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**Maryna Samilyk,**
**Tetiana Synenko,**
**Nataliia Bolhova,**
**Bohdan Lukhanin,**
**Nataliia Borozenets**

# ASSESSMENT OF THE RISK OF POLLUTION OF THE ECOSYSTEM AND AGRICULTURAL PRODUCTS IN THE ZONE OF MILITARY CONFLICT

*The object of research is the content of toxic elements in soils, pasture grass and cows' milk in settlements located near the combat zone. However, there is virtually no data on the contamination of territories located near the epicenter of military events. This does not make it possible to assess all potential risks of ecosystem contamination caused by military actions. The samples were collected in the territory of the Mykolaivka village community (Ukraine), which is located within a 50-kilometer zone from the state border with Russia. It was found that with an increase in the intensity of drone attacks (by 40%) and missile attacks (by 25%), an increase in the content of toxic metals Cd, Pb, and Cu in the soil was observed. The concentration of Cd (17.63 ± 0.27 ppm) found in sample S5 is the most threatening, as it is 294 times higher than the WHO recommended permissible level. In the tested soil samples, the maximum permissible concentration of lead is observed to be exceeded by 0.2–1 ppm. In May 2025, its content in the soil sampled in the village of Ulyanivka increased by 2.89 ppm, in the village of Tovsta by 2.57 ppm. In the pasture grass sample G3, an excess of Cd (0.07 ± 0.04 ppm), Pb (1.59 ± 0.44 ppm), and Zn (15.45 ± 4.74 ppm) was recorded. Cd content in milk in May 2025 ranges from 0.012–0.016 ± 0.01 ppm, which is 5–6 times higher than the WHO recommended values. Exceedance of the permissible lead level was also recorded in all samples, with the highest proportion (< 0.23 ± 0.11 ppm) in sample M9. The findings highlight the harmful effects of military activities on ecosystems and the safety of agricultural products, even in regions near conflict zones where no active combat is taking place. To address this, ongoing monitoring of soil and vegetation contamination, along with regular assessments of milk quality in these areas, is strongly recommended.*

***Keywords:*** *heavy metals, soil, milk safety, ecosystem contamination, military influence.*

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## 1. Introduction

Soil quality undergoes significant changes as a result of armed conflicts. Most pollutants are resistant to biological degradation or treatment. They remain in the soil and groundwater for decades and become a source of plant contamination, potentially harming the environment [1]. Therefore, determining the extent of soil contamination caused by military operations allows for an assessment of environmental risks and future negative consequences for terrestrial ecosystems. It has been established that soils on military sites remain significantly contaminated with toxic compounds for many decades. They contain harmful substances such as Sb, Pb, uranium (U), 2,4-dinitrotoluene, 2,4,6-trinitrotoluene, 1,3,5-trinitro-1,3,5-triazacyclohexane, and others [2]. These pollutants can enter groundwater, affecting drinking water sources, and can also join the food chain through contaminated plants, posing serious risks to human health and ecosystems.

It has been repeatedly proven that military activities lead to soil contamination with Pb and Cu [3]. During ground combat operations and bombing, Pb, Cu, Cd, Sb, Cr, Ni, and Zn accumulate in the soil [4]. They accumulate in the environment from weapon and fuel residues. These pollutants can enter the food chain, contaminate water sources, and cause direct harm through contact or inhalation. They can also disrupt ecosystems, affecting plant and animal life, as well as soil fertility and water filtration.

Cadmium is mainly used to manufacture batteries, particularly rechargeable nickel-cadmium batteries, which are used in various types of military equipment and vehicles. Lead is used in the production of bullets and other ammunition, as well as in the construction of military vehicles and aircraft. Zinc is used to galvanize metals in order to prevent corrosion, which is crucial for maintaining the integrity of military equipment and infrastructure. Chromium and nickel are often used in the production of stainless steel and other alloys for military vehicles, aircraft and naval vessels [5]. Antimony is used in metal alloys for the production of ammunition and batteries. Shooting range soils are considered a key anthropogenic source of Sb [6]. Thus, the main soil contaminants resulting from military operations are Cd, Pb, Zn, Cr, Ni and Sb.

