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# DETECTING CADMIUM BIOACCUMULATION IN SOIL AND ITS TRANSLOCATION INTO AGRICULTURAL PRODUCE

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*This paper quantifies transition factors (TFs) of Cd from soil to feed for dairy cattle (pasture grass, hay, straw) and to cow's milk.*

*The study area is a transit area for the movement of military air objects and is likely to be contaminated with heavy metals. Analysis of soil and agricultural produce could make it possible to establish the level of their safety.*

*Field studies were conducted in July and October 2025 in the village of Sulske (Ukraine), located within 50 km of the combat zone. The concentration of Cd, TFs, and the trophic factor of its transfer from feed to milk (TTF) were determined using generally accepted methods. The concentration of Cd in the soil ranged from 16.49 to 16.82 mg/kg, with the highest value in the soil of agricultural land. Bioaccumulation of Cd in straw (0.036 mg/kg) dominated in October; in grass (0.06 mg/kg) and hay (0.09 mg/kg) in July. Cd levels in grass ranged from 0.034 to 0.06 mg/kg, exceeding the permissible concentration recommended by the World Health Organization (WHO) by three times. Despite this, the TF value in all samples does not exceed 1, which indicates a slight diffusion of heavy metals from chernozems. The Cd concentration in milk was practically the same, exceeding the norm established in Ukraine (0.01 mg/kg) and was 3.8–4.6 times higher than the WHO recommended value. The highest trophic factor of Cd transfer from feed to milk (0.6) is possible when cows are fed straw in July. In October, this indicator is the same for all types of feed (0.3).*

*The study showed that Cd bioaccumulation occurs in soils, plants, and milk in the territories within a 50-kilometer zone of military operations. The results could be used for subsequent analysis while further monitoring the safety of agricultural produce in this area*

*Keywords: cadmium contamination, trophic transfer factor, transition coefficient, military operations, milk safety*

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## 1. Introduction

The accumulation of heavy metals in agricultural soils affects food security. Heavy metals can inhibit crop growth,

thereby reducing yields. In addition, heavy metals from agricultural produce enter the human body, causing toxic effects.

Cadmium (Cd) is an environmental pollutant that ranks eighth in the list of the 20 most dangerous substances of

priority designation due to its high toxicity and slow metabolism [1].

Cd pollution of agricultural soils occurs mainly as a result of atmospheric precipitation, irrigation water, fertilizers, pesticides, and industrial waste discharges. Anthropogenic pollution negatively affects soil fertility and structure, disrupts plant growth and the physiological activity [2].

Cadmium is of particular concern because of its high mobility in soils, high bioavailability, persistence in agricultural environments, as well as significant toxicity and non-biodegradability [3].

The toxic effects of Cd, its environmental effects, sources, health effects, and biological effects make it a pressing problem. This highlights the importance of monitoring Cd accumulation in the ecosystem and devising strategies to mitigate its impact on the safety of agricultural produce.

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## 2. Literature review and problem statement

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It is shown in [4] that plants can absorb Cd directly from the soil. As a rule, the accumulation of Cd in agricultural soils is facilitated by the long-term use of phosphate fertilizers, pesticides, and sewage sludge [5]. It is also known that Cd accumulates in plants along roads due to the deposition of gasoline combustion products in the soil [6]. However, no facts of Cd accumulation due to fuel combustion during the operation of agricultural machinery have been found.

Among the insufficiently studied sources of Cd in the environment are military operations. It is known that Cd can enter the soil from weapon residues [7], during ground combat operations and bombings [8]. Cadmium is used in the production of batteries, in particular nickel-cadmium, which are used in various types of military equipment and vehicles [9]. Therefore, at the sites of military equipment combustion, the maximum permissible concentration of Cd is usually exceeded. However, the radius of contamination has not been established.

The amount of cadmium that accumulates in soil due to environmental pollution has been shown to depend on the magnitude of emissions, transit, and retention [10]. The proportion of heavy metal pollutants in soil is mainly determined by the balance of sorption, leaching, and uptake by plants. Soil variables such as pH, redox state, organic matter, clay, water oxides, and free carbonates significantly affect these processes. At the same time, the concentration of the metal varies significantly depending on the type of soil, including forests and heavily developed agricultural lands. It remains unclear to what extent the level of bioaccumulation of heavy metals in different soils affects the safety of food products.

