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Evaluating the impact of missile weaponry residues on the phytotoxicity of agricultural lands in Ukraine

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Abstract. Military aggression against Ukraine has caused an unprecedented degradation of the country's land, threatening the state's food security and the ecological component of agroecosystems in general. This article is devoted to the assessment of the biological response of agricultural crops (*Triticum aestivum* L., *Brassica juncea* L., and *Cannabis sativa* L.) to a specific combination of physical and chemical soil disturbances in the impact zone of Iskander missile fragments in Chernihiv Oblast. Unlike traditional studies of craters, the novelty of this work lies in investigating the consequences of midair missile destruction, which resulted in the scattering of fragments and explosion products without the formation of deep craters on agricultural land. The research methodology was based on a laboratory pot experiment using a concentration gradient of the studied soil (from 12.5% to 100%) mixed with quartz sand. Elemental analysis of the substrates, performed using the X-ray fluorescence method, demonstrated an increase in Fe, Mn, Zn, Pb, and Zr concentrations parallel to the increase in the proportion of the studied soil; however, the recorded values did not exceed the established maximum allowable concentrations. The results of the seed germination analysis confirmed the absence of acute phytotoxicity, indicating the possibility of safe crop germination in areas with a similar type of damage. The main scientific value of the results lies in identifying the differentiated response of vegetative organs. The root system was observed to be the most sensitive indicator of chemical load: A significant inhibition of root growth was recorded in wheat and mustard compared with the control (sand), which is explained by both the direct action of toxicants and the adaptive response of plants to changes in the substrate structure. At the same time, the development of the aboveground part was characterized by a marked stimulation: In the variants with the maximum content of the studied soil (100%), the shoot length of wheat, mustard, and hemp significantly exceeded the control. The practical significance of the work lies in justifying the possibility of returning such lands to agricultural use after conducting targeted monitoring. The obtained data indicate a high adaptive potential of the studied crops, allowing them to be considered as promising species for phytoremediation and stabilization of damaged soils. Further research will be aimed at studying the mechanisms of metal bioaccumulation in the marketable part of the harvest and assessing the risks of their entry into human food chains.

Keywords: military soil degradation; phytotoxicity; heavy metals; *Triticum aestivum*; *Brassica juncea*; *Cannabis sativa*; food security.

Introduction

Agriculture is a critical sector of the Ukrainian economy. Currently, it suffers from military actions that significantly reduce the agricultural areas potentially available for crop production. Specifically, according to Mustetsa (2025), more than 150,000 km² of Ukrainian land is currently mined; the exact proportion of agricultural land within this statistic remains unknown. However, it is well established that these areas are no longer contributing to the nation's food supply.

Researchers in Ukraine and worldwide are actively discussing this issue, as grain buyers both domestically and in Europe are raising concerns regarding potential contamination with heavy metals, explosive residues, or other pollutants. Consequently, Ukrainian scientists are intensively studying this problem. Ongoing efforts include assessing field contamination with heavy metals following various shell impacts, investigating sites of destroyed military equipment, and analyzing both chemical and physical impacts on the soil. The latter significantly affects field conditions, particularly by accelerating erosion processes. For instance, Novakovska et al. (2025) demonstrated critical levels of chemical contamination in combat zones. Specifically, titanium concentrations at impact sites of unidentified projectiles exceeded background levels by 150 times. Furthermore, mechanical compaction by heavy machinery and the destruction of the humus layer during demining not only reduce fertility but also provoke irreversible wind and water erosion. Laboratory studies of soils in Kharkiv Oblast (Krainiuk et al., 2025), sampled from sites of ammunition blast and burnt equipment, revealed significant exceedances of maximum allo-

wable concentrations for lead, zinc, and copper. The authors noted high heterogeneity in chemical contamination, which creates risks of bioaccumulation in food chains and requires specific site-cleansing measures.