Soil contamination with heavy metals has also been documented as a result of wars in Syria, Iraq [7], Vietnam, Kuwait, and the Balkans [8]. Soil contamination leads to contamination of vegetation and, as a result, agricultural products, in particular cow's milk. Monitoring Pb and Cd in milk should be considered a fundamental part of health protection and product quality [9]. Heavy metals enter cow's milk mainly through livestock feed and drinking water (as well as through the atmosphere) [10]. In recent years, the contamination of milk with toxic elements (especially lead) has been recognized as one of the most serious aspects of environmental pollution for human health, as milk is widely

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consumed, especially by children [11]. To the best of our knowledge, no studies have been conducted on the concentration of heavy metals in milk from livestock living near or exposed to contamination as a result of the military conflict in Ukraine.

Environmental degradation resulting from military action can create a vicious cycle of ecosystem disruption, exacerbating resource scarcity and fueling further conflict. The war in Ukraine, which has been ongoing for more than 10 years, is an example of this trend. Against the backdrop of resource shortages caused by climate change, the resulting air pollution not only poses immediate health risks but also leads to long-term environmental degradation, which could further destabilize Eastern Europe [12].

This war is having a devastating impact on the environment. Analysis of soil samples taken from the Hetmansky, Desnyansko-Starogutsky and Holosiivsky national nature parks has shown that these protected areas are contaminated with elements classified as hazard classes I–III, such as Pb, Mn, Zn, Cu, V, Sr, etc. The pollution of these areas exceeds regional background values but is mainly within the maximum permissible concentrations [13].

It is known that almost 35% of Ukrainian territory is subject to soil degradation due to the consequences of the war. The land is mined or damaged, and some agricultural land is unsuitable for growing crops [14]. A number of studies have been conducted in the Kharkiv, Mykolaiv, Kherson, Zaporizhzhia, Kyiv, and Chernihiv regions. Since August 2024, the Sumy region has become a new hotspot on the map of hostilities in Ukraine. This territory is not only a direct zone of conflict, but also a transit zone for various airborne objects, as it shares a border with the aggressor country.

Analyzing the impact of the war on the environment of the Sumy region is extremely important for several reasons. It helps to understand the extent of immediate and long-term damage to ecosystems and human health, develop effective recovery strategies, and potentially prevent further environmental degradation. In addition, assessing environmental damage is vital for holding those responsible accountable and ensuring environmental justice. The impact of aerial bombing on agricultural land has already been studied, and the level of heavy metal contamination has been established [15] in some areas of the Sumy and Chernihiv regions. However, there is virtually no data on the impact of military operations on soil safety and agricultural production in this area.

Research into the impact of military operations on heavy metal content in soil began in April 2025 [16]. The initial results made it possible to determine the baseline level of contamination. Further measurements taken in May and July continued the monitoring process and made it possible to assess the dynamics of change.

Although individual case studies highlight specific instances of environmental damage, there is a lack of comprehensive research examining broader patterns of environmental degradation caused by war. This research gap highlights the need for a more thorough study of how war contributes to ecocide and to propose options for legal frameworks to protect the environment during and after conflicts.

Therefore, it is important to assess the environmental risks of soil and agricultural product contamination not only in areas where active combat operations are not taking place, but also in adjacent territories where military equipment and aircraft are constantly moving. This will make it possible to determine whether there is a threat to the ecosystem and agricultural production in areas located within a 50-kilometre zone of military conflict.

*The aim of research* is to assess the impact of military operations on the contamination of soil, pasture grass and cow's milk with heavy metals.

To achieve the aim, it is necessary to complete the following objectives:

1. To investigate the pH of the soil and the content of toxic elements in it.
2. To investigate the content of toxic elements in pasture grass.
3. To investigate the content of toxic elements in cow's milk.

