil contamination in the Kharkiv Oblast, which showed very high concentrations of all types of heavy metals, confirming the problem of soil contamination caused by military operations.

According to the Agency for Toxic Substances and Disease Registry (n.d.), the main explosive component in most shells is trinitrotoluene (TNT), which significantly reduces soil fertility and breaks down into carcinogenic substances that have a negative impact on the human body. Researcher V. Melnychenko (2024) noted that the source of heavy metals is the metal parts of shells, mines, bullets, etc., as they consist of alloys of various metals. When broken down, heavy metal particles interact with the soil-adsorption complex and, in most cases, convert to an exchangeable form, thereby becoming available to the plant root system. According to recent studies, explosions significantly degrade the

particle size distribution and geochemical composition of soils; consequently, strategies to mitigate this negative impact are being actively developed.

Researcher S. Shuliak *et al.* (2022) noted that different plants absorb heavy metals and trace elements in different ways, depending on the characteristics of their biochemical processes and the content of reserve substances and water in various organs. Studies have shown that the most intensive uptake of heavy metals and trace elements occurs in the following crops: sunflower, white mustard, lettuce, spinach, celery, rice, potatoes, and others. Accumulation occurs in leaves, root crops, and fruits. Therefore, these crops are quite actively used as remediators in soils with high heavy metal content. Researchers A. Bounar *et al.* (2020) noted that tomatoes are capable of absorbing various heavy metals, particularly zinc (Zn), lead (Pb), cadmium (Cd), chromium (Cr), and copper (Cu). Researchers Q. Tabassam *et al.* (2023) demonstrated through their studies that tomatoes absorb the highest amounts of lead, zinc, and manganese; however, these studies were conducted under conditions involving wastewater exposure.

According to the findings of C. Pérez-Figueroa *et al.* (2023), the greatest uptake occurs through the root system, leaves, and fruits; therefore, tomatoes can accumulate relatively large amounts of heavy metals, and this factor must be taken into account, particularly when growing them on land affected by military hostilities. Recent studies have focused intensively on changes in the physicochemical parameters of soils affected by military operations, but very few studies have examined remediation methods using various agricultural crops or other technical crops. Economic activity in affected areas is only just beginning to recover; therefore, the issue of heavy metal migration and soil remediation methods is highly relevant, which was the primary rationale for conducting this study. The objective of the study was to examine the agrochemical and agroecological condition of soils affected by military operations and to analyse changes in these conditions during the cultivation of agricultural crops.

MATERIALS AND METHODS

Soil samples were collected from a field in Snihurivka that had been affected by hostilities in the spring and fall of 2022 and which, in the spring of 2025, belonged to the company InAgro. The field underwent demining, and it was not until the fall of 2024 that analyses were conducted to determine the content of macronutrients (ammonium nitrogen, exchangeable phosphorus, exchangeable potassium, heavy metals – mobile compounds of zinc (Zn), manganese (Mn), iron (Fe), lead (Pb), cadmium (Cd), and copper (Cu)) and physicochemical properties (pH and

chloride anion (Cl⁻) content) were conducted. Soil sampling in 2024 took place at the following coordinate

points, which are listed in Table 1. Figure 1 shows the sampling points for the studied samples on a map.

Table 1. Coordinates of soil sampling points at the experimental field in Snigirivka in 2024

Point Number	Coordinates	Number of Samples Taken
Point 1	47°04'30.9" N 32°46'12.0" E	3
Point 2	47° 04' 32.7" N 32° 46' 07.2" E	3
Point 3	47° 04' 27.1" N 32° 46' 14.0" E	3
Point 4	47°04' 57.5" N 32°56' 08.9" E	3