Conversely, not all studies characterize Ukrainian soil contamination as universally critical. For example, an analysis of soil samples from ten locations in the Sumy, Kharkiv, and Chernihiv regions demonstrated the nonuniform nature of chemical pollution in active combat zones (Datsko et al., 2025). A comparative analysis of craters and background plots showed that the levels of manganese, strontium, and rubidium at the impact sites were often comparable to control points, suggesting a cumulative impact of both military and agrotechnical factors. This underscores the need for a differentiated approach to land rehabilitation that accounts for both direct war consequences and the general regional ecological context. This perspective is shared by Hlavatskyi et al. (2025); their study of Kharkiv chernozems using geochemical and magnetic methods indicated that military impact primarily manifests through physical destruction and loss of fertility rather than total chemical poisoning. Although heavy metal levels at missile and aerial bomb impact sites only slightly exceeded background values, localized catastrophes (such as helicopter crashes) caused cadmium concentrations to increase twelvefold, highlighting the need for targeted monitoring of "hot spots".

As laboratory research in these areas becomes increasingly difficult due to the hazards of soil sampling, Solokha et al. (2025) presented a methodology for the rapid identification of contaminated lands in Kharkiv Oblast based on the integration of open-source intelligence (OSINT), GIS technologies, and satellite monitoring. By geolocating military debris and

analyzing field roads, a mapping system was developed to document critical heavy metal exceedances. Using Maxar satellite imagery within the Kyinka community, Bonchkovskiy et al. (2023) identified an extensive network of craters on arable land, with the total volume of displaced soil exceeding 3,100 m³. It was established that the total area of direct mechanical destruction and indirect chemical impact accounts for over 430 hectares, confirming a critical level of soil cover degradation due to active hostilities. Technologies for assessing military-induced soil damage are evolving rapidly; for example, Kholoshyn et al. (2023) proposed a universal approach to monitoring military destruction based on decoding spectral patterns from satellite data to identify damage zones in biological cover and lithogenic bases.

However, it is vital not only to document contamination but also to investigate whether it leads to phytotoxicity for future crops or the accumulation of toxins in food products. In Mykolaiv Oblast, Hradovych et al. (2024) analyzed signs of soil phytotoxicity in the context of war, proving that profile degradation due to bombing and petroleum contamination creates critical risks for biological cycling. Phytotoxicity studies of an impact crater from a Shahed-136 UAV revealed a pronounced species-specific response: Complete growth inhibition was observed in *Lepidium sativum* and *Brassica napus*, while *Raphanus sativus* exhibited adaptive stress resistance. These data confirm the heterogeneity of contamination, requiring a differentiated approach to phytoremediation and monitoring of heavy metals and rare earth elements (Kovrov et al., 2026). Similarly, a study in Benghazi (Libya) revealed a clear spatial pattern of heavy metal distribution around landmine blast sites, with Pb, Cd, and Hg concentrations decreasing rapidly with distance (Al-Traboulsi & Alaib, 2023). Their study on *Vicia faba* L. confirmed the total unsuitability of contaminated soils for agriculture, as seeds sown near the blast site failed to germinate, and surviving plants at a distance of six meters showed significantly reduced growth and foliage.

Nevertheless, not all plants are adversely affected by heavy metals; some species act as accumulators, which can be utilized for postwar land restoration. For instance, El-Keblawy et al. (2024) evaluated three indigenous species in the UAE (*Pennisetum divisum*, *Tetraena qatarensis*, and *Brassica tournefortii*), identifying their high capacity for accumulating phytotoxic metals (PTMs). *Brassica* was most effective in accumulating Fe and Zn, while *Tetraena* demonstrated extremely high strontium (Sr) concentrations.

Despite the significant number of studies on the chemical composition of contaminated soils, the question of the actual biological response of crop plants to the specific combination of missile residues remains insufficiently explored. Therefore, the objective of this study was to evaluate the biological response of test crops to the specific combination of physical and chemical soil disturbances in the impact zone of an Iskander type missile on agricultural land.

Material and methods

The study site is located 2 km southwest of the village of Lavy, Sosnytsia District, Chernihiv Oblast. In March–April 2024, an area of 70 hectares was impacted by an Iskander missile system strike. A distinctive feature of sampling at this location is that the missile was destroyed in midair, resulting in the scattering of fragments across the field without the formation of a characteristic impact crater (Fig. 1).