## 2. Materials and Methods

### 2.1. The object and hypothesis of research

*The object of the research* is the content of toxic elements in soils, pasture grass and milk in settlements located near the combat zone. The main working hypothesis of the study is that the movement of various military aircraft causes contamination of soil and soil cover with toxic elements. Since pasture grass is contaminated, this can lead to contamination of cows' milk.

### 2.2. Materials

The research was conducted in April, May and July 2025 in the territory of the Mykolaivka village community in Sumy district, Sumy region (Ukraine). Samples were taken in settlements located near the state border with Russia: Ulyanivka village (29 km), Tovsta village (39 km), and Sulske village (43 km). The distance to the military zone is 20 km.

Aircraft, helicopters, missiles, unmanned aerial vehicles, guided aerial bombs, etc. are constantly moving through this territory. Missile and Shahid strikes were recorded in the villages of Tovsta and Ulyanivka (Sumy Regional Military Administration, n.d.). However, soil samples were taken from undamaged areas at least 1 km away from the crater. Field research was conducted three times in each settlement. In the village of Ulyanivka S1 (in April), S2 (in May), S3 (in July). In the village of Tovsta S4 (in April), S5 (in May), S6 (in July). In the village of Sulske S7 (in April), S8 (in May), S9 (in July).

Grass samples from pastures were also collected three times (in April, May and July) in each settlement. In the village of Ulyanivka G1 (in April), G2 (in May), G3 (in July). In the village of Tovsta G4 (in April), G5 (in May), G6 (in July). In the village of Sulske G7 (in April), G8 (in May), G9 (in July).

In these same settlements, samples of whole milk were collected from cows grazing on pastures in the soil and grass sampling area. Samples M1, M2 and M3 were collected in the village of Ulyanivka, M4, M5, M6 in the village of Tovsta, and M7, M8, M9 in the village of Sulske in April, May and July, respectively.

### 2.3. Research on the content of toxic elements in soil

To collect soil samples, a vertical cut was made to a depth of at least 20 cm. The selected sample was kneaded by hand, roots and stones were removed, and it was placed in a large container. To form an average sample, the soil in the container was thoroughly mixed. After that, they poured it onto the film and evenly distributed it into 4 parts. From each part, they took 100–200 grams of soil and placed it in a bag for transporting samples (the total volume of the average sample was at least 0.5 kg).

Soil samples were dried at 100°C for 6 hours and ground using a PM-5M mill (Ukraine). They were sieved through a brass sieve with hole diameter of 1 mm. The average sample for analysis was taken according to the standard method, in particular, the soil was spread out on paper with a thickness of up to 1 cm, divided into 9 equal squares and a few grams were taken from each to fill the cuvette for analysis. The content of heavy metals was determined using pXRF (Thermo Scientific Niton XL 2, USA) at high and low wavelengths for 90 seconds for each wave in triplicate.

Twenty-seven chemical elements were identified, but only seven (Cd, Pb, Zn, Cr, Ni, Sb, Cu) are shown in this study, the accumulation of which may be related to military operations.

Soil pH was determined according to DSTU ISO 10390:2001 using a pH meter-millivoltmeter pH-150MA.

### 2.4. Research on the content of toxic elements in pasture grass

Grass samples were collected from pastures where soil samples were taken. To form a sample, the green part of the plants was cut at three different points of the experimental plot. The collected plants were thoroughly mixed, and an average sample weighing 1 kg was selected.

Heavy metals (Pb, Cd, Zn, Cu) in grass were determined by absorption spectrometry using an AAS-30 spectrophotometer (Germany). The mass fraction of heavy metals was determined according to GOST 30178-96. Preliminary mineralization according to DSTU 7670:2014.

**2.5. Research on the content of toxic elements in milk**

Cow's milk samples were collected from private farms of cows grazing in the study areas. For analysis, unseparated milk collected during midday milking was used. The content of toxic elements in milk was determined by atomic absorption spectrometry according to GOST 30178-96. Preliminary mineralization was carried out according to DSTU 7670:2014.