Source: developed by the authors

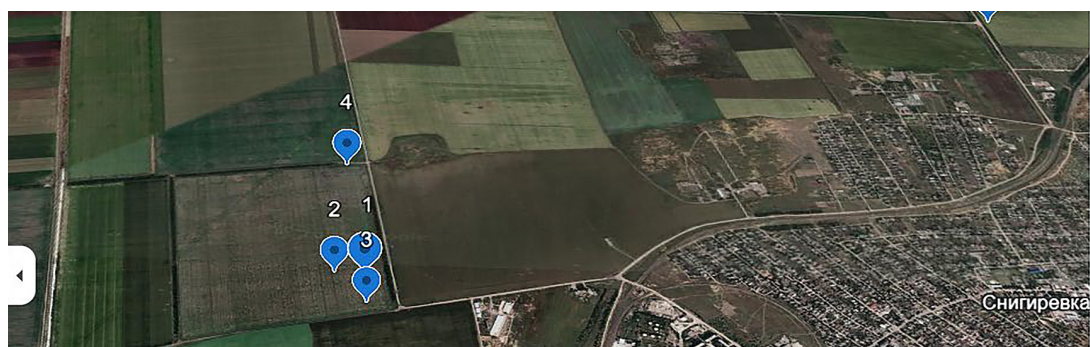


Figure 1. Soil sampling points for analysis of agrochemical parameters and heavy metal content

Source: developed by the authors

Since there were craters and mines at the sampling sites, these locations were selected for the study. In 2025, the plot was reclaimed, and the “Inagro” company planted tomatoes in this field, applying $N_{20}P_{20}K_{20}$ fertilizer and using a drip irrigation system. Soil sampling in 2025 was conducted in the summer (June) during the active vegetative growth phase of the plants at identical coordinate points, with the addition of an extra point at coordinates 47°04' 56.0" N, 32°46' 07.1" E, as this point exhibited pronounced “weeding out” of the plot. Samples of irrigation water were also collected from the drip irrigation system and from a canal of the Ingulets Irrigation System to determine the extent of water’s impact on soil chemical parameters. The soils were also analysed for nutrient content, heavy metals, pH, and chloride content. The analyses were conducted in accordance with DSTU ISO 10381-1:2004 (2006). Irrigation water was tested for heavy metals (Zn, Cu, Mn, Pb, Cd, Fe) using an ammonium acetate extraction at pH 4.8 followed by the ICP method (inductively coupled plasma spectrometry) with an Avio200 instrument (country of manufacture: USA), as well as for the content of soluble salts of potassium (K⁺), sodium (Na⁺), calcium (Ca⁺²) and magnesium (Mg⁺²), cations, and salts of bicarbonate (HCO₃⁻), carbonates (CO₃⁻²),

sulfates (SO₄⁻²) and chlorides (Cl⁻) in accordance with DSTU ISO 10381-1:2004 (2006) and DSTU ISO 10381-2:2004 (2006). The ICP method has a detection limit for the concentration of trace elements and heavy metals of 0.05 ppm (mg/kg of soil).

The soils were also analysed for the content of explosive substances (dinitrotoluene and trinitrotoluene) using chromatography at the Sokolovsky Institute of Soil Science. The results were statistically analysed using Microsoft Excel and online statistical software. Each soil sample from each sampling point and each irrigation water sample were analysed in triplicate (n = 3). All results were tested for normality using the Shapiro-Wilk test to determine the suitability of the parametric t-test for identifying statistical differences between the results by either confirming the null hypothesis ($p > 0.05$) or rejecting it ($p < 0.05$) based on the critical value of the t-test. Differences between the results for soil and irrigation water were determined using Student’s parametric paired t-test, since the results for the soils were interrelated and the studies were conducted at the same locations but at different times, while the irrigation water came from the same source and had traveled a certain distance through the drip irrigation system. The MPC (maximum permissible

concentrations) values for heavy metals, specifically the content of mobile compounds of lead (Pb), copper (Cu), cadmium (Cd), and manganese (Mn), were determined in accordance with regulatory document MVV 081/36-0833-12 (Kopilevych *et al.*, 2012).

RESULTS AND DISCUSSION

The results of the studies revealed changes in nutrient content, heavy metal concentrations, and chemical

properties at various sampling sites affected by military operations. At site 1 (47°04'30.9" N, 32°46'12.0" E), there was a statistically significant increase in nutrient content, except for mobile potassium, and a significant decrease in the content of mobile heavy metal compounds (Zn, Cu, Mn, Pb, Cd, Fe), as well as a statistically significant decrease in pH (Table 2). In 2024, the MPC values for mobile compounds of copper (Cu) and lead (Pb) were exceeded (3 mg/kg and 6 mg/kg, respectively).