The soil cover of the site is represented by grey forest soil on loess-like loams. The soil is characterized by a low humus content (organic matter – 2.5%) and a strongly acidic reaction (pH), which leads to a deficiency of calcium and magnesium. At the same time, a high level of supply of nitrate nitrogen, mobile phosphorus, and exchangeable potassium was recorded.

The sampling methodology involved taking point samples at the sites where missile fragments fell. A composite average sample was prepared by mixing these samples using the "envelope" method. This substrate was used as the basis for studying the direct impact of weaponry residues on the phytotoxic properties of the soil and the development of test crops.

The laboratory stage of the research began with bringing the samples to an air-dry state. The prepared soil was ground until it passed through a sieve with 1 mm meshes using a PM-5M laboratory soil grinder (Spectrometer-65 LLC, Kyiv, Ukraine), which ensured the homogeneity of the samples for further analysis. To measure the content of heavy metals and other chemical elements at the sampling sites, the elemental composition was analyzed using the X-ray fluorescence method with a Niton XL3t GOLDD+ (Thermo Scientific, Waltham, MA, USA) device. It is im-

portant to note that to assess the potential toxic load on the crops before starting the experiment, a concentration gradient was created by mixing the studied soil with pure quartz sand. The experimental variants included the following ratios of the sampled soil content: 12.5%, 25%, 50%, and 100%. Sand served as the control variant (Table 1). It is worth mentioning that none of the presented chemical elements exceeded the maximum allowable concentrations (MAC) according to the Resolution of the Cabinet of Ministers of Ukraine as of December 15, 2021, No. 1325.

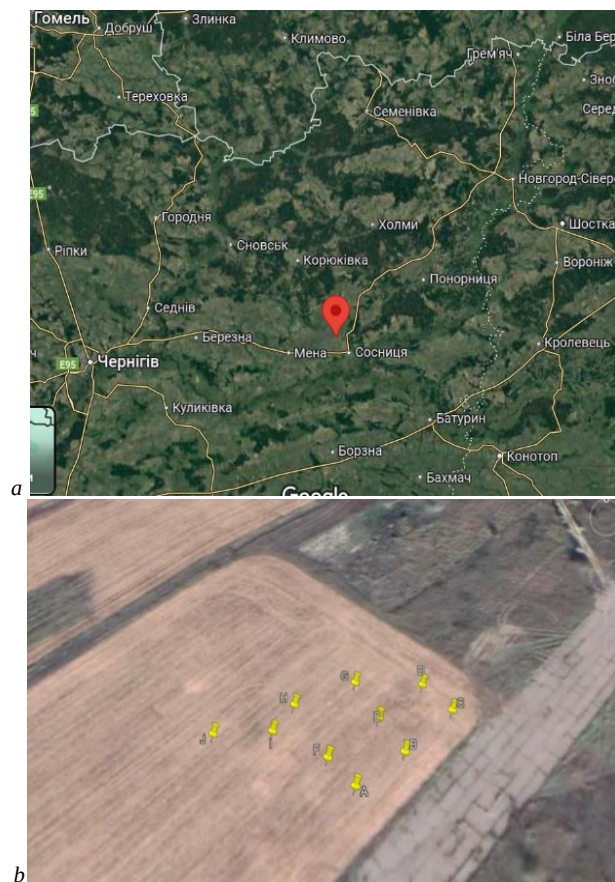


Fig. 1. Crater: a – location; b – places of sampling

The crops cultivated during the experiment were *Triticum aestivum* L., *Brassica juncea* L., and *Cannabis sativa* L. The selection of these test crops was based on two key factors: first, the need to assess the phytotoxic impact on representatives of different taxonomic groups with varying sensitivity to chemical stress and second, the economic significance of these crops for the agricultural sector of the Northeastern Forest-Steppe of Ukraine. This allowed us to forecast food security risks when restoring land use. Each variant was performed in triplicate.