**2.6. Statistical analysis**

The final results are presented as the mean ± standard deviation obtained from three independent exposures conducted in three separate studies. Student's *t*-test was used to assess the statistical significance of the difference between groups. Differences were considered significant at a probability level of $p \leq 0.05$.

**3. Results and Discussion**

**3.1. Soil research results**

Analysis of soils in the territory of the Mykolaivka territorial community showed (Table 1) that there is a significant excess of cadmium content in the soil.

It is difficult to prove a direct impact of the escalation of the military situation in the region, since attacks by guided bombs from multiple launch rocket systems, mortars, and tube artillery decreased in May 2025. However, the number of FPV drone attacks increased significantly (by 40%), and missile strikes quadrupled. Internal combustion engines and jet engines are sources of Cd pollution of the ecosystem. The increase in the number of missile strikes on the Sumy region could have led to the accumulation of this toxin in the soil. It was found that in May 2025, the concentration of Cd in all soil samples increased by 2–4 ppm compared to the values obtained in April 2025. The highest accumulation of Cd per month was observed in the Tovsta village (an increase of 4.16 ppm), the lowest in the Sulske village (an increase of 2.71 ppm).

Cd is one of the most toxic heavy metals; its toxicity can be considered multidirectional. It poses a health risk to both humans and animals. Cd has no biological function in plant growth, but readily accumulates in plants and edible parts of crops through the metabolism of essential plant nutrients such as Zn and Fe. Given the serious health risks associated with cadmium, the accumulation of this toxin in the soil may pose a serious threat to the future environmental safety of the region.

Also, in the experimental soil samples (S2, S5, S6), the maximum permissible Pb concentration was exceeded by 0.2–1 ppm. Thus, in May 2025, the content of the soil sampled in the Ulyanivka village increased by 2.89 ppm, in the Tovsta village – by 2.57 ppm. In July 2025, soil Pb concentrations decreased in all experimental samples.

Burning rocket fuel, especially those containing lead compounds, can lead to significant Pb accumulation in soil. This accumulation has a variety of harmful effects, including impaired plant growth, disruption of soil ecosystems, and potential risks to human health.

Pb is a highly toxic metal that affects nearly every organ in the body. Of all organs, the nervous system is the most affected target of lead toxicity in both children and adults. Long-term lead exposure in adults can result in decreased performance on some cognitive tests that measure nervous system function. Considering that some studies indicate the possibility of soil contamination with Pb as a result of artillery shelling, it can be assumed that this led to the accumulation of this metal in the soil.

Ni, which was found in large quantities in samples S2 (38.28 ± ± 0.69 ppm), S5 (39.79 ± 0.80 ppm), and S8 (35.93 ± 0.49 ppm), may also pose a potential threat. Accumulation of Ni in soil as a result of military actions poses significant risks due to its toxicity and potential contamination of the ecosystem. Although Ni is not the only metal released, it is a common byproduct of explosions and weapon residues, potentially affecting soil, water, and even human health.

Since military activities, including explosions, weapons use, and destruction of military equipment, can release nickel into the soil. This could be the reason for the increase in its share of the soil in May 2025 and July 2025. Nickel can accumulate from ammunition, vehicle components, and other materials used in military operations. Ni is a heavy metal that, in high concentrations, can be toxic to plants and animals, especially humans. It can disrupt various biological processes, which can lead to health problems. The results also showed a significant accumulation of Cu in the soil. Since there was no soil study in this area before the war, it is difficult to prove that the increase in its concentration is related to military action. Since the soil samples were collected in non-arable areas, it can be argued that the increase in their mass fraction is not caused by active agricultural activity.