It is known [11] that Cd can enter the food chain and be dangerous for living organisms. It poses serious health risks, accumulates rapidly in tissues, and causes developmental delay in children. It also has a serious impact on the auditory system, cardiovascular system and kidneys. This is especially true for children who are more susceptible to the effects of toxic substances. An option to solve this problem is to assess the safety of food products and exclude them from the diet if contamination is detected.

A serious concern for global food security is the trophic transfer of heavy metals from primary sources to food chains and adjacent ecosystems [12]. Bioaccumulation and transfer of Cd into cow milk through grazing in contaminated areas

pose a global risk to newborns, children, and adults [13]. However, there is limited research on the impact of military operations on Cd bioaccumulation and its translocation in milk.

In particular, an increase in the proportion of heavy metals in feed and milk has been recorded in the Mykolaiv territorial community of Sumy oblast [14, 15]. Exceeding the level of some heavy metals in soil, grass, and milk does not prove that the contamination was caused by military operations. However, these data indicate the need for further monitoring of the safety of agricultural produce in the territories within the 50-kilometer combat zone.

Trophic transfer (TTF) of heavy metals from primary sources to the human food chain is a serious problem. The uptake of heavy metals by plants leads to toxicity in the food chain through the consumption of products grown in contaminated soil. This can negatively affect the health of consumers.

Our review of the literature [7–10] revealed many studies on the distribution of heavy metal sources in agricultural soils. However, there is practically no data on the bioaccumulation of cadmium in soil and agricultural produce in the area near the war zone. In particular, it is not known whether military aircraft contaminate agricultural produce grown in the areas through which they transit with toxic substances. All this allows us to state that it is advisable to conduct a study on determining the concentration of Cd in agricultural produce grown within a 50-kilometer war zone.

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## 3. The aim and objectives of the study

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The purpose of our study is to determine the level of cadmium contamination of soils, feed, and cow's milk within a 50-kilometer zone of active hostilities. This will make it possible to establish the safety of raw milk in the territory near the zone where active hostilities are being conducted.

To achieve the goal in the studied area, it is necessary:

- to determine the concentration of Cd in the soil, green and dry feed, cow's milk;
- to determine the coefficient of Cd transfer from the soil to the above-ground part of plants;
- to determine the trophic factor of Cd transfer from plants to milk.

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## 4. Materials and methods

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### 4.1. The object and hypothesis of the study

The object of our study is the coefficients of Cd transfer (TF) from soil to feed for dairy cattle (pasture grass, hay, straw) and to cow's milk. The subject of the study is mass concentration of Cd in soil, feed for dairy cattle (grass, hay, straw), and whole cow's milk; coefficient of Cd transfer from soil to the aboveground part of plants; trophic factor of Cd transfer from plants to milk.

It is hypothesized that feed grown on soils within a 50-kilometer combat zone can accumulate excess Cd, which could pose risks to human and animal health. In particular, Cd accumulated in grass can pass into cow's milk, making this product dangerous for consumers. The cause of Cd accumulation in the study area may be fuel combustion products formed during the flight of missiles, drones, and guided bombs. They can accumulate in the air and settle on

the soil cover. The accumulation of toxic substances on the plant cover can cause them to enter the body of dairy cattle. As a result, they can cause milk contamination. Therefore, it is advisable not only to determine the concentration of Cd in the soil but also establish the coefficient of its transfer to milk. The study will make it possible to prove or disprove the impact of hostilities on the safety of milk produced in the 50-kilometer zone from the border with the aggressor state.

**4. 2. Materials**

Field research was conducted in July and October 2025 in the village of Sulske, Sumy oblast (Ukraine), which is located within a 50-kilometer combat zone (Fig. 1).



Fig. 1. Map of the study area (Sumy region, Sumy oblast, Ukraine), represented as a Google map image

Airplanes, helicopters, missiles, drones, guided bombs, etc. are constantly moving over this territory.

**4. 3. Soil studies**

Samples were taken at a depth of 2–20 cm on pasture (S1 – in July, S2 – in October) and on traditionally cultivated agricultural land (S3 – in July, S4 – in October). Preliminary preparation of soil samples consisted of separation of small stones and other non-soil materials. Samples were dried in a drying oven at 105°C and then crushed and sieved through a sieve with a mesh size of 0.2 mm. Soil analysis was performed by the X-ray fluorescence method using pXRF (Thermo Scientific Niton XL 2).