Table 2. Physicochemical parameters and concentrations of mobile heavy metal compounds and nutrients at Point 1 of the experimental field in Snihurivka in 2024-2025

Point 1	2years	pH	NH ₄ ⁺ mg/kg	P ₂ O ₅ pure mg/kg	K ₂ O pure mg/kg	Fe ppm	Mn ppm
47°04'30.9" N 32°46'12.0" E	2024	8.21 ± 0.04	126.3 ± 1.53	93.25 ± 1.01	171.6 ± 3.51	-	15.37 ± 0.25
	2025	7.9 ± 0.1	3.6 ± 0.17	193.33 ± 18.9	198.3 ± 28.71	-	9.07 ± 1.33
T-test		8.95	156.27	9.69	1.84*		8.35
Point 1	years	Zn ppm	Cu ppm	Pb ppm	Cd ppm	Cl- mg/kg	TNT
47°04'30.9" N 32°46'12.0" E	2024	12.7 ± 0.5	3.12 ± 0.56	19.28 ± 0.86	0.26 ± 0.02	0.18 ± 0.02	+
	2025	-	-	0.12 ± 0.04	-	0.13 ± 0.03	-
T-test		!	!	36.87		2.4*	

Note: * – no statistically significant difference between results; TNT – presence of the explosive trinitrotoluene and its decomposition products; - – concentration of the component under study is below the instrument's detection limit; yellow color – MPC exceeded; ! – statistical analysis could not be performed due to very low values for one of the results

Source: developed by the authors

The results showed a significant improvement in soil quality compared to 2024 in terms of heavy metal content, particularly mobile copper and lead compounds, as well as the absence of the explosives TNT (trinitrotoluene) and DNT (dinitrotoluene), indicating a possible positive impact of reclamation processes, irrigation, and the uptake of these compounds by tomato plant parts. An increase in the content of the nutrient P₂O₅, which is associated with fertilization, and a significant decrease in the content of ammonium nitrogen have been observed, indicating either its intensive uptake by plants or a possible deficiency of this nutrient. The content of exchangeable potassium remains at the same level, indicating an adequate level of fertilization with potassium compounds.

A similar trend was observed in the analysis of soil samples from Point 2 (47°04'30.9" N, 32°46'12.0" E) (Table 3). In 2024, only copper (Cu) compounds exceeded

the MPC – 5.16 mg/kg > 3.0 mg/kg. At this sampling point, no statistically significant difference was observed between the results of the paired t-test ($t_{crit} = 2.78$ for $n = 5$, at $p < 0.05$) for the content of exchangeable potassium, exchangeable manganese (Mn) compounds, and chloride anions (Cl⁻). A statistically significant neutralisation of the pH level is observed, along with a significant decrease in the content of all heavy metals compared to 2024. Therefore, at this site, a significant improvement in chemical composition is also observed due to the effects of irrigation and phytoremediation. The nutrient content follows exactly the same trend as at Point 1: a decrease in ammonium nitrogen, an increase in exchangeable phosphorus, and a stable level of exchangeable potassium (according to Chirikov). Furthermore, no explosive substances were detected in the 2025 soil samples, which also indicates a positive trend toward recovery.

Table 3. Physicochemical parameters and concentrations of mobile heavy metal compounds and nutrients at Point 2 of the experimental field in Snihurivka in 2024-2025

Point 2	years	pH	NH ₄ ⁺ mg/kg	P ₂ O ₅ pure mg/kg	K ₂ O pure mg/kg	Fe ppm	Mn ppm
47°04'32.7" N 32°46'07.2" E	2024	8.21 ± 0.08	63.0 ± 1.67	51.81 ± 1.59	162.23 ± 3.16	-	20.45 ± 1.32
	2025	6.7 ± 0.27	5.5 ± 0.7	241.0 ± 59.9	225.67 ± 66.12	-	15.9 ± 3.6
T-test		8.97	89.44	5.44	1.65*		2.06*