The highest concentration of Cu in the soil was observed in May 2025 (21.46 ± 0.32 ppm, 21.69 ± 0.44 ppm, and 19.74 ± 0.25 ppm, respectively). Copper accumulation in soil can be harmful, affecting plant growth, soil microbial activity, and potentially posing a risk to human and animal health. Although Cu is an essential micronutrient for plants, excessive amounts can become toxic, leading to reduced crop yields and even affecting soil fertility. Cu pollution was found to exert significant selection pressure on soil microbiota, as demonstrated by beta diversity and correlation analysis between taxa and Cu content. Regular monitoring of Cu levels in soil is critical to identify potential contamination and take appropriate action. It is therefore also advisable to examine the content of this trace element in the soil and vegetation.

**Table 1**

pH level and content of toxic elements in the soil

| Indicator | Maximum permissible concentration value in Ukraine, ppm | Maximum permissible concentration value to the WHO, ppm | Research samples, ppm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | S1 | S2 | S3 | S4 | S5 | S6 | S7 | S8 | S9 |
| pH | – | – | 6.9 ± 0.03 | 6.9 ± 0.03 | 7.0 ± 0.03 | 7.0 ± 0.01 | 6.9 ± 0.01 | 7.1 ± 0.01 | 7.3 ± 0.03 | 7.4 ± 0.03 | 7.3 ± 0.03 |
| Cd | 3.0 | 0.06 | 13.5 ± 0.02 | 17.1 ± 0.17 | 16.4 ± 0.19 | 13.47 ± 0.12 | 17.63 ± 0.27 | 16.18 ± 0.05 | 13.75 ± 0.05 | 16.46 ± 0.10 | 16.49 ± 0.09 |
| Pb | 32.0 | 10.0 | 7.57 ± 1.20 | 10.46 ± 0.24 | 8.96 ± 1.42 | 8.42 ± 0.14 | 10.99 ± 0.11 | 10.21 ± 0.15 | 7.98 ± 0.32 | 9.26 ± 1.50 | 8.21 ± 1.33 |
| Zn | – | 50.0 | 7.19 ± 0.09 | 9.27 ± 0.51 | 10.19 ± 0.08 | 7.75 ± 0.21 | 10.49 ± 0.18 | 10.35 ± 0.43 | 6.72 ± 0.26 | 8.93 ± 0.27 | 10.19 ± 0.18 |
| Cr | – | 100.0 | 17.69 ± 2.97 | 22.70 ± 3.70 | 27.21 ± 4.45 | 19.57 ± 0.16 | 16.15 ± 0.09 | 27.24 ± 4.62 | 16.39 ± 2.79 | 24.85 ± 0.13 | 31.01 ± 0.11 |
| Ni | – | 40.0 | 27.04 ± 4.44 | 38.28 ± 0.69 | 29.98 ± 5.87 | 29.81 ± 0.40 | 39.79 ± 0.80 | 33.40 ± 5.04 | 23.46 ± 4.08 | 35.93 ± 0.49 | 29.97 ± 5.38 |
| Sb | 4.5 | 36.0 | 19.37 ± 0.11 | 24.93 ± 0.26 | 23.90 ± 0.19 | 19.46 ± 0.13 | 25.82 ± 0.25 | 23.67 ± 0.18 | 17.78 ± 3.02 | 23.89 ± 0.08 | 21.29 ± 3.63 |
| Cu | – | 8.39 | 16.76 ± 0.48 | 21.46 ± 0.32 | 19.44 ± 0.70 | 16.78 ± 0.55 | 21.69 ± 0.44 | 19.37 ± 0.79 | 16.51 ± 0.09 | 19.74 ± 0.25 | 17.66 ± 2.48 |

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The detected changes in the chemical composition of the soils indicate significant anthropogenic influence associated with military actions. Such changes not only reduce fertility but also have a direct impact on the state of the vegetation cover. Plants, as a component of the ecosystem, are sensitive to changes in environmental conditions – especially to pollution with heavy metals, a decrease in the level of humus, or soil compaction from explosions. This can lead to a decrease in biodiversity, degradation of meadows, forest belts, and agricultural crops.

### 3.2. Pasture grass research results

The following analysis examines how military actions have affected the vegetation cover of areas located in the area near military operations, as well as the potential consequences this has for the restoration of ecosystems. The results of the study of the content of toxic substances in pasture grass are presented in Table 2.