**4. 4. Feed research**

Grass (G1 – in July, G2 – in October) and hay (H1 – in July, H2 – in October) samples were taken on pastures where dairy cattle graze. Straw samples (ST1 – in July, ST2 – in October) were taken on an arable land where soil samples were taken.

The selected feed samples were washed with distilled water to remove dust and soil particles. The washed feed was dried in a drying oven at 60°C until constant weight was reached and ground into powder. Then 1 g of the powder was placed in flasks and digested in a solution of chloric and nitric acid (in a ratio of 1:3) at a temperature of 200–300°C. The samples were cooled at room temperature and filtered through filter paper. The filtrate was analyzed using an AAS-30 atomic absorption spectrophotometer (Germany).

**4. 5. Milk research**

Milk samples (M1, M2 in July and October, respectively) were collected from private households from cows grazing in the study areas. Whole milk obtained during lunch milking was analyzed. The Cd content in milk was determined by atomic absorption spectrometry using a PinAAcle900T spectrometer (USA).

**4. 6. Research on the trophic transfer factor and Cd transfer coefficient**

The trophic transfer factor (TTF) of Cd from grass to milk and the transfer coefficient (TF) of cadmium from soil to terrestrial plants were determined using generally accepted formulas [16]

$$TTF = \frac{C_m}{C_g}, \tag{1}$$

where  $C_g$  is the Cd concentration in plant raw materials, mg/kg;  $C_m$  – Cd concentration in milk, mg/kg.

The transfer coefficient (TF) of Cd from soil to terrestrial plants was calculated from the following formula

$$TF = \frac{C_g}{C_s}, \tag{2}$$

where  $C_g$  is the Cd concentration in plant raw materials, mg/kg;  $C_s$  – Cd concentration in soil, mg/kg.

The value of  $TF \geq 1$  means that the plant is able to accumulate heavy metals.  $TF \leq 1$  indicates that the plant avoided them or has no ability to bioaccumulate.

**4. 6. Statistical analysis**

The final results are represented as the mean ± standard deviation obtained from three independent extracts conducted within three separate studies. To assess the statistical significance of the difference between groups, the Student *t*-test was used. Differences were considered significant at a probability level of  $p \leq 0.05$ . All data are represented in tabular and graphical forms using a bar chart.

**5. Results of investigating the level of cadmium contamination of soils and agricultural produce**

**5. 1. Results of investigating the Cd concentration in soil, green and dry fodder, cow’s milk**

The results of our analysis of soil, pasture grass, hay, straw, and cow’s milk are shown in Fig. 2–4.

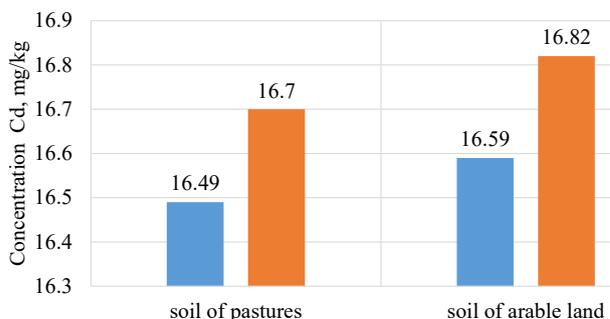


Fig. 2. Cd concentration in test soil samples

The results showed that in July, the concentration of Cd in the soil of pastures and arable land within the same settlement practically did not differ (0.1 mg/kg). The results exceeded the maximum permissible concentration established in Ukraine by 5.5–5.6 times. At the same time, the concentration of Cd in the soil of pastures in July 2025 was 275–278 times higher than that recommended by the World Health Organization (WHO). And its concentration in the soil of arable land for agricultural purposes exceeded the WHO maximum permissible norm by 277–280 times. In October, the concentration of Cd in soils increased, compared to July, by 0.21 mg/kg in the soil of pastures and by 0.23 mg/kg in the soil of arable land. This indicates an excess of the maximum permissible concentration in Ukraine by 5.6 times, and the WHO recommended concentration by 278–280 times.

The concentration of Cd in feeds used for feeding dairy cattle is shown in Fig. 3.