The plants were grown in pot experiments, with each container containing 100 grams of substrate. Accordingly, 10 viable seeds of each crop were sown into each substrate variant. Laboratory germination was determined by conducting a germination test in a controlled environment. The seeds were placed on a moist substrate and maintained at an optimal temperature (20–22 °C). The final count of germinated seeds was performed on the seventh day, considering only those seedlings that showed well-developed essential structures, which characterize their potential for further growth under field conditions. At the final stage of the experiment, a morphological assessment was performed by measuring the lengths of the root and the shoot. The total duration of the experiment was 14 days (Fig. 2).

Statistical data processing, including ANOVA and Duncan's multiple range test, was performed using the Statistica 10.0 software (StatSoft Inc., Tulsa, USA).

Results

The seed germination in the substrates with concentration gradients of the studied soil is shown in Table 2. The germination rates remained stable, ranging from 83.3% to 96.7% (Table 2).

Table 1
Content of chemical elements in the studied substrates (N = 3, ppm)

Concentration gradient, %	Zr	Sr	Rb	Th	Pb	Zn	Fe	Mn	Cr	V	Ti	U
0*	79.82 ± 0.51	14.71 ± 0.30	14.16 ± 0.49	<LOD**	<LOD	<LOD	3980.22 ± 58.95	<LOD	15.34 ± 3.16	34.73 ± 4.09	1850.24 ± 17.97	<LOD
12.5	51.51 ± 0.40	15.11 ± 0.40	13.34 ± 0.72	<LOD	<LOD	<LOD	4140.94 ± 41.84	<LOD	22.36 ± 2.40	37.58 ± 0.52	1073.48 ± 9.85	<LOD
25	310.62 ± 4.54	54.06 ± 0.99	38.29 ± 0.70	5.02 ± 0.51	7.12 ± 1.79	11.41 ± 1.54	8808.75 ± 129.28	187.37 ± 7.16	48.23 ± 3.78	75.69 ± 3.66	3631.63 ± 21.50	<LOD
50	259.62 ± 2.72	50.68 ± 0.85	34.93 ± 0.64	4.26 ± 0.08	6.96 ± 1.19	16.30 ± 1.67	8857.78 ± 63.93	172.40 ± 7.97	45.99 ± 3.99	62.84 ± 0.90	2540.95 ± 49.32	<LOD
100	547.11 ± 2.19	103.58 ± 0.66	70.16 ± 0.64	8.49 ± 1.32	15.89 ± 2.10	33.47 ± 0.61	14631.64 ± 181.43	388.91 ± 14.55	56.71 ± 2.88	88.32 ± 1.19	3512.44 ± 23.21	6.67 ± 0.72

Notes: *0% – control group (100% pure quartz sand); 12.5–50.0% – experimental substrates prepared by mixing pure sand with the studied soil in the respective weight ratios; 100% – undiluted studied soil collected from the impact site; ** <LOD – limit of detection of the chemical element by the device.



Fig. 2. General view of seedlings of the studied crops growing on 100% concentrated soil substrate from the study area

For all three test objects (*Triticum aestivum* L., *Brassica juncea* L. and *Cannabis sativa* L.), the maximum germination values ($96.7 \pm 5.8\%$) were recorded at the minimum concentration of the studied soil (12.5%). This indicator slightly exceeded the control values (90.0–93.3%), which may indicate a primary stimulating effect of microdoses of mineral elements present in the soil from the impact site. At the maximum concentra-

tion (100.0% studied soil), a slight decrease in germination was observed for mustard and hemp (down to $86.7 \pm 5.8\%$), while wheat maintained a high level of $90.0 \pm 0.0\%$.

The results of ANOVA showed that the concentration of the studied soil did not have a statistically significant effect on the laboratory germination of the seeds ($F = 1.31$; $P = 0.26$). Since the p-value significantly exceeds the critical level of 0.05, it can be concluded that the chemical load of the degraded soils does not inhibit the initial stage of ontogenesis for the selected crops. The observed fluctuations in germination rates are within the range of natural variation and are not determined by the toxic effects of the substrate.