Table 3, Continued

Point 2	years	Zn ppm	Cu ppm	Pb ppm	Cd ppm	Cl- mg/kg	TNT
47°04'32.7"N 32°46'07.2"E	2024	10.45±0.56	5.16±0.32	4.38±0.07	0.19±0.03	0.65±0.05	+
	2025	0.01±0.01	-	0.15±0.06	-	0.57±0.06	-
T-test		8.25	!	62.57		2.4*	

Note: * – no statistically significant difference between results; TNT – presence of the explosive trinitrotoluene and its decomposition products; - – concentration of the component under study is below the instrument's detection limit; yellow color – MPC exceeded; ! – statistical analysis could not be performed due to very low values for one of the results

Source: developed by the authors

Analysis of soil samples from Point 3 (Table 4) also reveals a statistically significant decrease in the content of mobile heavy metal compounds and trace elements, as well as a decrease in the content of exchangeable potassium and ammonium nitrogen. The acidity and chloride levels remain stable, indicating no

significant changes in the salt composition of the soil solution. Furthermore, as in the previous samples, no traces of explosive residues were found in these samples. In 2024, the MPC was exceeded by the concentrations of mobile compounds of copper (Cu) and lead (Pb), which were also present at Point 1.

Table 4. Physicochemical parameters and concentrations of mobile heavy metal compounds and nutrients at Point 3 of the experimental field in Snihurivka in 2024-2025

Point 3	years	pH	NH ₄ ⁺ mg/kg	P ₂ O ₅ pure mg/kg	K ₂ O pure mg/kg	Fe ppm	Mn ppm
47°04'27.1" N 32°46'14.0" E	2024	7.99±0.09	101.47±4.24	150.03±2.6	344.7±3.1	-	25.6±1.55
	2025	8.03±0.06	5.73±0.21	237.7±13.6	285.0±19.9	-	11.5±1.8
T-test		0.53*	36.85	10.95	5.13	!*	10.36
Point 3	years	Zn ppm	Cu ppm	Pb ppm	Cd ppm	Cl- mg/kg	TNT
47°04'27.1" N 32°46'14.0" E	2024	11.6±0.52	5.16±0.32	11.47±1.12	0.33±0.04	0.55±0.05	+
	2025	0.01±0.01	-	0.09±0.03	-	0.45±0.21	-
T-test		8.35	!	17.6	!	0.85*	

Note: * – no statistically significant difference between results; TNT – presence of the explosive trinitrotoluene and its decomposition products; - – concentration of the component under study is below the instrument's detection limit; yellow color – MPC exceeded; ! – statistical analysis could not be performed due to very low values for one of the results

Source: developed by the authors

Analysis of soil samples from Point 4 (Table 5) also reveals a statistically significant decrease in the content of mobile heavy metal compounds and micronutrients, but a marked increase in the content of exchangeable potassium and phosphorus, indicating a possible unevenness in the field's fertilization. The pH and chloride

levels remain stable, indicating no significant changes in the salt composition of the soil solution. Furthermore, as in previous samples, no traces of explosive substances were found in the samples. As in previous samples, the maximum permissible concentration values for 2024 were exceeded by copper and lead compounds.

Table 5. Physicochemical parameters and concentrations of mobile heavy metal compounds and nutrients at Point 4 of the experimental field in Snihurivka in 2024-2025

Point 4	years	pH	NH ₄ ⁺ mg/kg	P ₂ O ₅ pure mg/kg	K ₂ O pure mg/kg	Fe ppm	Mn ppm
47°04'57.5" N 32°56'08.9" E	2024	7.68±0.18	98.0±3.0	57.67±2.15	245.3±9.5	-	18.3±1.2
	2025	7.53±0.21	3.8±0.64	574.3±37.6	949.7±168.1	-	7.9±1.5
T-test		0.93*	53.2	23.8	7.25	!	9.6
Point 4	years	Zn ppm	Cu ppm	Pb ppm	Cd ppm	Cl- mg/kg	TNT
47°04'57.5" N 32°56'08.9" E	2024	6.17±0.37	3.3±0.24	15.14±0.92	0.25±0.02	0.58±0.15	+
	2025	0.1±0.03	-	0.16±0.03	-	0.51±0.42	-
T-test		28.7	!	28.23	!	0.28*	