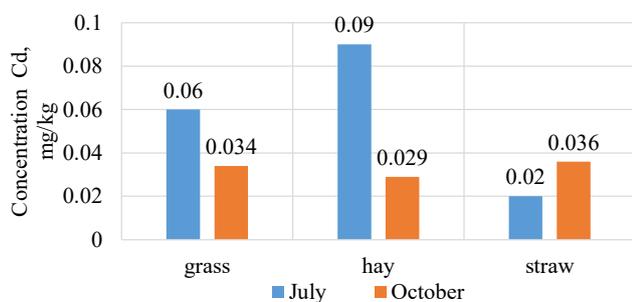


Fig. 3. Concentration of Cd in samples of feed for dairy cattle

The highest concentration of Cd was recorded in a hay sample collected in July ( $0.09 \pm 0.04$  mg/kg), and the lowest in straw ( $0.02 \pm 0.01$  mg/kg), collected in July. In October, the concentration of Cd in grass and hay samples decreased significantly, while in straw, on the contrary, it increased. The concentration of Cd in all feed samples was within the permissible limit in Ukraine. However, the concentration of Cd in fresh grass in both July and October exceeded the WHO recommended permissible concentration ( $< 0.02$  mg/kg) by 3 and 1.7 times, respectively.

The results of milk analysis are shown in Fig. 4.

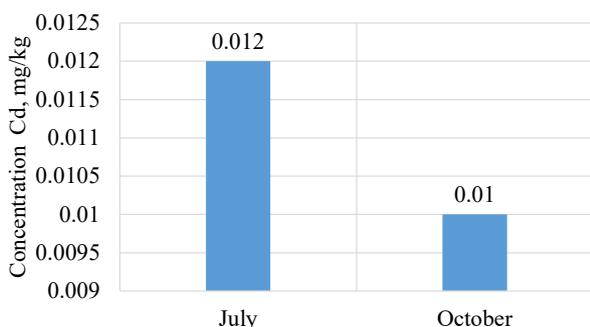


Fig. 4. Concentration of Cd in milk samples

According to the results of our study, it was found that in July and October, the concentration of Cd in milk practically did not differ, slightly exceeding the norm established in Ukraine (0.01 mg/kg). Taking into account the WHO rec-

ommended normative value (0.0026 mg/kg), the norm was exceeded by 3.8–4.6 times.

**5. 2. Results of Cd transfer from soil to pasture grass, hay, and straw**

The results of calculating the coefficient of Cd transfer from soil to pasture grass, hay, and straw are given in Table 1.

Table 1  
Cd transfer coefficient from soil to pasture grass, hay, and straw

Sample	Cd concentration, mg/kg	TF		Permissible concentration of Cd, mg/kg	
		July	October	WHO	in Ukraine
S1	$16.49 \pm 0.09$	-	-	$<0.06$	$<3.0$
S2	$16.70 \pm 0.05$	-	-		
S3	$16.59 \pm 0.05$	-	-		
S4	$16.82 \pm 0.05$	-	-		
G1	$0.06 \pm 0.03$	0.004	-	$<0.02$	$<0.3$
G2	$0.034 \pm 0.02$	-	0.002		
H1	$0.09 \pm 0.04$	0.005	-	0.5–1.0	$<1.0$
H2	$0.029 \pm 0.02$	-	0.002		
ST1	$0.02 \pm 0.01$	0.001	-		
ST2	$0.036 \pm 0.02$	-	0.002		

The results showed that despite significant soil contamination, low bioaccumulation in plants ( $TF \leq 1$ ) was observed. The highest Cd transfer coefficient was recorded in July from pasture soil to hay (0.005), and the lowest from arable land soil to straw in July (0.001). It is worth noting that the bioaccumulation of Cd in grass and hay collected on pastures is significantly higher than in straw collected on arable land for agricultural purposes. In October, the bioaccumulation of Cd in all types of feed is the same and is 0.002.

**5. 3. Results of the transfer of Cd from pasture grass, hay, and straw to cow’s milk**

The trophic factor of Cd transfer from plants to milk shows the efficiency of the movement (transfer) of this heavy metal from the diet of animals (contaminated plants, feed) to their milk. It helps assess the risks to human health associated with the consumption of milk from contaminated areas.

The results of the trophic factor of Cd transfer from pasture grass, hay, and straw to cow’s milk are given in Table 2.