Analysis of pasture grass showed that the content of Cd, Pb, and Zn exceeds the maximum permissible concentrations recommended by WHO, but does not exceed the maximum permissible concentrations recommended in Ukraine. It should be noted that the level of Cd increased significantly in May 2025 and July 2025. The highest content (0.07 ± 0.04 ppm) was recorded in grass collected in July 2025 in the Ulyanivka village (sample G3), which is closest to the border with Russia and the zone of active military operations. It should be noted that in April 2025, the Cd content was within the permissible limits in all samples. This can be explained by the fact that green grass often has lower levels of heavy metals due to a combination of factors related to plant growth and soil conditions. Young green plants that emerge in early spring may have higher levels of heavy metal uptake, but the total biomass and surface area available for uptake are also lower. As the grass grows and matures by May 2025, the total amount of heavy metals absorbed increases, but the concentration per unit biomass may decrease due to dilution.

The highest content of Pb (1.59 ± 0.44 ppm) and Zn (15.45 ± ± 4.74 ppm) was also recorded in sample G3. These results indicate that the increase in the intensity of shelling in areas within 30 km of the combat zone leads to contamination of the soil cover with heavy metals. Despite the excess of maximum permissible concentrations, intensive accumulation of heavy metals compared to their content in the soil is not observed. All experimental soil samples belong to deep low-humus chernozems and had a pH within 6.9–7.4. In particular, it affects the solubility, bioavailability and translocation of heavy metals in plant species [17]. At high pH, metals tend to form poorly soluble phosphates and carbonates. In contrast, at low pH, they are likely to exist in more bioavailable free ionic forms [18]. Thus, pH has a significant impact on the mobility of heavy metals, causing metal ions to become less active, reducing the environmental risk associated with their presence in soil.

The changes in vegetation cover that have been identified relate not only to a reduction in biodiversity, but also to the quality of forage crops grown in the affected areas. Plants contaminated with heavy metals and explosive residues end up in the diet of cattle. Due to bioaccumulation mechanisms, these substances can accumulate in the animals' bodies and eventually end up in food products, particularly milk.

### 3.3. Milk research results

Therefore, the next step was to investigate the content of some toxic elements in cow's milk. The results of this analysis are presented in Table 3.

**Table 2**

The content of toxic elements in pasture grass

| Indicator | Maximum permissible concentration value in Ukraine, ppm | Maximum permissible concentration value to the WHO, ppm | Research samples, ppm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | G1 | G2 | G3 | G4 | G5 | G6 | G7 | G8 | G9 |
| Cd | 0.3 | 0.02 | < 0.007 | 0.048 ± 0.02 | 0.07 ± 0.04 | < 0.007 | 0.037 ± 0.02 | 0.04 ± 0.03 | < 0.007 | 0.051 ± 0.03 | 0.06 ± 0.03 |
| Pb | 30.0 | 0.3 | < 0.09 | 1.05 ± 0.54 | 1.59 ± 0.44 | < 0.09 | 0.25 ± 0.11 | 0.86 ± 0.26 | < 0.09 | 0.38 ± 0.15 | 0.34 ± 0.15 |
| Zn | – | 0.6 | 3.28 ± 1.52 | 8.29 ± 3.02 | 15.45± 4.74 | 3.75 ± 1.70 | 4.51 ± 1.99 | 13.93 ± 4.32 | 4.12 ± 1.87 | 7.75 ± 2.91 | 14.43 ± 4.46 |
| Cr | – | 1.3 | < 0.002 | < 0.002 | < 0.002 | < 0.002 | < 0.002 | < 0.002 | < 0.001 | < 0.001 | < 0.001 |
| Ni | – | 2.0 | < 0.001 | < 0.001 | < 0.001 | < 0.002 | < 0.002 | < 0.002 | < 0.001 | < 0.001 | < 0.001 |
| Sb | – | – | < 0.005 | < 0.005 | < 0.005 | < 0.007 | < 0.007 | < 0.007 | < 0.004 | < 0.004 | < 0.004 |
| Cu | – | 10.0 | 2.05 ± 0.89 | 1.29 ± 0.57 | 1.70 ± 0.76 | 1.84 ± 0.80 | 1.54 ± 0.68 | 1.67 ± 0.75 | 2.8 ± 1.14 | 1.32 ± 0.61 | 1.85 ± 0.83 |