Note: * – no statistically significant difference between results; TNT – presence of the explosive trinitrotoluene and its decomposition products; - – concentration of the component under study is below the instrument's detection limit; yellow color – MPC exceeded; ! – statistical analysis could not be performed due to very low values for one of the results

Source: developed by the authors

An analysis of the chemical composition of irrigation water in a drip irrigation system revealed no high levels of heavy metals or trace elements (Table 6); however, a slight change in the chemical composition of the irrigation water was observed during its transport from

the irrigation canal to the drip system – a statistically significant shift (as indicated by the one-sample t-test, $t_{crit}=2.8$) in the pH toward the alkaline side, a decrease in the level of sulfate anions (SO_4^{2-}), and a decrease in the total salt concentration as measured by TDS.

Table 6. Chemical composition of irrigation water for the field in Snihurivka in 2025

Water/Systems	Year	pH	SO_4^{2-} mg/l	CO_3^{2-} mg/l	HCO_3^- mg/l	Ca^{+2} mg/l	Mg^{+2} mg/l	Na^+ mg/l
Irrigation System	2025	7.1±0.1	529±5.3	-	232±5.2	136±2.5	109±2.3	435±15.8
Ingulets Irrigation System Canal	2025	8.0±0.1	564±8.3	-	226±5.1	139±3.4	112±3.2	464±14.3
T-test		11.02	6.16	*	1.43*	1.23*	1.32*	2.36*
Water/systems	K^+ mg/l	EC _w mcm	TDS mg/l	Pb ppm	Cd ppm	Mn ppm	Zn ppm	Cu ppm
Irrigation System	20±0.36	3.9±0.1	1,920±65.2	-	-	0.02±0.01	-	-
Ingulets Irrigation System Canal	21±0.54	4.1±0.1	2,070±66.2	-	-	0.02±0.1	-	-
T-test	0.38*	2.45*	2.8	*	*	*	*	*

Note: * – no statistically significant difference between the results; yellow indicates a high level of the indicator, which may lead to negative consequences

Source: developed by the authors

Due to its salinity, the water is of limited suitability for irrigation and may therefore pose a certain risk of soil salinisation. The water has elevated levels of sodium, potassium, and magnesium salts, as well as sulfate anions. At the same time, it contains safe levels of mobile heavy metal compounds; therefore, during the study period, there was no statistically significant effect on heavy metal content. However, in the long term, the use of this irrigation water may have negative effects on the soil's physicochemical parameters, specifically on the level of salinisation, the potential formation of saline crusts, and changes in soil density, without the implementation of additional soil improvement measures.

DISCUSSION

The study results demonstrated that, immediately following combat operations, soils that had been impacted by shells or other explosive substances exhibited elevated levels of mobile copper and lead compounds, as confirmed by researchers O. Shebanina *et al.* (2024). At the same time, studies by Z. Altahaan & D. Dobslaw (2024) indicate a significant increase in the content of mobile compounds of other heavy metals, such as iron (Fe), manganese (Mn), cadmium (Cd), and chromium (Cr), which does not align with the results of this study. This may be explained by the fact that soil studies began two years into the war, and during this period, natural factors led to a decrease in the concentration of mobile heavy metal compounds. Most scientific studies by foreign researchers, such as H. Kanwal *et al.* (2024), examine the impact of heavy metals

from wastewater, industrial emissions, pollution, and other sources; however, the direct impact of military operations on the concentration of mobile heavy metal compounds has been little studied, which underscores the relevance of this study.

According to research by scientists such as B. Ponce-Lira *et al.* (2022), the use of conventional tillage has led to increased levels of heavy metals; however, these studies were primarily conducted on soils not contaminated by military operations and examined other soil types. However, most other studies still confirm the negative impact of standard tillage on heavy metal content, as demonstrated by the research of D. Or *et al.* (2021) and O. Bonchkovskiy *et al.* (2025). Therefore, in this case, the results of this study present a rather contradictory finding regarding the positive effect of tillage on heavy metal content in soils, which requires further investigation.