Table 2  
Trophic factor of Cd transfer from feed to milk

Sample	Cd concentration, mg/kg	TTF		Permissible concentration of Cd, mg/kg	
		July	October	WHO	in Ukraine
M1	$0.012 \pm 0.01$	-	-	0.0026	$<0.01$
M2	$0.01 \pm 0.01$	-	-		
G1	$0.06 \pm 0.03$	0.2	-	$< 0.02$	$<0.3$
G2	$0.034 \pm 0.02$	-	0.3		
H1	$0.09 \pm 0.04$	0.13	-		
H2	$0.029 \pm 0.02$	-	0.3		
ST1	$0.02 \pm 0.01$	0.6	-	0.5–1.0	$<1.0$
ST2	$0.036 \pm 0.02$	-	0.3		

The highest trophic factor of Cd transfer from feed to milk was recorded in July from straw to milk (0.6). When

consuming hay, Cd bioaccumulation in milk will be lower compared to grass and straw, as evidenced by the obtained data. In October, this indicator is the same for all types of feed (0.3).

## 6. Discussion of the results of investigating the safety of agricultural produce within the 50-kilometer zone of military operations

According to our data (Fig. 2), the concentration of Cd in all soil samples significantly exceeds the maximum permissible values established both according to Ukrainian legislation and according to WHO recommendations. At the same time, the concentration of Cd in the soil of pastures and arable land was almost the same in July ( $16.49 \pm 0.09$  mg/kg and  $16.59 \pm 0.05$  mg/kg, respectively). In October, its content in both samples increased significantly. This is probably due to the intensity of air strikes in the oblast. In October 2025, Sumy oblast suffered more than 2,700 attacks, including a record 434 guided aerial bombs (CABs), 313 drones, and 17 missile strikes [16]. The concentration of Cd in the soil of the arable land was 0.23 mg/kg higher than in the soil of the pastures. These results significantly exceed the indicators in soil-agricultural systems of other countries. In particular, the concentration of Cd in the soils of the eastern edge of Lake Dunting ranged from 0.04 to 2.95 mg/kg (average 0.24 mg/kg) [17].

Compared with previous studies conducted in the experimental area (in the village of Sulske) in April 2025 [15], the concentration of Cd in the soil of the pastures increased by 2.95 mg/kg.

However, according to the results from other researchers [18] who analyzed soil samples from areas directly affected by the explosions and from sites located 500 meters away in the Sumy oblast, high levels of Pb and Ni were reported. They did not record an increase in Cd levels in the soil.

Cadmium is one of the most toxic heavy metals, and its toxicity can be considered multidirectional. It poses a health risk to both humans and animals [19]. Cadmium has no biological function in plant growth, but it readily accumulates in all plants and edible parts of crops through the metabolic pathway of essential plant nutrients such as Zn and Fe. Thus, when it enters the human and animal food chains, it can cause a wide range of acute and toxic effects [20]. Given the serious health risks associated with Cd, the accumulation of this toxin in the soil may be a serious threat to the further ecological safety of this region.

The detected concentrations of Cd in grass, hay, and straw (Fig. 3) did not exceed the maximum permissible values established in Ukraine (Table 1). According to the WHO recommendation, the Cd content in grass should not exceed 0.02 mg/kg. However, it was found that in July the Cd concentration in pasture grass was  $0.06 \pm 0.03$  mg/kg, which is three times higher than the norm. In October, the Cd concentration in grass decreased slightly, but exceeded the WHO recommended value by 0.014 mg/kg.

However, in April 2025 [15], the Cd concentration in pasture grass was significantly lower ( $< 0.007 \pm 0.09$  mg/kg) and did not exceed the WHO recommended limits. This can be explained by the fact that the content of heavy metals in green grass is often lower due to a combination of factors related to plant growth and soil conditions. Younger plants, such as those that appear in early spring, may have a higher level of heavy metal uptake, but their total biomass and

surface area for absorption are smaller. As the grass grows and matures until July, the total amount of heavy metals absorbed increases, but the concentration per unit biomass may decrease due to dilution.

According to the results [20] reported by Chinese scientists, Cd concentrations in agricultural produce ranged from 0.01 to 2.19 mg/kg (average 0.18 mg/kg). Thus, it can be argued that in the territory within 50 km of the combat zone this indicator is lower. That is, no significant bioaccumulation of the toxic metal in plants is observed. This is probably due to the quality of the soil. All the studied samples belonged to deep low-humus chernozems (pH = 6.9–7.4). At high pH, metals tend to form poorly soluble phosphates and carbonates [21]. This significantly affects the mobility of heavy metals, causing metal ions to become less active, reducing the environmental risk associated with their presence in the soil. Bioconcentration usually decreases with increasing concentration of heavy metals in the soil. This indicates that bioconcentration coefficients may be higher in uncontaminated soils than in contaminated ones [22].