The analysis of morphometric parameters of *Triticum aestivum* L. revealed the response of the test crop to soil contamination with explosion products (Table 3). Despite the potential phytotoxicity of the sample from the missile impact site (100% of impacted soil), the highest shoot length among all variants was recorded: Its average length reached 21.30 ± 1.96 cm, which significantly exceeds the control (16.58 ± 2.89 cm) and other experimental groups. At the same time, the root length data differ significantly from the clear trend observed for the shoot. In particular, the greatest root length was recorded in the control variant (sand) and amounted to 9.49 ± 3.17 cm, which was accompanied by the highest level of variability among all groups. The lowest value was noted in the 50% concentration variant with an indicator of 1.84 ± 0.75 cm.

According to the ANOVA results, the concentration of the studied soil has a significant impact on the formation of wheat shoot length, as indicated by the high F-statistic value (11.14) at a significance level of $P < 10^{-4}$. This statistically verifies the absence of a phytotoxic effect of the soil from the missile impact site (100% of impacted soil) compared with the control group, as the observed growth parameters remained within or exceeded the control range. At the same time, the influence of the studied factor was also significant for root length; specifically, the high F-statistic value (14.28) at a significance level of $P < 10^{-5}$ confirms that the recorded inhibition of root length in all experimental variants compared with the control was a regular consequence of the influence of the studied substrate components.

The analysis of the growth of *Brassica juncea* L. (Table 4) revealed a clear dependence of seedling development on the concentration of the studied soil in the substrate.

The growth of the shoot part of the seedlings showed a steady upward trend with increasing soil concentration. The minimum shoot length was recorded in the control group (4.18 ± 0.47 cm). A significant increase in this parameter was observed starting from a 12.5% concentration (4.90 ± 0.60 cm), with the maximum value reached at a 100% concentration (6.22 ± 0.69 cm). According to the statistical indices (α , β , γ), the stimulation of shoot growth in all experimental variants compared with the control was reliable and reached its peak in the undiluted studied soil.

Table 2
Laboratory seed germination of the studied crops depending on the substrate composition (N = 45, %)

Crop	Control (0%)	12.5%	25%	50%	100%
<i>Triticum aestivum</i> L.	90.00 ± 10.00^{ab}	96.67 ± 5.77^a	83.33 ± 5.77^a	93.33 ± 5.77^{ab}	90.00 ± 0.00^{ab}
<i>Cannabis sativa</i> L.	93.33 ± 5.77^{ab}	96.67 ± 5.77^a	93.33 ± 5.77^{ab}	93.33 ± 5.77^{ab}	86.67 ± 5.77^{ab}
<i>Brassica juncea</i> L.	93.33 ± 5.77^{ab}	96.67 ± 5.77^a	93.33 ± 5.77^{ab}	93.33 ± 5.77^{ab}	86.67 ± 5.77^{ab}

Note: mean $\pm$ SD followed by different superscript letters (α , β) within the table indicate statistically significant differences at $P < 0.05$ according to Duncan's multiple range test.

Table 3

Mean values and variability parameters of shoot and root length of *Triticum aestivum* L. depending on the concentration of the studied soil in the substrate (cm, N = 30)

Concentration gradient, %	Shoot length	Root length
0	16.58 ± 2.89 ^a	9.49 ± 3.17 ^d
12.5	17.77 ± 2.95 ^{ab}	3.16 ± 1.84 ^c
25	17.92 ± 3.22 ^{ab}	2.98 ± 0.86 ^b
50	18.44 ± 2.55 ^b	1.84 ± 0.75 ^b
100	21.30 ± 1.96 ^c	4.75 ± 2.00 ^a

By contrast, the root system of *Brassica juncea* L. exhibited a different reaction. The maximum root length was observed in the control group (3.84 ± 0.43 cm). All experimental variants showed a significant decrease in root growth compared with the control. The most pronounced inhibition occurred at 25% and 50% concentrations, as confirmed by the statistical index "b" according to Duncan's multiple range test. Interestingly, at a 100% concentration, some stabilization of root growth was observed (2.34 ± 0.66 cm), although this value remained significantly lower than the control level.