According to the monograph by Ya. Tsytisiura *et al.* (2022), the main agents of biological remediation are various plants, bacteria, fungi, and other organisms that act as hyperconjugates of various forms of heavy metals. For example, based on the results of numerous studies, the use of plants such as Sarpet mustard and white mustard (*Brassica juncea* L. and *Sinapis alba* L.), creeping wheatgrass (*Elymus repens* L.), osier (*Salix viminalis* L.), blue amaranth (*Amaranthus blitum* L.), rapeseed (*Brassica napus* L.), and buckwheat (*Fagopyrum esculentum* L.). Most legumes actively adsorb lead compounds from the soil: vetch (*Vicia*), alfalfa (*Medicago sativa* L.), peas (*Pisum sativum* L.), and fava beans (*Vicia faba* L.), but no vegetable crops are listed, since during

the growing season, compared to legumes and brassicas, they absorb significantly fewer nutrients, albeit due to higher soil acidity. These plants may be better able to absorb heavy metals in the form of an aqueous solution; therefore, this physiological aspect requires further study.

According to research by Asian scientists M. Lestari & A. Rosyidah (2022), weeds with fairly vigorous growth absorb large amounts of heavy metals, and in crop production, many of these plants are consumed as part of the diet. This uptake is particularly pronounced for mobile lead compounds. Therefore, in this study, a large number of weeds were allowed to germinate before tomato sowing, and this may have influenced the study results. In addition, various chelating agents (EDTA, etc.) are used to enhance remediation processes, based on the findings of S. Noller *et al.* (2022), which are often components of many complex micronutrient fertilizers; when combined with biological remediation, they can maximise effectiveness, significantly reduce the availability of heavy metals to plant organs, and enhance their leaching into lower soil layers, among other effects. In this study, chelated micronutrients were used, which may also have influenced the process of reducing heavy metal content in the soil, particularly divalent cations, as they are most readily chelated by chelating agents.

After treating the contaminated soil and planting tomatoes in it, there was a sharp decrease in the heavy metal content, confirming the positive impact of the treatment and remediation processes. The active uptake of heavy metals by tomatoes has been confirmed by studies conducted by researchers such as A. Bounar *et al.* (2020) and V. Melnychenko (2024), which must be taken into account when using these fruits for food; further research is needed on the extent to which tomato plants absorb heavy metals from soils contaminated by military operations in Ukraine. Studies by H.A. Hashem *et al.* (2018) and D. Dessu & M. Regasa (2025) confirm the high potential of tomato plants to absorb heavy metals due to their biochemical characteristics and the high acidity level in tomato fruits, which enhances the solubility and accumulation of these metals. This study did not directly measure heavy metal content in tomato plants, a factor that should be considered in future research. The results of this study are largely consistent with those of previous studies. In most publications, the results show a positive correlation between the influence of various plants and the reduction of heavy metal content in different soils, as is the case in this study. At the same time, the use of vegetable crops, particularly tomatoes, for soil phytoremediation,

taking into account the specific patterns of heavy metal accumulation in different plant organs, remains insufficiently studied.

CONCLUSIONS

As a result of hostilities, dangerous levels of copper (Cu) and lead (Pb) compounds, as well as the presence of explosive residues (TNT, DNT), were observed in the soil of the experimental field in the town of Snigurivka in 2024 (only copper (Cu) compounds exceeded the MPC – $5.16 \text{ mg/kg} > 3.0 \text{ mg/kg}$). The concentration of mobile Pb compounds decreased significantly from 19.28 to 0.12 mg/kg at sampling point 1, and at point 4 – from 15.14 to 0.16 mg/kg. The concentration of mobile Zn compounds also decreased significantly from 12.7 mg/kg to 0.01 mg/kg of soil at site 1, which was the lowest reduction compared to other sites, where the reduction was also very significant. The concentration of mobile Cu compounds decreased to a level below the instrument's detection limit. Soil cultivation, the planting of crops (tomatoes), and the use of irrigation likely led to a reduction in the concentrations of all mobile heavy metals, indicating the remediation of the studied soils.