The concentration of Cd in milk is dangerously high (Fig. 4) as it is at the limit of the permitted norm in Ukraine ( $0.012 \pm 0.01$ – $0.01 \pm 0.01$  mg/kg in July and October, respectively) and is 3.8–4.6 times higher than the WHO recommended value (Table 2). The highest trophic factor of Cd transfer from straw to milk was recorded in July from straw (0.6). When consuming hay, the bioaccumulation of Cd in milk will be lower compared to grass and straw, as evidenced by the obtained data. In October, this indicator is the same for all types of feed (0.3). According to the results of other researchers, the highest level of Cd in milk (12 mg/l) was recorded in the barite mining area in India [13].

Taking into account all the results obtained, whole milk produced within the 50-kilometer zone of military operations requires careful control of safety indicators before processing and consumption.

The practical significance of the results of this study will be useful for milk processing enterprises and farmers. Also, there are opportunities to apply our results in strategic planning and substantiation of directions for the post-war reconstruction of national food security in general and its agricultural sector. A real assessment of the safety of agricultural produce produced in the territories within the 50-kilometer zone from the border with the aggressor state will make it possible to establish the scale of the impact of military operations and assess the real threat to food security and sustainable development of the region as a whole. For the Mykolaiv territorial community in Sumy oblast, where the test samples were taken, the data obtained could become the basis for devising a strategy for post-war recovery and would also make it possible to take immediate measures to increase the safety of agricultural produce.

The limitations of this study include the significant difference between the maximum permissible concentrations of heavy metals in Ukrainian legislation and international legislation. This does not allow us to fully establish the extent of contamination of agricultural produce in border areas.

The disadvantage of this study is that the milk of one private household in this settlement was analyzed. Note that previous studies [15] demonstrated the results of the analysis of milk samples taken at three settlements of this territorial community.

Therefore, there is a need for further research aimed at monitoring the level of safety of agricultural produce in this area:

1. The concentration of Cd in the soil was found to be 278–280 times higher than the standard, and in pasture grass 1.7–3 times higher than the standard. In hay and straw, the concentration of Cd does not exceed the standard. In milk, the Cd norm was recorded to be 3.8–4.6 times higher than the standard. The reason for the Cd norm in milk is probably that in the studied period, the basis of the cows' diet was pasture grass.

2. The coefficient of Cd transfer from the soil to the aboveground part of plants in July is within 0.001–0.005, in October it is 0.002 in all types of feed. This indicates a low bioaccumulation of this heavy metal in the vegetation cover. Such results confirm that the transition of heavy metals from the chernozem, to which all the experimental samples belonged, to the vegetation cover is low.

3. The trophic factor of Cd transfer from feed to milk does not exceed 1. Its translocation is not critical yet. However, raw milk in the study area is subject to careful control of safety indicators. The studies will be continued in April 2026. During that period, the experimental cows will be fed dry feed (hay and straw), which could allow us to establish the actual, rather than the predicted, trophic factor of Cd transfer from feed to milk.

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#### Conflicts of interest

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The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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#### Data availability

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All data are available, either in numerical or graphical form, in the main text of the manuscript.

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#### Use of artificial intelligence

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

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#### Authors' contributions

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**Maryna Samilyk:** Conceptualization, Investigation, Resources, Writing – Reviewing and Editing, Supervision, Project Administration; **Serhii Bokovets:** Resources, Writing – Drafting, Funding; **Oleh Bakhmat:** Verification, Formal Analysis, Funding; **Ulyana Nedilska:** Methodology, Data Curation, Funding; **Taisia Ryzhikova:** Verification, Formal Analysis, Funding; **Ihor Hnoievnyi:** Methodology, Writing – Drafting, Funding; **Dmytro Hrinchenko:** Writing – Drafting, Funding; **Alla Petrenko:** Writing – Drafting, Funding; **Anna Hotvianska:** Writing – Drafting, Funding; **Yevhen Yevtushenko:** Writing – Drafting, Visualization, Funding.

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