The conducted one-way analysis of variance confirmed the high statistical significance of the studied factor's influence on the growth processes of mustard. The obtained F-statistic values for shoot length (F = 44.7) at a significance level of $P < 10^{-6}$ and root length (F = 59.7) at a significance level of $P < 10^{-6}$ significantly exceed the critical values. These data statistically confirm the nonlinear response of the crop to changes in substrate concentration, where the chemical composition of the soil from the impact site acts as a powerful factor influencing both the stimulation of the aerial part and the regular inhibition of the root system.

Table 4

Mean values and variability parameters of shoot and root length of *Brassica juncea* L. depending on the concentration of the studied soil in the substrate (cm, N = 30)

Concentration gradient, %	Shoot length	Root length
0	4.18 ± 0.47 ^a	3.84 ± 0.43 ^d
12.5	4.90 ± 0.60 ^b	1.99 ± 0.48 ^c
25	4.91 ± 0.18 ^b	1.46 ± 0.23 ^b
50	5.15 ± 0.74 ^b	1.93 ± 1.02 ^b
100	6.22 ± 0.69 ^c	2.34 ± 0.66 ^a

The analysis of morphometric parameters of *Cannabis sativa* L. seedlings indicates a specific response of vegetative organs to changes in the concentration of the studied soil in the substrate.

The development of the aboveground part is characterized by high stability at low and medium concentration levels. In the variants with 12.5%, 25%, and 50% of the studied soil, shoot length indicators (ranging from 6.14 to 6.90 cm) exhibit no statistically significant differences from the control (6.63 ± 1.17 cm) and form a single homogeneous group "a". However, in the undiluted studied soil (100%), a significant stimulation of growth was observed, with the shoot length reaching 8.36 ± 1.09 cm, which is statistically confirmed by the index "b".

By contrast, the root system demonstrated a more complex, nonlinear response dynamic. The highest root growth rates were recorded at a 12.5% concentration (2.65 ± 0.86 cm), which exceeds the control values (2.09 ± 0.63 cm) and belongs to the statistical group "cd". A subsequent increase in the proportion of the studied soil to 25% led to a significant inhibition of root growth to the minimum values in the experiment (1.59 ± 0.44 cm, group "bc"). After this point, there was observed a trend toward length recovery in the root system, which reached 2.47 ± 0.74 cm in the 100% soil variant (group "a"), indicating the high adaptive capacity of hemp to the chemical composition of the substrate from the impact site.

Table 5

Mean values and variability parameters of shoot and root length of *Cannabis sativa* L. depending on the concentration of the studied soil in the substrate (cm, N = 30)

Concentration gradient, %	Shoot length	Root length
0	6.63 ± 1.17 ^a	2.09 ± 0.63 ^d
12.5	6.38 ± 0.79 ^a	2.65 ± 0.86 ^{cd}
25	6.14 ± 1.03 ^a	1.59 ± 0.44 ^{bc}
50	6.90 ± 1.24 ^a	1.89 ± 0.43 ^{ab}
100	8.36 ± 1.09 ^b	2.47 ± 0.74 ^a

The results of the one-way analysis of variance confirm the high statistical significance of the studied factor's influence on the growth parameters of the *Cannabis sativa* L. seedlings. High F-statistic values for shoot length (F = 17.6) at a significance level of $P < 10^{-5}$ and root length (F = 12.4) at a significance level of $P < 10^{-5}$ indicate that the intergroup variability caused by different soil concentrations in the substrate significantly exceeds the random deviations within the samples. At the same time, the factor had a greater influence specifically on the development of the aboveground part (MS_{Effect} = 20.3), pointing to a pronounced morphological response of the shoot to changes in substrate conditions.