**Table 3**

The content of toxic elements in cow's milk

| Indicator | Maximum permissible concentration value to the WHO, ppm | Research samples, ppm | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | M9 |
| Cd | 0.0026 | < 0.01 | < 0.016 ± 0.01 | < 0.015 ± 0.01 | < 0.01 | < 0.014 ± 0.01 | < 0.012 ± 0.01 | < 0.01 | < 0.014 ± 0.01 | < 0.016 ± 0.009 |
| Pb | 0.02 | < 0.02 | < 0.19 ± 0.09 | < 0.20 ± 0.1 | < 0.02 | < 0.17 ± 0.08 | < 0.18 ± 0.09 | < 0.02 | < 0.19 ± 0.09 | < 0.23 ± 0.11 |
| Zn | 5.0 | 1.62 ± 0.81 | 4.31 ± 0.91 | 4.88 ± 2.16 | 1.57 ± 0.80 | 2.84 ± 1.35 | 3.2 ± 1.52 | 1.61 ± 0.80 | 2.95 ± 1.4 | 2.57 ± 1.25 |
| Cr | 0.05 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |
| Ni | 0.02 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 | < 0.0001 |
| Sb | – | < 0.002 | < 0.002 | < 0.002 | < 0.003 | < 0.003 | < 0.003 | < 0.001 | < 0.001 | < 0.001 |
| Cu | 1.5 | 0.11 ± .05 | 0.09 ± 0.05 | < 0.06 | 0.1 ± 0.05 | 0.07 ± 0.04 | < 0.04 | 0.11 ± 0.05 | 0.05 ± 0.02 | < 0.05 |

The research results showed that all milk samples contained excess cadmium. It should be noted that the cadmium content in May 2025 and July 2025, when the largest number of explosions and air attacks are recorded in the studied areas, increases. The highest Cd content was recorded in milk samples M2 (0.016 ± 0.01 ppm) and M9 (0.016 ± 0.009 ppm), collected 29 and 43 km from the border in May 2025 and July 2025. In April 2025, the Cd content in milk in all populated areas did not exceed 0.01 ppm. The accumulation of this metal in milk may pose a health risk, especially with long-term exposure. Although the Cd levels in some milk samples may be immediately dangerous, chronic exposure can lead to a variety of health problems. Cd is a known carcinogen and can damage many organ systems, including the kidneys and reproductive system.

Also, in May 2025 and July 2025, a significant increase in Pb was observed in all experimental samples. Particularly high Pb levels were recorded in July 2025 in sample M9 (< 0.23 ± 0.11 ppm). It should be noted that in April 2025, the mass fraction of Pb in all samples remained within the WHO-recommended limits (< 0.02). Pb is a toxin that primarily affects the human nervous and vascular systems. Pb poisoning can cause anemia, lethargy, kidney and brain damage, and death.

An increase in zinc content was found in milk samples in May 2025 and July 2025. Its especially high amount was found in sample M3 (4.88 ± 2.16 ppm). The negative impact of high Zn levels in the body can lead to side effects such as nausea, vomiting, loss of appetite, abdominal cramps, and diarrhea.

The recorded concentrations of Cu ranged from 0.04 to 0.11 ± ± 0.05 ppm in milk, which does not exceed the WHO established concentration (1.5 ppm). The highest concentration was recorded in milk in April 2025. Traces of trace elements (Cr, Ni, Sb) in milk samples indicate the need for regular monitoring, as long-term exposure to these heavy metals can seriously threaten the health of consumers.