In terms of agrochemical indicators, a significant decrease in ammonium nitrogen (NH_4^+) was also observed at point 4, from 126.3 to 3.6 mg/kg, indicating its substantial uptake by plants and possible complex formation with heavy metal compounds. An increase in available phosphorus (P_2O_5) to 574.3 mg/kg was also observed at point 4, which is most likely due to the effects of intensive fertilization. Irrigation water reduces heavy metal levels, as it has minimal concentrations, but it has a high degree of mineralisation, which must be taken into account in the future to prevent soil salinisation and alkalization. Irrigation water was characterised by high mineralisation, with TDS values ranging from 1,920 to 2,070 mg/l, but with safe levels of heavy metals, which may also be a factor in the reduction of heavy metal content in the soil samples. At all study sites in 2025, a significant decrease in the content of the explosive substances TNT and DNT was observed, which also confirms the impact of soil treatment and reclamation methods on their concentrations. Reclamation and agronomic measures lead to positive changes in soil acidity, nutrient status, and the direct impact of plants on soil chemical parameters, which must be utilised for the remediation of war-affected soils in Ukraine. Further research is needed on the use of various crop plants for the remediation of soils affected by military operations. In the future, a more detailed study is required of the extent to which tomatoes and other crop plants absorb mobile heavy metal compounds in

order to develop the most optimal strategy for soil re-mediation in Ukraine.

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CONFLICT OF INTEREST

None.

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Зміна динаміки вмісту поживних елементів, мікроелементів та важких металів у ґрунтах півдня України, вражених бойовими діями

Олександр Бабич

Асистент

Миколаївський національний аграрний університет

54008, вул. Георгія Гонґадзе, 9, м. Миколаїв, Україна

<https://orcid.org/0000-0002-4271-3629>

Михайло Федорчук

Доктор сільськогосподарських наук, професор

Миколаївський національний аграрний університет

54008, вул. Георгія Гонґадзе, 9, м. Миколаїв, Україна

<https://orcid.org/0000-0001-7028-0915>

Анотація. На території півдня України з лютого по листопад 2022 року дуже активно проводилися бойові дії, що мало вплив на хімічні показники сільськогосподарських земель, через що постає питання забруднення ґрунтів важкими металами та вибуховими речовинами. Метою дослідження було визначення агроєкологічного стану вражених бойовими діями ґрунтів півдня України в 2024 і в 2025 роках і проведення порівняльного аналізу змін даних показників після початку обробки та висіву томатів компанією InAgro. В статті проведено порівняльний аналіз вмісту мікроелементів (Zn, Mn, Fe, Cu), поживних елементів (рухомого азоту, фосфору та калію), деяких фізико-хімічних (кислотний показник pH) та хімічних показників (вміст хлорид-аніонів) та важких металів (Cd, Pb) у 2024 і 2025 роках земель Снігурівської територіальної громади, компанії InAgro. В період 2022-2024 років не проводили вирощування будь-яких сільськогосподарських культур. На досліджуваних ґрунтах господарством проводилось удобрення $N_{20}P_{20}K_{20}$, що є оптимальним для томатів, і проводиться крапельне зрошення з використанням води Інгулецької зрошувальної системи. Результати показали значне зниження вмісту важких металів та мікроелементів у порівнянні з 2024 роком з високою статистичною вірогідністю (Pb – зниження в середньому з 12,57 ppm до 0,13 ppm (в 100 разів), Cd – з 0,26 ppm до значень нижче 0,05 ppm (більше ніж в 5 разів), Cu – з 4,19 ppm до значень нижче межі вимірювання ($< 0.05\text{ ppm}$), Mn – з 19,3 ppm до 11,09 ppm (на 42 %), Zn – з 10,23 ppm до 0,03 ppm (в 340 разів)) що пов'язане із висаджуванням культурних рослин (*Solanum lycopersicum* L.) та інтенсивним використанням зрошення. Практичне значення отриманих результатів полягає у розумінні ступеня впливу культурних рослин на вміст важких металів і мікроелементів у ґрунті і визначенні потенційної небезпеки вмісту даних елементів у харчових частинах культурних рослин

Ключові слова: ремедіація; томати; зрошення; агроєкологічні показники; Інгулецька зрошувальна система