Discussion

The analysis of the morphometric parameters of the studied crops revealed a consistent difference between the development of the aboveground and underground parts of the plants. A key factor determining the short length of the shoots in the control groups was the nutrient poverty of the substrate. The pure sand used in the control is an abiotic environment with a deficiency of macro- and micronutrients, which limits shoot growth. By contrast, the addition of the studied soil, despite the presence of potential explosion products, enriches the substrate with organic matter and mineral components, stimulating the growth processes of the aboveground biomass in all experimental variants.

The response of the shoot part of wheat and mustard demonstrated a clear positive correlation with soil concentration: Maximum values were recorded in variant V4, where the shoot length significantly exceeded the control. This indicates that the nutrient resource of the studied soil completely offsets the potential toxic impact of explosion products during the early ontogeny of the shoots. Hemp (*Cannabis sativa* L.) showed a similar trend, although a certain stabilization of growth was observed at low concentrations (12.5–25.0%), indicating a higher tolerance of this crop to a nutrient-poor substrate compared with other test objects.

Unlike the shoot, the root system proved to be a much more sensitive indicator of phytotoxicity. The greatest root length in wheat and mustard was observed specifically in the control, which is a typical adaptive response of plants to nutrient deficiency in sand – active root elongation to search for resources. The addition of soil caused a sharp inhibition of root growth, particularly pronounced at a concentration of 25%. This decline in the growth of the root system indicates that at this specific concentration, the negative effect of potential toxicants outweighs the positive trophic effect of substrate enrichment.

Special attention should be paid to the hormesis effect recorded in *Cannabis sativa* L. and *Triticum aestivum* L. at the lowest concentration of the studied soil. In these cases, the root length was higher than or close to the control, which is explained by the stimulating influence of microdoses of stress factors against the background of improved mineral nutrition. High variance values at medium concentrations confirm the instability of the physiological state of the plants, while the uniformity of indicators in the 100% variants indicates the successful completion of the primary adaptation phase of the crops to the specific chemical composition of the studied soil. The specific morphological response of *Cannabis sativa* L. seedlings observed in our study, characterized by stable shoot growth even at high substrate concentrations, aligns with recent findings on the high tolerance of industrial hemp to multimetal contamination. Research indicates that hemp varieties can maintain significant biomass and plant height even in soils strongly contaminated with copper, arsenic, cadmium, and lead. This resilience is primarily attributed to a specialized distribution strategy, where the plant acts as a phytoattenuation agent by retaining most toxic elements (ranging from 47.6% to 92.9% depending on the element) within the root system. Such a mechanism prevents the translocation of pollutants to the aboveground organs, which explains the stimulating effect on shoot length recorded in our experiment and supports the potential for safe nonfood utilization of hemp grown on anthropogenically degraded and military-affected agricultural lands (Guo et al., 2024).

It is well known that anthropogenic pressure leads to a critical accumulation of heavy metals in the soil, causing complex disruptions of physiological and biochemical processes in plants, including an imbalance in nutrient uptake, disorganization of chloroplasts, and the development of oxidative stress. Studies of various test crops, such as *Brassica juncea* and *Cannabis sativa*, demonstrate their ability for accumulation and translocation of toxicants, with roots usually acting as the main barrier where the largest portion of metals accumulates (Sperdouli, 2022). An interesting study was performed by Handayani et al. (2023), who investigated the

effect of biosynthesized silver nanoparticles on *Ipomoea aquatica* and *Brassica rapa*. It highlighted the pronounced species-specificity of the plant response to the pressure resulting from metal contamination of the substrate. In this case, mustard proved to be significantly more sensitive to the toxic action of silver than water spinach. The authors note that even at identical concentrations of nanoparticles (30–50 mg/L), phytotoxic effects can vary from a complete absence of influence on germination to a significant inhibition of biomass and seedling height. This confirms the scientific hypothesis that different agricultural crops have unique barrier mechanisms and different levels of tolerance to the accumulation of nanoscale metals in the tissues.