The practical significance of this research lies in obtaining real data on the safety of agricultural products in the territories within the 50-kilometer combat zone. According to the research results, there are possibilities of applying the obtained results in strategic planning and substantiation of directions of post-war reconstruction of national food security in general and its agricultural sector. A real assessment of the safety of agricultural products produced in the territories within a 50-kilometer zone from the border with the aggressor state will allow to establish the scale of the impact of military actions and assess the real threat to food security and sustainable development of the region as a whole.

The limitations of this research are that it is impossible to compare the results with the toxicity indicators of agricultural products before the start of a full-scale invasion due to the lack of such data. Another disadvantage is the inability to unequivocally prove that the main source of pollution is military aircraft, since in conditions of active hostilities other factors can also affect the level of pollution – fires, destruction of infrastructure, movement of dust masses, changes in the hydrological regime, etc. The current research is primarily descriptive and preliminary in nature, since it covers the results obtained during one season.

Further research is planned to be aimed at increasing the volume of empirical data, in order to deepen the analysis and create a mathematical model of the migration of toxic elements in the "soil – plant – milk" system. This will allow scientifically justifying or disproving the hypothesis about the impact of military actions on the level of pollution of agricultural lands and livestock products.

## 4. Conclusions

1. A study conducted on the example of the Sumy region, in particular the territory of the Mykolaivka community, located near the zone of active hostilities, revealed significant environmental consequences of military shelling. In particular, soil degradation was recorded, manifested in contamination with heavy metals (Cd, Pb, Sb, Cu). The most threatening is the concentration of Cd (17.63 ± 0.27 ppm), detected in a sample taken from the village of Tovsta in May 2025, as it is 294 times higher than the WHO recommended permissible level.

2. It was found that the content of toxins (Cd, Pb, Zn) in the vegetation cover exceeds the maximum permissible norms. At the same time, the level of pollution could be significantly higher. However, the bioavailability of heavy metals for plants from deep low-humus chernozems (pH 6.9–7.4) is lower compared to acidic soils. In a sample of pasture grasses in the village of Ulyanivka, excess concentrations of Cd (0.07 ± 0.04 ppm), Pb (1.59 ± 0.44 ppm) and Zn (15.45 ± 4.74 ppm) were recorded. Such negative phenomena may become a prerequisite for the deterioration of the state of vegetation. In particular, they may lead to a decrease in biodiversity and inhibition of natural processes of self-renewal of ecosystems. As well as to the emergence of risks for the sustainable use of natural resources in regions affected by russian aggression.

3. Analysis of cow's milk showed that contamination of soil and pasture grass leads to contamination of milk with heavy metals, in particular, cadmium and lead. Cd content in milk in May ranges from 0.012 to 0.016 ± 0.01 ppm, which is 5–6 times higher than the WHO recommended values. Exceedance of the permissible level of lead was also recorded in all samples, with the highest proportion (< 0.23 ± 0.11 ppm) in sample M9.

## Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, which could affect the research and its results presented in this article.

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## Data availability

The manuscript has no related data.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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✉ ***Maryna Samilyk,*** *Doctor of Technical Sciences, Professor, Department of Technology and Food Safety, Sumy National Agrarian University, Sumy, Ukraine, e-mail: maryna.samilyk@snau.edu.ua, ORCID: https://orcid.org/0000-0002-4826-2080*

***Tetiana Synenko,*** *PhD, Department of Technology and Food Safety, Sumy National Agrarian University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0002-5300-5142*

***Natalia Bolgova,*** *PhD, Associate Professor, Department of Technology and Food Safety, Sumy National Agrarian University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0002-0201-0769*

***Bohdan Lukhanin,*** *PhD Student, Department of Technology and Food Safety, Sumy National Agrarian University, Sumy, Ukraine, ORCID: https://orcid.org/0009-0009-6092-4444*

***Nataliia Borozenets,*** *PhD, Associate Professor, Department of Higher Mathematics and Physics, Sumy National Agrarian University, Sumy, Ukraine, ORCID: https://orcid.org/0000-0003-1023-4241*

✉ *Corresponding author*