A comparative analysis of the obtained data with the results of the study (Palchykov et al., 2025) allows us to assert that the revealed growth stimulation of the aboveground parts of *Triticum aestivum* L., *Brassica juncea*, and *Cannabis sativa* in variants with a high concentration of the studied soil is a consequence of the trophic factor prevailing over the toxic impact of explosion products in the early stages of ontogeny. While the control (sand) acts as an inert medium with a biogen deficiency, the addition of anthropogenically altered soil enriches the substrate with organic matter and mineral elements, which, according to the concept of hormesis, nullifies the inhibitory effect of TNT residues and other compounds. At the same time, the pronounced inhibition of the root system in all experimental groups compared with the control aligns with the authors' conclusions regarding the primary vulnerability of underground organs to chemical stress; moreover, the drop in root growth in variant V2 (25%) may indicate reaching a critical threshold of phytotoxicity before the activation of adaptive mechanisms, confirming the need to consider agrochemical changes in damaged soils when assessing environmental risks in combat zones. A comparison of the data obtained in our study with the results of the study on the impact of arsenic on *Cannabis sativa* and *Brassica juncea* confirms the trend toward high tolerance of these crops, which was observed in both works. According to the data (Picchi et al., 2022), they can increase biomass even under conditions of significant chemical pressure without visible signs of phytotoxicity. However, while in the mentioned study the main stress marker was a significant decrease in biomass (by 25–50%), our experiment observed the opposite effect of shoot growth stimulation, explained by the advantage of the studied soil's nutrient resource over its toxic action. This indicates that, unlike industrial arsenic contamination, soils from missile impact sites have a specific influence where a negative reaction is clearly manifested only at the root system level, while the aboveground part demonstrates adaptive growth stimulation against the background of substrate enrichment with biogenic elements. The high viability and shoot stimulation observed in our experiment, particularly at lower soil concentrations, align with evidence that specific nanomediators can effectively promote growth under heavy metal stress by elevating chlorophyll content and suppressing oxidative stress. This supports the hypothesis that the negative impact of substrate toxicity from missile impact sites can be partially offset by the plants' internal adaptive mechanisms, similar to the mitigative effects observed with reduced graphene oxide nanoparticles in wheat plants under lead stress. Such a stabilization of physiological processes is often associated with the enhanced activity of antioxidant enzymes, including ascorbate peroxidase, superoxide dismutase, peroxidase, and catalase, which effectively neutralize reactive oxygen species generated due to soil contamination (Zhan et al., 2024).

It is also important to note that all crops selected for the study have been actively researched by scientists for use in phytoremediation measures in contaminated soils. This applies to mustard, as reflected in the studies by Sut-Lohmann et al. (2023), Zunaidi et al. (2024), and Yatsenko et al. (2024). The scientists have come to the same conclusion regarding *Cannabis sativa* L. Furthermore, after the absorption of heavy metals from the soil, they propose using the plant for biofuel production (Kumar et al., 2017; Rheay et al., 2021). Furthermore, the study by Nayak et al. (2015) confirmed the effectiveness of using *Triticum aestivum* L. in the phytoextraction of hexavalent chromium.

Conclusions

The conducted research revealed the nature of the impact of soils degraded by combat operations on the early ontogenetic stages of *Triticum aestivum*, *Brassica juncea*, and *Cannabis sativa*. The scientific novelty of the work lies in identifying a differentiated response of vegetative organs: While the root system demonstrated maximum length in the sand, the control substrate, as an adaptive response to nutrient deficiency in it, the

aboveground parts of the experimental variants showed growth stimulation caused by the trophic enrichment of the substrate with biogenic elements from the studied soil. The practical significance of the results lies in substantiating the possibility of further using these areas for agricultural production, as the recorded total concentrations of elements did not exceed the maximum allowable levels according to the Resolution of the Cabinet of Ministers of Ukraine No. 1325, and the laboratory experiment revealed no critical inhibition of the physiological state of the crops. Further research is planned to study the accumulation of heavy metals in the generative organs of plants and to assess the quality of the resulting products to ensure food security in liberated territories. In future works, special attention will be paid to the dynamics of toxicant transfer from the soil into trophic chains under conditions of prolonged crop vegetation directly in field conditions.

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